CAE Oxford Aviation Academy

POWERPLANT

ATPL GROUND TRAINING SERIES

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Printed in Singapore by KHL Printing Co. Pte Ltd

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1

Piston Engines - Introduction

Introduction

Man's early attempt at powered flight was thwarted by the lack of a suitable engine to provide the necessary power. The steam engine widely in use at the time was heavy and inefficient. Combustion took place outside of the engine and much of the heat energy produced was wasted to the atmosphere.

In 1862 Beau de Rochas developed an engine where the combustion process took place inside the engine, but in 1876 it was Nikolaus Otto who first succeeded in producing a working engine based on the principle. The principle of operation of the engine is accomplished by inducing a mixture of air and fuel into a cylinder, which is then compressed by a piston.

The mixture is ignited and the rapid rise in temperature causes the gas pressure in the cylinder to rise and forces the piston down the cylinder. Linear movement of the piston is converted into rotary motion by a connecting rod and crankshaft. The burnt gases are then exhausted to atmosphere. The engine converts heat energy into mechanical energy.

Internal Combustion Engines fall into three main categories, compression ignition engines (Diesels), two-stroke and four-stroke spark ignition engines and Wankel rotary engines. These notes cover in detail the construction and operation of the four-stroke engine which is commonly used in aviation, and generally referred to as the Piston Engine.

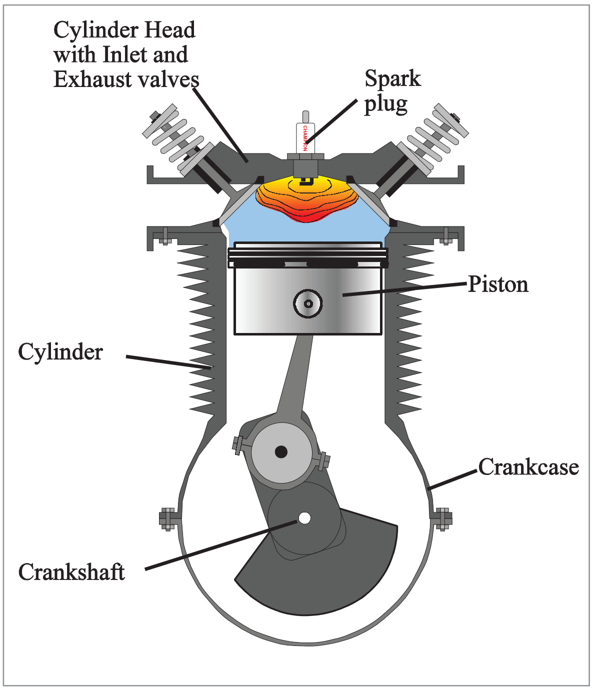


Figure 1.1

Before we look at the operation and construction of the piston engine an understanding of the following terms, definitions and theories will be required.

Terminology

Force:
A Force is that which, when acting on a body which is free to move, causes it to move, or conversely, that which stops, or changes the direction of a moving body.

Force is produced when a mass is accelerated. Force = Mass × Acceleration ($F = m \times a$) e.g. A force moves the piston down the cylinder (Units: newtons or pounds force).

Work:
The **Work Done** by a force is defined as the product of the **Force** and the **Distance** moved in the direction of the applied force. (Units: joules or foot pounds) e.g. The piston is moved from the top to the bottom of the cylinder by a force.

Energy:
Energy is the capacity of a body to do work.

Energy comes in many forms: Heat, Light, Chemical, Kinetic, Potential. (Units: joules)

The Law of Conservation of Energy states that: **"Energy can be neither created nor destroyed; only its form may be changed"**. The chemical energy of the fuel is converted to heat energy during combustion in the engine. The engine then converts this to mechanical energy.

Power:
Power is the rate of doing work. Work Done per unit time. (Units joules/second = watts or foot pound/minute = horsepower) Work is done as the piston moves in the cylinder. It is moved so many times a minute, and so the power can be measured. The horsepower is a measurement of power which is equal to 33 000 foot pounds a minute.

Dynamics

Newton's Laws of Motion deal with the properties of moving objects (or bodies). It is easy to see a piston or crankshaft move, but air is also a body, and will obey Newton's Laws. It should be remembered that air is the working fluid within the engine.

First Law.
"A body will remain at rest or in uniform motion in a straight line unless acted on by an external force".

To move a stationary object or to make a moving object change its direction a force must be applied. The mixture of fuel and air for a piston engine does not want to flow into the cylinder, a force must make it flow. The piston moving down the cylinder does not want to stop. This opposition of a body to change its motion or state of rest is called **Inertia**. Newton's 1st Law has no units of measurement. It is a property a body possesses, when stationary or moving. ***Newton's 1st Law is known as the Inertia Law.***

Second Law.
"The acceleration of a body from a state of rest, or uniform motion in a straight line, is proportional to the applied force and inversely proportional to the mass".

The energy released by the fuel during combustion increases the pressure energy of the air in the cylinder, and work can be done. The force to move the piston can be controlled by changing the pressure in the cylinder. The mass of the piston is accelerated to a velocity. Mass × Velocity is defined as Momentum. It is similar to inertia but only applies to moving bodies, and has units of measurement. kg and metres per second. ***Newton's second Law is known as the Momentum Law.***

Third Law.
"For every action there is an equal and opposite reaction".

Many examples of the application Newton's third Law can be observed. The recoil of a gun as the bullet is forced from its barrel, the snaking of a hose as water is forced from its nozzle, and the operation of the jet engine**. *Newton's third Law is known as the Reaction Law.***

Thermodynamics:
Is the study of Heat/Pressure energy. (Or the behaviour of gases and vapours under variations of temperature and pressure).

First Law.
"Heat and Mechanical energy are mutually convertible and the rate of exchange is constant and can be measured".

*(If two moving surfaces are rubbed together without lubrication, heat will be generated and can be measured with a temperature gauge. This is **Mechanical** energy converted into **Heat** energy, conversely, when fuel is burned in a piston engine, the **Heat** energy in the fuel is converted to **Mechanical** energy by the action of pistons and crankshaft. This too can be measured.)*

Second Law.
"Heat cannot be transferred from a region at a lower temperature to one at a higher temperature without the expenditure of energy from an external source".

(Heat will naturally flow from a radiator to the colder atmosphere which surrounds it, but the expenditure of energy is required to lower the temperature of a refrigerator to a level below that of the surrounding atmosphere.)

Bernoulli's Theorem

Daniel Bernoulli, a Swiss scientist (1700-1782), discovered certain properties relating to fluids in motion. These were expressed in the mathematical statement that the total energy in a moving fluid or gas is made up of three forms of energy - the energy due to the height or position **(the potential energy),** the energy due to pressure, and the energy due to movement **(the kinetic energy)** - and that in the streamline flow of an ideal fluid the sum of all these is constant.

When considering the flow of air the potential energy can be assumed to be constant; the statement can therefore be modified, for all practical aerodynamic purposes, by saying that the kinetic energy plus the pressure energy of a smooth flow of air is always constant. Thus, if the kinetic energy is increased, the pressure energy drops proportionately so as to keep the total energy constant.

A Venturi Tube

A practical application of Bernoulli's theorem with which the pilot should be familiar is the Venturi tube, sometimes called a convergent/divergent duct *(Figure 1.2)* The Venturi tube has an inlet which narrows to a throat, and an outlet section, relatively longer, which increases in diameter towards the rear.

Constant Mass Flow (The Continuity Equation)

For a flow of air to remain streamlined the volume passing a given point in unit time (the mass flow) must remain constant; if a Venturi tube is positioned in such an airstream then, for the air to remain streamlined, the mass flow through the Venturi must remain constant. Mass Flow is dependent on the Area × Density × Velocity and is a constant. This is known as the continuity equation.

To do this and still pass through the reduced cross-section of the throat the speed of flow through the throat must be increased. In accordance with Bernoulli's theorem this brings about an accompanying pressure and temperature drop. The use of Venturi tubes have many applications in aircraft systems. For example the pressure drop at the throat of the Venturi forms the basic principle of operation of the carburettor *(Chapter 8).*

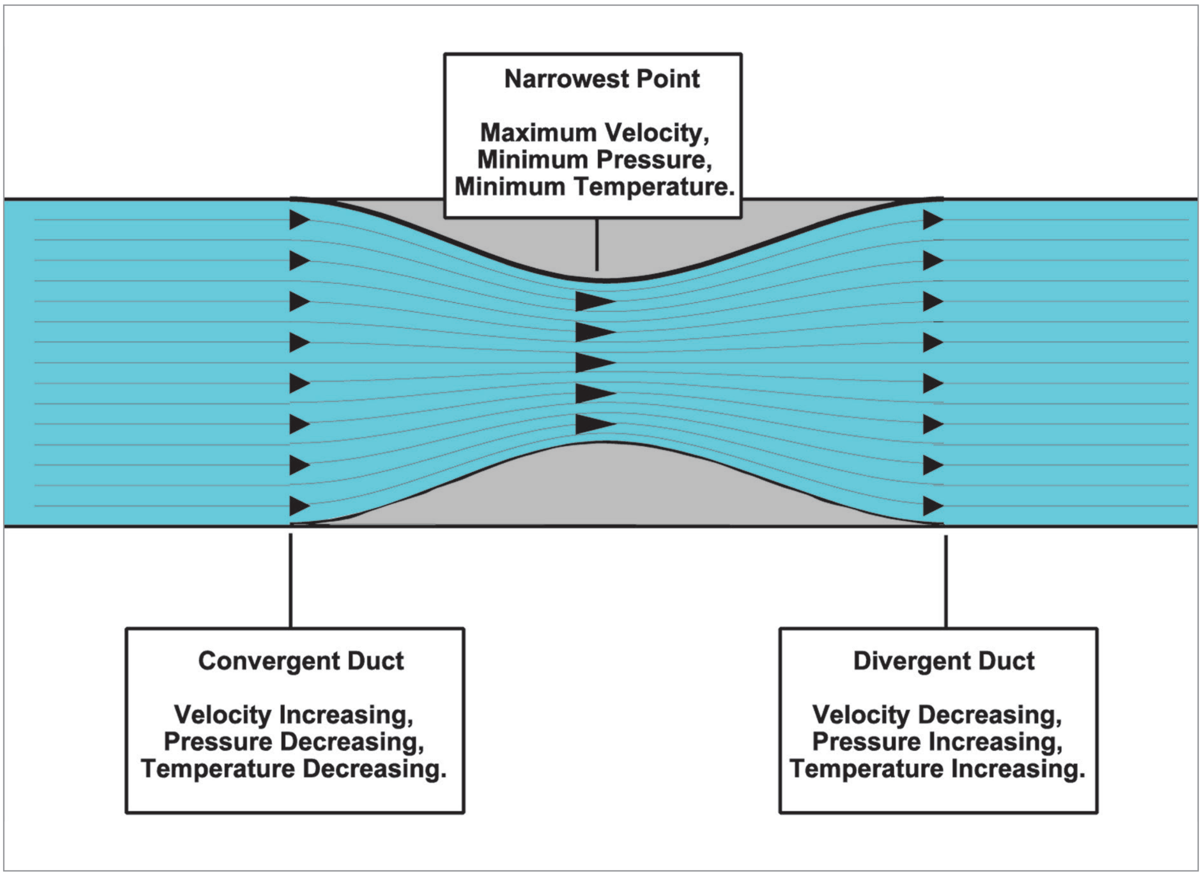


Figure 1.2 A Venturi

The Gas Laws

Boyle's Law states that: "In a gas held at a constant temperature, the volume is inversely proportional to the pressure." or:

$$P \times V = K$$

where P is the absolute pressure of the gas, and V is the volume occupied when the pressure is P.

Hence the product of the absolute pressure and volume of a given quantity of gas is constant **when the temperature does not change.**

Charles's Law

Charles's Law, or Gay-Lussac's Law states that: "If any gas is held at a constant pressure, its volume is directly proportional to the absolute temperature".

$$\frac{V}{T} = K$$

The Combined Gas Laws

The Combined Gas Law is a combination of Boyle's law and Charles's Law and represents the relationship between Volume, Pressure and Temperature.

This may be shown as:

$$\frac{P \times V}{T} = K$$, alternatively, where K is the gas constant $P \times V = K \times T$

or $$\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2}$$

The Application of the Combined Gas Law

The changes in **pressure, volume** and **temperature** within the engine cylinder as the piston moves between the top and the bottom of its stroke are illustrated in *Figure 1.3* overleaf.

These movements are known as the four **strokes** of an internal combustion engine (where combustion takes place in the engine cylinder, and not externally as in the case of a steam engine) as explained in the Otto cycle text which follows, it will be seen that only one useful or power stroke is available during the cycle which occupies two revolutions of the crankshaft. It will be appreciated that although the piston moves up and down the cylinder ("strokes") four times, there are,in fact, theoretically, five events in the cycle.

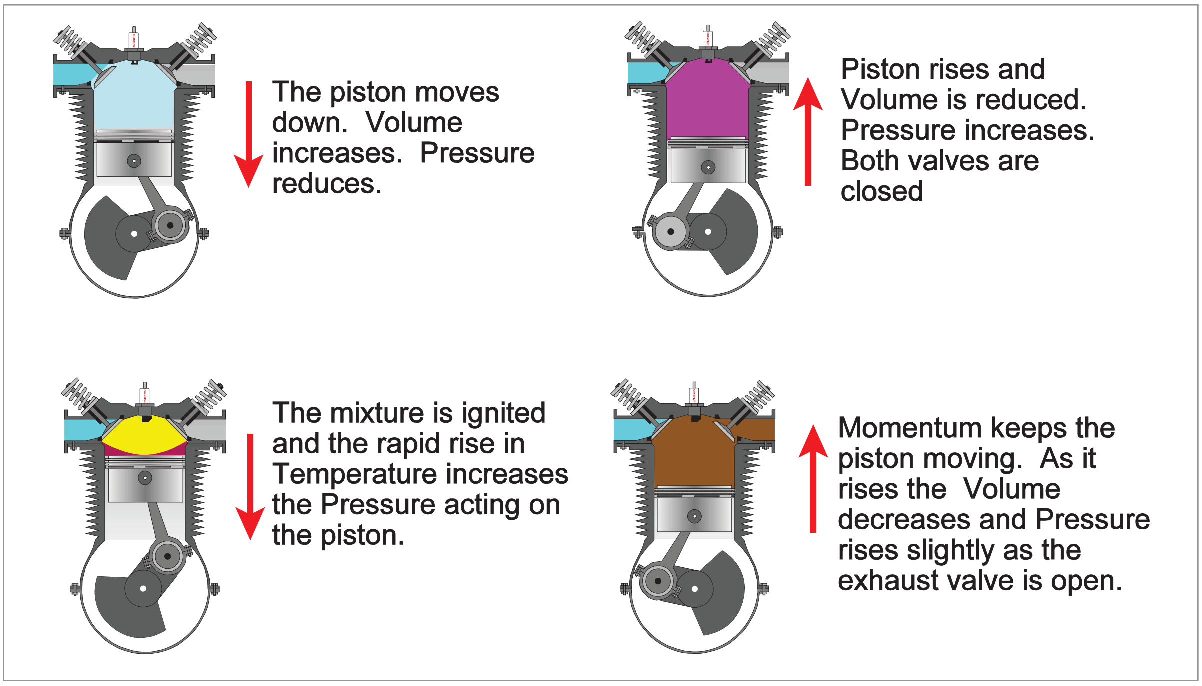


Figure 1.3

Diesel Engines

Historically credit for the design of 'cold-fuel' compression-ignition does not lie with Rudolf Diesel.

In 1891 Herbert Akroyd Stuart invented the 'cold-fuel' injection system similar in operation to modern-day automotive and aero-engine applications pre-dating Diesel's design.

In 1892 Rudolf Diesel designed and patented a similar engine to Akroyd Stuart's known as the 'hot-bulb' system where the fuel was introduced to the engine utilizing a compressed-air delivery which 'pre-heated' the fuel allowing an easier start to be achieved.

Thereafter although strictly Akroyd Stuart's design the compression-ignition engines became known as 'Diesels'. Cold-fuel compression-ignition engines were developed further because they can run faster, weigh less and are simpler to maintain.

Diesel engines for use in aircraft are by no means a new idea. Aero-diesels appeared during the late 1920s.

The mechanical parts of the diesel engine are similar to those of a conventional gasoline-driven engine with the exception that diesels reciprocating parts are slightly heavier in order to cope with higher compression-ratios within.

Recent developments in materials technology, superchargers and design have brought the diesel to comparable weights with conventional engines and indeed, with even better power/ weight ratios. These developments have given way to recent certified retro-fits being trialled in the Warrior PA28 and the Cessna 172.

Terms and Formulae

	Quantity	Symbol	Standard Units	Formula
1	Potential Difference	V	Volts, V	$V = IR$
2	Current	I	Amperes, A	$I = V/R$
3	Resistance	R	Ohms, Ω	$R = V/I$
4	Power	P	Watts. W	$P = V \times I$ or $P = I^2R$
5	Force	F	Newtons, N Pounds force, lbf	$F = ma$
6	Mass	m	Kilograms, kg Pounds, lb	$F = ma$
7	Density	ρ	kg/m^3 or lb/ft^3	$\rho = m/V$
8	Moment	M	Newton Metres Pounds Feet	$M = F \times d$
9	Velocity	v	metres/sec ft/sec	$v = d/t$
10	Acceleration	a	m/sec^2 or ft/sec^2	$a = F/m$
11	Pressure	P	Pascals, Pa (N/m^2) lb/in^2	$P = F/A$
12	Area	A	m^2 or in^2	$A = F/P$
13	Volume		m^3 or ft^3	
14	Frequency		Hertz, Hz	cycles/sec
15	Work Done		Joules, J or ft lb	$Wd = F \times d$
16	Potential Energy	PE	Joules, J	$PE = m \times g \times h$
17	Kinetic Energy		Joules, J	$KE = 1/2mv^2$
18	Efficiency		$\dfrac{\text{Useful work output}}{\text{Total energy input}}$	

Chapter

2

Piston Engines - General

Engine Layout

The power of an engine can be increased by adding cylinders producing multi-cylinder engines. This is a more efficient way of increasing power than making a single cylinder larger, and also has the benefit of making the engine run smoother. There are various types of engine design with regard to cylinder arrangement.

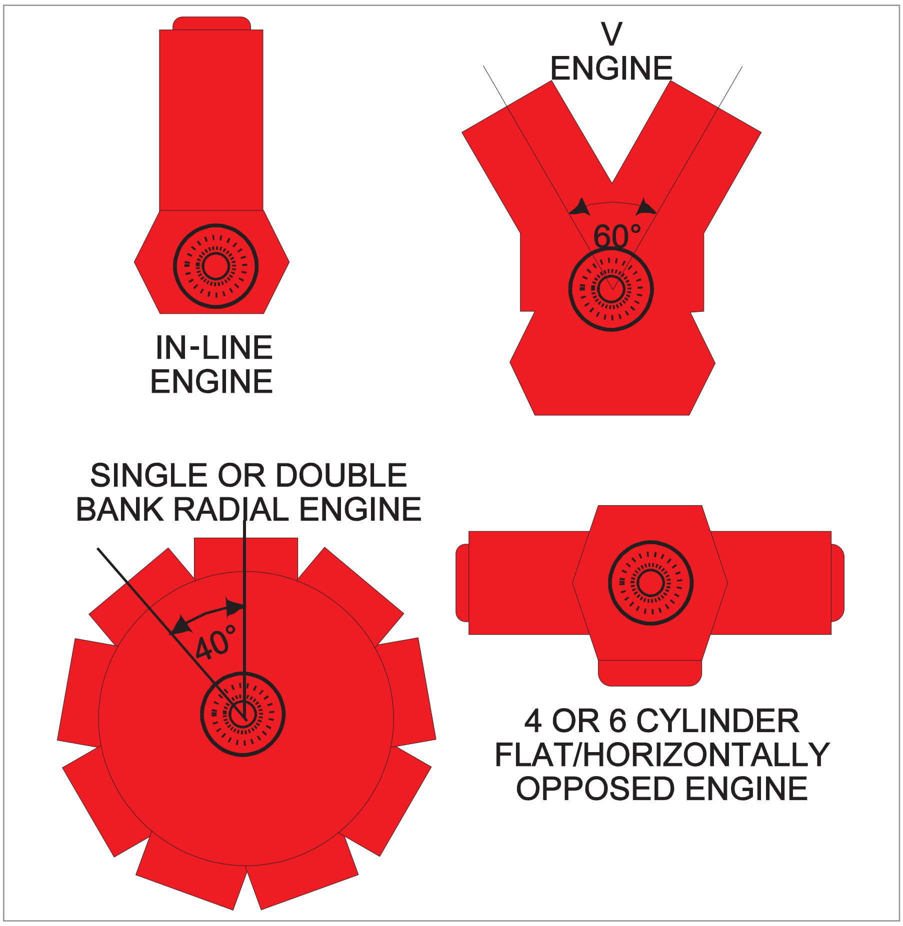


Figure 2.1 Engine Layouts

The cylinder arrangement selected for a particular engine will depend on the type of cooling of the engine, the power required, and role of the aircraft. Early aircraft used **In-line** engines. These have their cylinders arranged in a straight line, one after the other, they can be liquid or air-cooled. The air-cooled variants are limited to around six cylinders. Many in-line engines are inverted, so that the crankshaft is at the top and pistons below. The propeller is driven from the crankshaft and this arrangement gave greater ground clearance for the propeller.

The **V Engine** arrangement was used for larger more powerful engines of eight to twelve cylinders. These engines powered the fighter aircraft of World War 2. Liquid-cooled, the V arrangement of cylinders could easily be streamlined into the fuselage so reducing drag. The liquid cooling system however increased weight and complexity of the engine. Like the in-line engine they could also be inverted.

The **Radial Engine** gave a large frontal area to the aircraft, but was short in length. The pistons are arranged radially around a single-throw crank. Although drag was increased the engines were light, rigid and produced high power.

Radial engines always have an odd number of cylinders. By placing further rows of cylinders behind the first produced **Double** and **Triple Bank** radials. These engines, although very powerful, had the disadvantages of being heavy and presenting a large frontal area as they were air-cooled.

Most modern light aircraft use four or six cylinder engines arranged in the **Flat/Horizontally Opposed** configuration. This arrangement makes for a short rigid engine, which is easily streamlined.

The Theoretical Otto Cycle

In the introduction, the basic principle of operation of the piston engine was explained. The following paragraphs will explain in detail changes to the piston, valves, ignition and state of the gas throughout the operation. It was stated that the engine works on a four stroke cycle.

A **Stroke** is defined as the linear distance that the piston moves in the cylinder. When the piston is at the top of the stroke it is said to be at **Top Dead Centre (TDC)**, and when at the bottom of the stroke **Bottom Dead Centre (BDC).**

The piston is connected to a crankshaft. and as the piston moves from TDC to BDC the crankshaft rotates **180°**. The complete cycle taking **720°** (4 × 180) The **Stroke** is equal to **Twice the Crank-throw.** *Figure 2.2* an engine which has a bore equal to the stroke is known as **over-square**.

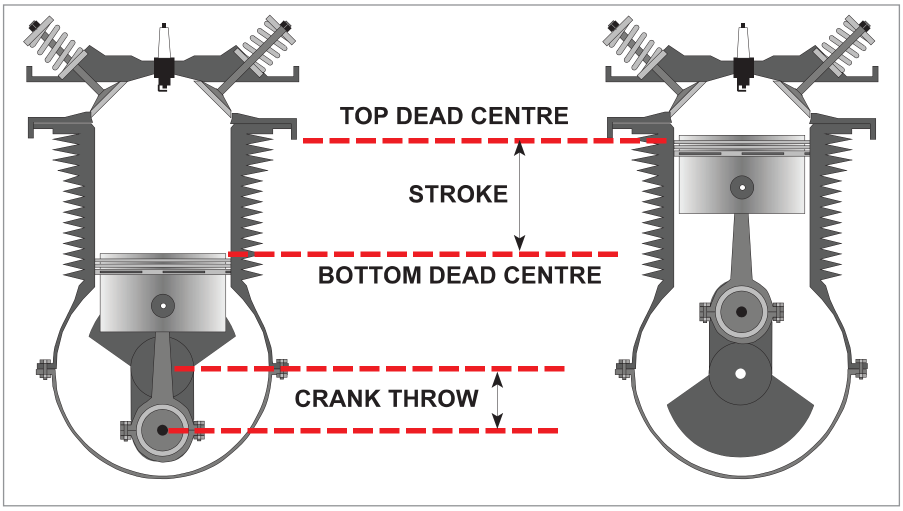
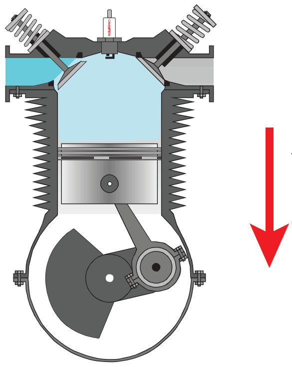


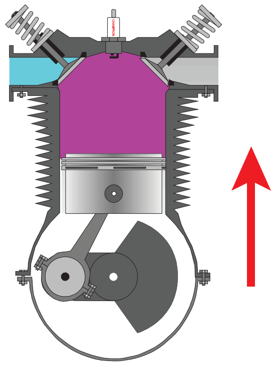
Figure 2.2

The internal diameter of the cylinder is called the **Bore.** These terms are used to explain the Otto cycle. Piston and valve positions are related to degrees of crankshaft movement, and position in relation to TDC and BDC.

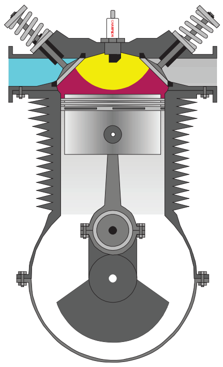
The four strokes of the Otto cycle are shown in *Figure 2.3.*



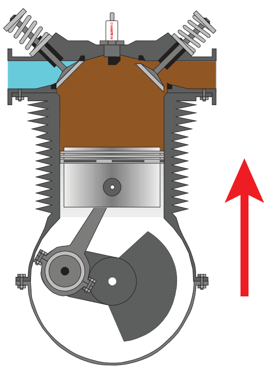
1. The inlet valve is open, permitting flow from atmosphere, through the carburettor into the cylinder.
The piston is moving down and the cylinder volume is increasing. The cylinder pressure is decreasing below ambient. The charge temperature is decreasing. The mass of the charge is increasing.



2. Both of the valves are closed trapping the induced mixture in the cylinder. The piston is moving up. The cylinder volume is decreasing. The cylinder pressure is increasing. The temperature of the charge is increasing. The mass of the charge is now fixed.



3. Both valves are still closed. The piston is stationary at the top of the stroke (TDC)
The temperature of the charge is increasing rapidly during combustion. The VOLUME IS UNCHANGED due to the stationary piston, hence the internal combustion engine is known as a ‘CONSTANT VOLUME ENGINE’.
Pressure increases rapidly with the temperature increase. The piston is forced down by the pressure increase. The cylinder volume is therefore increasing. This means that cylinder pressure is decreasing, and as a function of that, the temperature decreases.



4. The exhaust valve is now open to atmosphere. The piston moving up forces the exhaust gas past it to the atmosphere. The atmosphere provides a resistance to the flow of exhaust gas which is termed ‘EXHAUST BACK PRESSURE’. Because of this the pressure in the cylinder increases slightly which causes the temperature to rise also.

Figure 2.3 The four strokes of the Otto Cycle

The Operation of the Theoretical Otto Cycle

The four strokes are:

a) Induction
b) Compression
c) Power
d) Exhaust

When the piston is at TDC at the end of the compression stroke an electrical spark is produced at the spark plug, and ignites the fuel air mixture. It should be appreciated that this does not result in an explosion of the mixture, but is a controlled burning. This event is called **Combustion.** The combustion process takes place with the piston at TDC. The volume in the cylinder at that moment in time is constant. Combustion is said to take place at **Constant Volume**.

In the theoretical Otto cycle there are **Five Events**:

a) Induction
b) Compression
c) Combustion
d) Power
e) Exhaust

These events can be shown graphically by a valve timing diagram **-** *Figure 2.4.* The timing diagram shows the relationship between the events, and degrees of crankshaft rotation. Each arc between TDC and BDC represents 180° of crankshaft rotation.

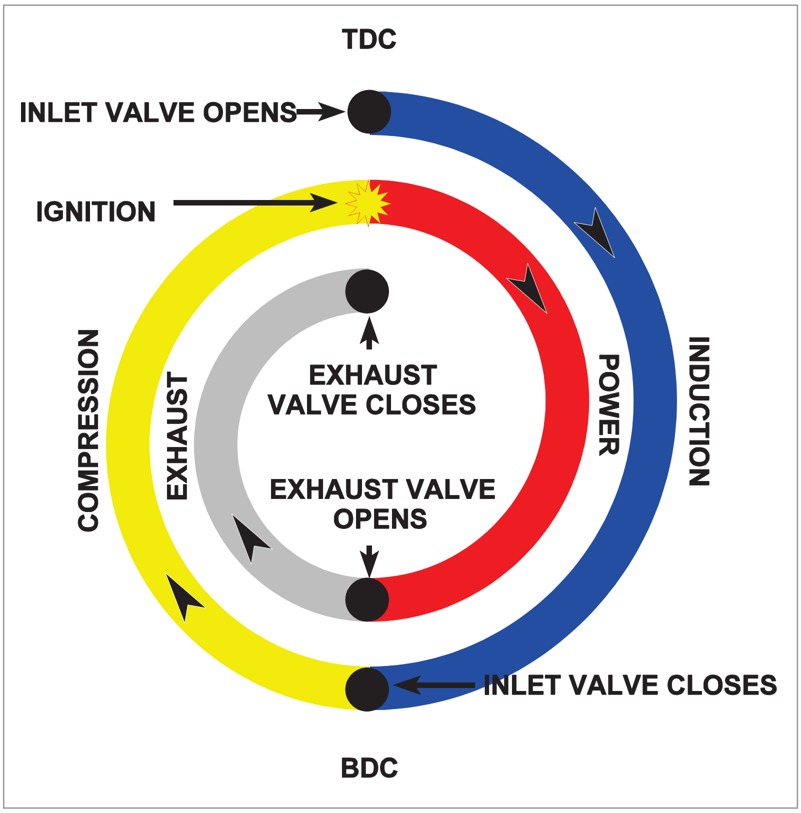


Figure 2.4 The theoretical timing diagram for the Otto Cycle

The Operation of the Practical Otto Cycle

In practice the theoretical cycle proved to be inefficient and it was necessary to modify the times of valve openings and closings and ignition. A typical practical timing diagram is shown in *Figure 2.5* and the reasons for the modified timings are discussed below.

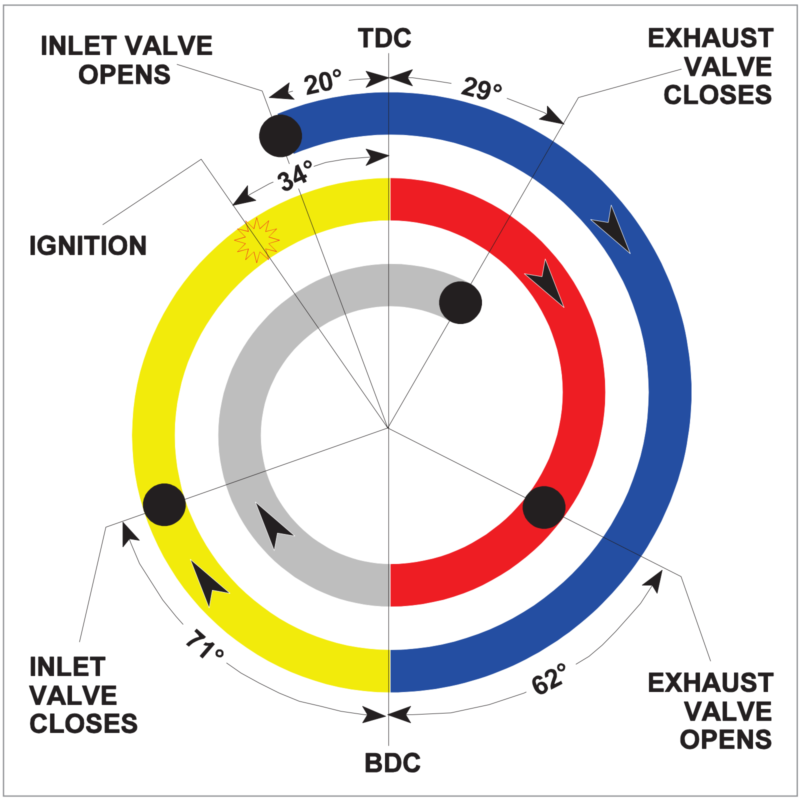


Figure 2.5 A practical valve and ignition timing diagram

The Induction Stroke

Opening the inlet valve before TDC ensures that the valve is fully open early in the induction stroke, there is then no time-lag between the piston moving down and the mixture flowing into the cylinder as would otherwise occur due to the inertia of the mixture. The inflowing mixture can thus keep up with the descending piston.

The momentum of the mixture increases as the induction stroke proceeds, and towards the end of the stroke, it is such that the gases will continue to flow into the cylinder even though the piston has passed BDC and is moving upwards slightly. The closing of the inlet valve is therefore delayed until after BDC when the gas pressure in the cylinder approximately equals the gas pressure in the induction manifold.

The Compression Stroke

As the piston moves upwards, the inlet valve closes and the gas is compressed. By squeezing the gas into a smaller space the pressure that it will exert when burnt is proportionally increased.

It should be noted that as the gas is compressed it becomes heated adiabatically, in the same way that a bicycle pump warms up in action, as well as by conduction from its hot surroundings, and the pressure consequently rises to a higher value than that to be expected from the reduction in volume alone.

Adiabatic

Adiabatic means without loss or gain of heat. With present technology it is not possible to compress or expand a gas without gain or loss of heat.

The Power Stroke

Before the piston reaches TDC on the compression stroke the gas is ignited by a spark, the momentum of the moving parts carrying the piston past the TDC whilst the flame is spreading. As the flame spreads through the combustion chamber the intense heat raises the pressure rapidly to a peak value which is reached when combustion is complete, this coincides with the piston being at about 10° past TDC.

If the exhaust valve is not opened until BDC the pressure of the gases remaining in the cylinder would create a back pressure resisting the upward movement of the piston. As the piston descends on the power stroke, the pressure falls rapidly and by 45° of crank angle after TDC. is approximately half its peak value, and by 90° of crank angle after TDC. most of the energy in the gases has been converted into mechanical energy. If the exhaust valve is opened before BDC the residual pressure will start the first stage of exhaust scavenging, so that by BDC there will be no back pressure on the piston.

This **pressure scavenging** does not produce a significant loss of mechanical energy because:

a) There is only a short distance left for downward movement of the piston after the exhaust valve is opened.

b) Relatively little pressure is still being exerted on the piston by the cooled expanded gases.

The Exhaust Stroke

Finally the piston moves upward forcing the remaining gases out of the cylinder. The exhaust valve is left open after TDC to permit the gases to scavenge the cylinder as completely as possible by their momentum.

About the position of TDC. and BDC, the distance the piston moves is very small compared to the large angular movement of the crankshaft. This is called the **Ineffective Crank Angle** - *Figure 2.6*. As there is little change in the cylinder volume at these times, the weight of charge into the cylinder and the exhaust of the burnt gases can be improved by opening the valves early and closing them late. These changes to the valve timing are named **Valve Lead, Valve Lag and Valve Overlap** (*see Figure 2.5*).

Valve Lead

Is when the valve opens before the theoretical opening time. *(Inlet valve opens before TDC, exhaust valve opens before BDC).*

Valve Lag

Is when the valve remains open after the theoretical closing time. *(Inlet valve remains opens after BDC, exhaust valve remains open after TDC).*

Valve Overlap

Is a period when both valves are partially open together. During this period the action of the exhaust gases flowing out of the cylinder tends to reduce the gas pressure in the cylinder below the gas pressure in the induction manifold. The mixture commences to flow into the area of low pressure and assists in displacing the remaining burnt gases and by doing so improves the volumetric efficiency of the engine by inducing a greater weight of charge into the cylinder.

The valve timing for a particular engine is fixed, and does not vary with engine speed.

Control of power in the piston engine is achieved by varying the quantity of air which enters the cylinder; this in turn will vary the pressure rise during combustion. The pilot controls a valve, the **Throttle** to vary the quantity of air.

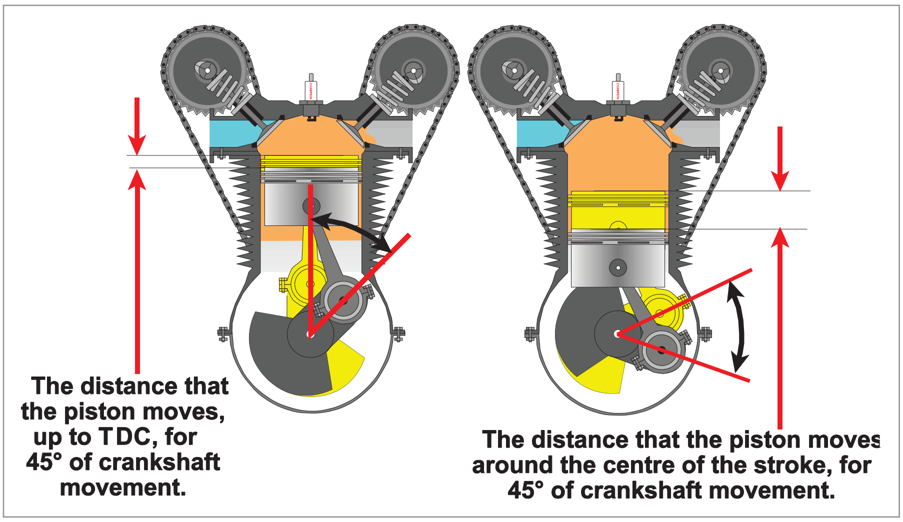


Figure 2.6 Ineffective crank angle

The variations in pressure within the cylinder during the four strokes can be measured and indicated graphically by a device which produces an **Indicator diagram**. The device plots pressure against volume, and the graph is also known as a **PV diagram**. This small attachment, fitted to research and experimental engines, consists basically of a pressure transmitter fitted into the combustion chamber of the engine, (in a similar manner to a sparking plug), activating a moving pen which traces cylinder pressure variation against piston position, as shown in *Figure 2.7*.

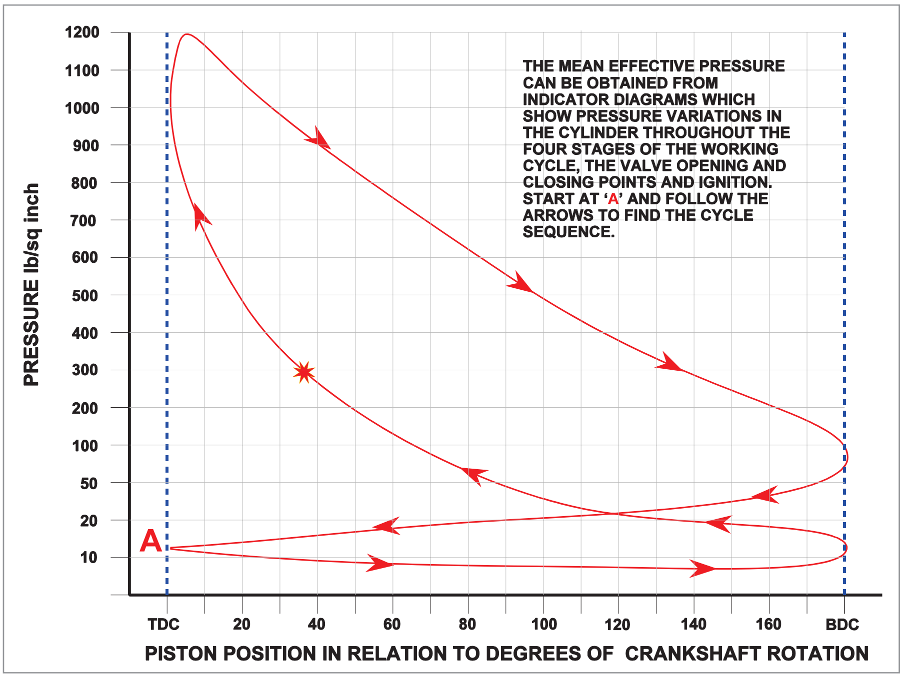


Figure 2.7 A typical indicator diagram

The indicator diagram is used to plot the maximum pressures obtained, this determines the shape and the area enclosed by the graph. This area is representative of the work done on the air and the power produced.

Figure 2.9 shows the indicator diagram opened out so that the pressure areas under the curve can be more easily compared and measured.

The area within the power column represents work done on the piston during the power stroke and the blue areas represent work done by the piston in compressing the charge and exhausting the cylinder against back pressure. This results in an average reading of pressure on the piston during the working cycle being available which is termed the **Indicated Mean Effective Pressure (IMEP).**

The pilot is not given a display in the cockpit of the IMEP but what can be displayed is manifold pressure which is representative of cylinder pressure. This is displayed on the **manifold pressure gauge.** Opening the throttle increases manifold pressure and closing the throttle will reduce it. The Manifold Absolute Pressure gauge (MAP) is normally calibrated to read in inches of mercury.

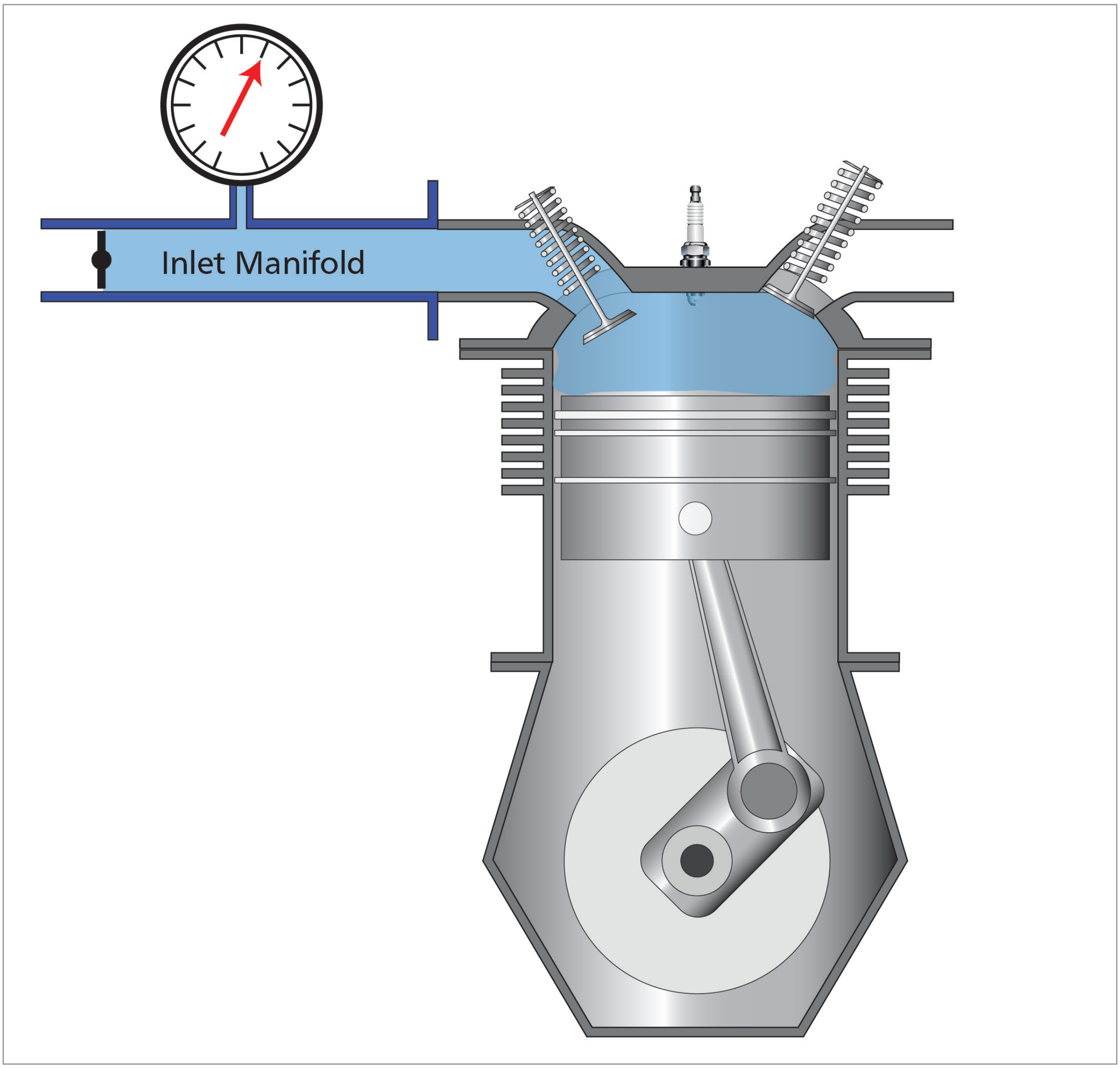


Figure 2.8 Manifold absolute pressure gauge

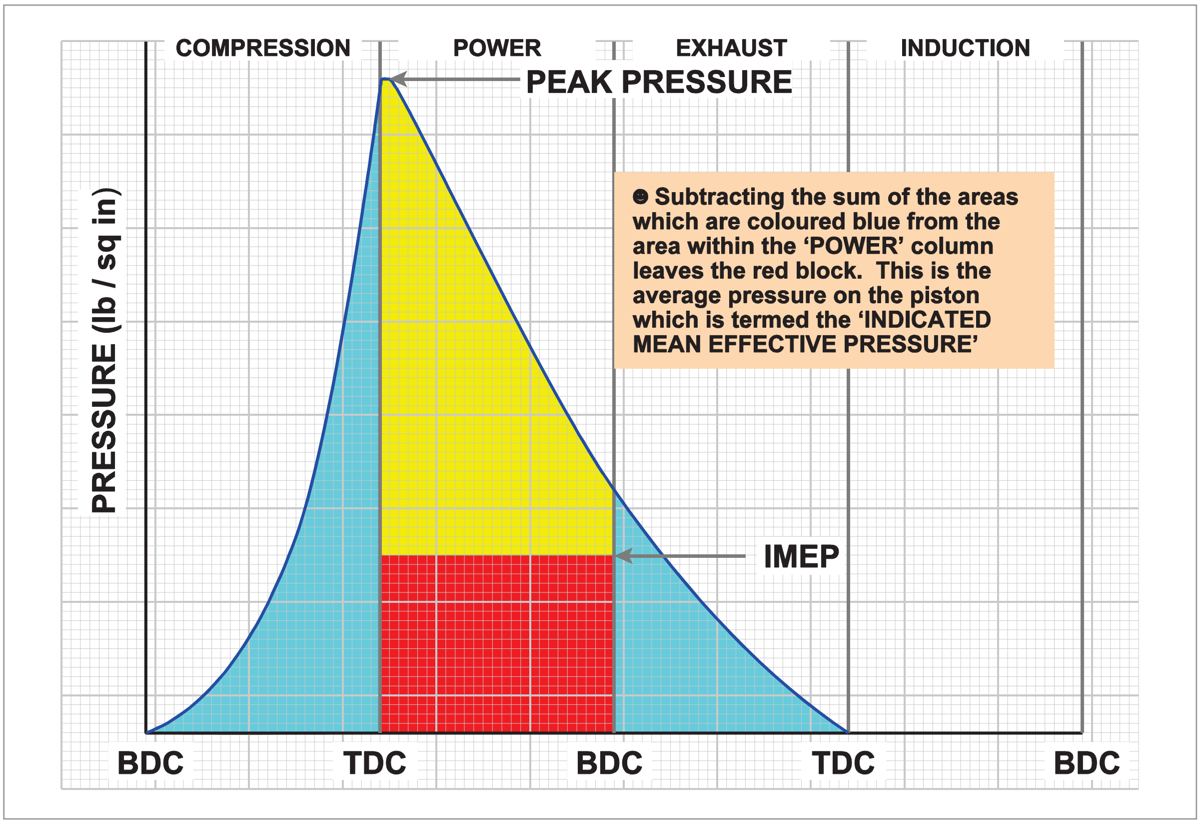


Figure 2.9 An indicator diagram plotted against stroke for simpler calculation of pressure areas

Having found the pressure in the cylinder it is now possible by calculation using the known constants, area of piston, (bore), distance moved (stroke), number of cylinders and time. To calculate the **INDICATED HORSEPOWER (IHP)** of the engine concerned, use the formula:

$$\text{IHP} = \frac{P \times L \times A \times N \times E}{33\,000}$$

where:
P = Indicated Mean Effective Pressure (lb/in^2)
L = Length of Stroke (ft)
A = Area of cylinder (in^2)
N = The number of cylinders
E = Effective working strokes/min (rpm)

In the introduction, power was defined as the rate of doing work. Work is done when a force is moved through a distance. A force acts on the piston - (lb) The piston moves through the distance of the stroke - (ft) It does this so many times a minute. This multiplies out as ft-lb per minute.

The inventor of the steam engine James Watt calculated that the average horse could move 1lb a distance of 33 000 ft in 1 minute - (550 ft/lb/second). This is why P L A N E is divided by the constant of 33 000 and the unit of power referred to as horsepower.

The SI unit of power is the watt, and 750 watts is approximately equal to 1 horsepower.

IHP is only a theoretical value of power. In moving the piston and turning the crankshaft power is used. This is called **Friction Horsepower**, (FHP), and must be deducted from the IHP. The power then left to do useful work (for example driving a propeller) is called Brake Horsepower (BHP).

Power to Weight Ratio

Power to Weight Ratio (Specific Power Output) is a comparison of an engine's power output per unit weight (kW/kg or horsepower/lb) expressed as a ratio.

For example: An engine weighing 1000 lb (450 kg) and producing 250 hp (190 kW) would produce a power to weight ratio of 0.42 kW/kg, or 0.25 hp/lb.

Specific Fuel Consumption (SFC)

The increase in energy given to the air comes from the heat released by burning the fuel. This in turn produces power in the engine. The weight of fuel burnt, in lb, for the power produced BHP in unit time (hours) is called the **Specific Fuel Consumption**.

Engine designers strive to get as much power as possible from the engine, for the minimum weight of fuel burnt. During operation a reduction in power for the same weight of fuel burnt, is defined as an **Increase in Specific Fuel Consumption**, and a reduction in fuel burnt for the same, or more power a **Decrease in Specific Fuel Consumption.**

SFC is affected by engine design and **pilot operation** of the engine. Since the pilot has no control over design, correct operation of the engine is essential if performance figures are to be attained.

Engine Efficiencies

The engine is a machine that converts heat energy into mechanical energy. Sadly there are losses in this transfer; engine design will try to reduce these losses. As stated previously the IHP developed in the engine is reduced by FHP, leaving BHP to do useful work.

The term efficiency means simply a comparison of what is got out of a system, with what is put in to the system. The efficiency of any mechanical device must be less than unity, it is usual to express it as a ratio.

Mechanical Efficiency

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100\% \qquad \text{Thus the mechanical efficiency} = \frac{\text{BHP}}{\text{IHP}} \times 100\%$$

A typical value of mechanical efficiency would be in the region of 80 - 85%.

Thermal Efficiency

The efficiency at which the heat energy released by the combustion of the fuel is converted to work done in the engine is known as the **Thermal Efficiency.**

$$\text{Thermal Efficiency} = \frac{\text{heat converted into work}}{\text{heat energy available within the fuel}} \times 100\%$$

Engine design and the use of correct fuels increase thermal efficiency. A good value for thermal efficiency in an internal combustion engine would be 25 - 28%.

As previously stated, air is the working fluid within the engine. Added to this is fuel, so it is actually a mixture of air and fuel that enters the cylinders. The power of the engine is determined by the maximum weight of mixture (charge) induced, and the subsequent rise in pressure during combustion. Due to inertia and factors affecting the density of the mixture, it is not possible to fill the cylinder completely during the induction stroke.

Volumetric Efficiency

The ratio of the weight of mixture induced to that which would fill the cylinder under normal temperatures and pressures is called **Volumetric Efficiency.**

$$\text{Volumetric Efficiency} = \frac{\text{weight of mixture actually induced}}{\text{weight of mixture which could fill cylinder}} \times 100\% \quad \text{at normal temperatures and pressures.}$$

The volumetric efficiency of the engine is indicative of how well the engine is breathing. This is affected by design, i.e. valve lead, lag and overlap. It is also affected by variables such as, exhaust back pressure, resistance to flow and the force pushing the mixture into the cylinder. If the force is the difference in pressure between atmospheric and the cylinder pressure during induction, the engine is said to be **Normally Aspirated.**

A normally aspirated engine will have a volumetric efficiency of between 75-85% maximum. One way to improve the volumetric efficiency and hence power, is to increase the force pushing the mixture into the cylinder. This is called **Supercharging** and is covered later in these notes.

Compression Ratio

The work done on the mixture by the piston during the compression stroke depends on the weight of mixture induced and the pressure that it is raised to. The pressure rise will depend on the reduction in volume. There are three volumes that need to be considered. They are defined below and illustrated in *Figure 2.10*.

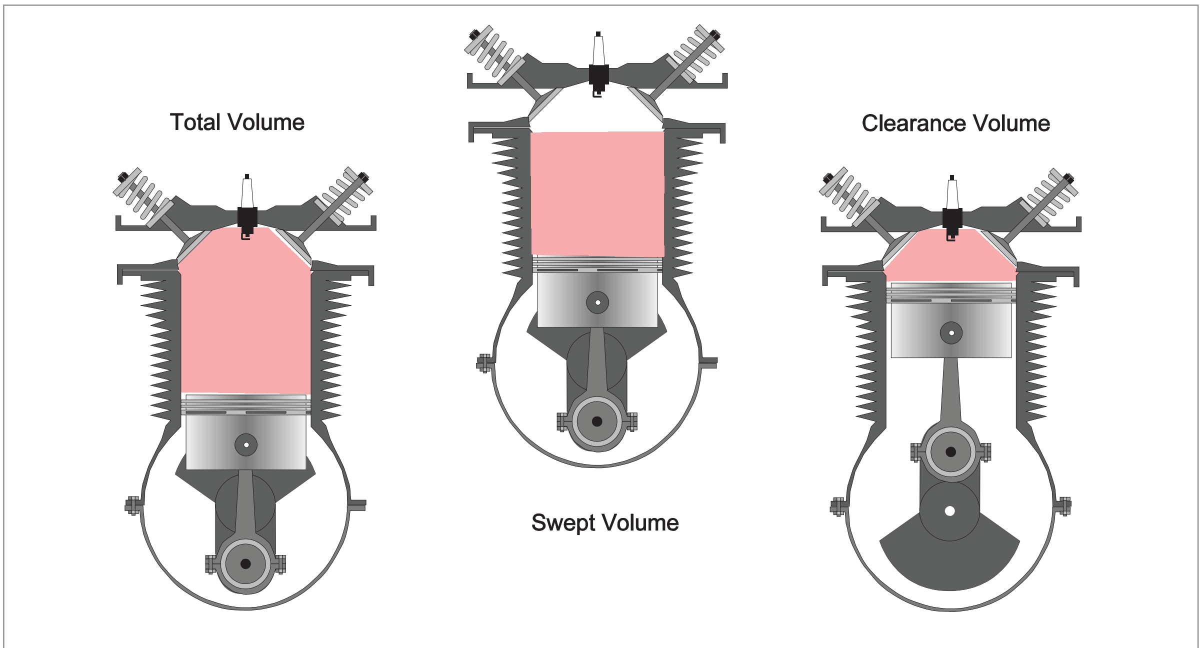


Figure 2.10

Total Volume is the volume above the piston when the piston is at BDC.

Swept Volume is the volume displaced by the piston during a single stroke. Swept volume = cross-sectional area of the cylinder × the stroke.

Clearance Volume is the volume above the piston crown when the piston is at TDC, this forms the combustion chamber. Total Volume = Swept Volume + Clearance Volume. The increase in pressure is called the **Compression Ratio** of the engine.

The Compression Ratio is the ratio of the total volume enclosed in the cylinder with piston at BDC, to the volume at the end of the compression stroke with the piston at TDC.

$$\text{Compression Ratio} = \frac{\text{Total Volume}}{\text{Clearance Volume}}$$

EXAMPLE. If the swept volume is equal to 1300 cc, and the clearance volume is equal to 200 cc the compression ratio would be equal to:

Total Volume = Swept Volume + Clearance Volume

Total Volume = 1300 + 200

$$\text{Compression Ratio} = \frac{\text{Total Volume}}{\text{Clearance Volume}}$$

$$\text{Compression Ratio} = \frac{1500}{200}$$

Compression Ratio = 7.5 : 1

Note: *An increase in compression ratio will result in better fuel utilization (hence greater **Thermal Efficiency**) and a higher mean effective pressure provided the correct fuel is used. This, however, will be at the expense of higher loading on the moving parts due to an increased working pressure.*

Engine Construction

The main components of the engine were stated in the introduction. The following is a more detailed explanation of the mechanical components and their function.

The Crankcase

The crankcase is usually made in two halves to make installation and removal of the crankshaft easier, it houses the main bearings for the crankshaft, supports the cylinders and provides mounting faces and spigots for the attachment of the other main engine casings.

Generally made of light alloy, it forms a sealed chamber for the lubricating oil, and is provided with the means of attaching the engine to its mounting frame in the aircraft see *Figure 2.11*.

A vent to atmosphere is normally provided in order that gas pressure build-up in the crankcase is avoided.

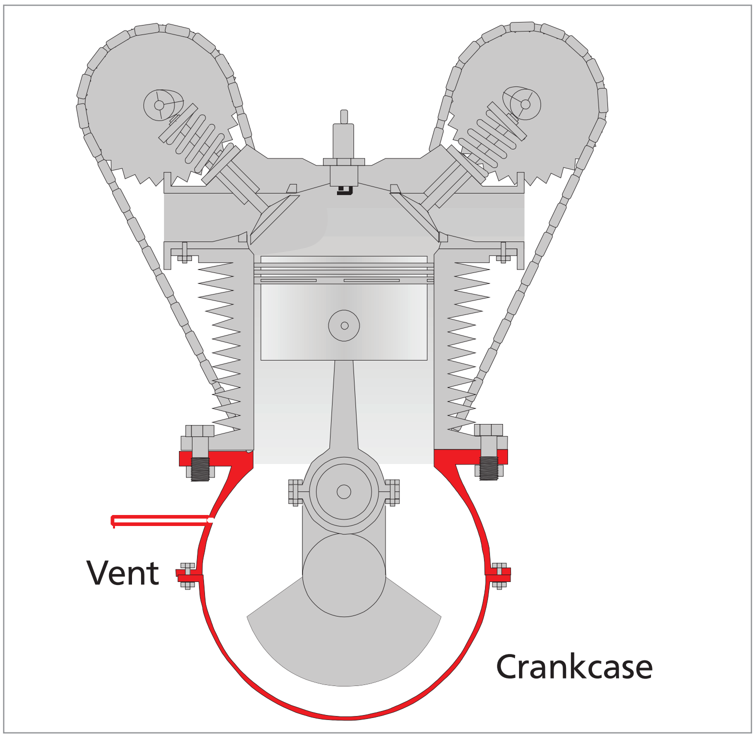


Figure 2.11

Crankshaft (Cranked-shaft)

The crankshaft, illustrated in *Figure 2.12*, converts the reciprocating or linear motion of the pistons into rotary motion, and transmits torque to the propeller, and provides the drive for accessories. The offset **Crank Throw** also determines the piston stroke.

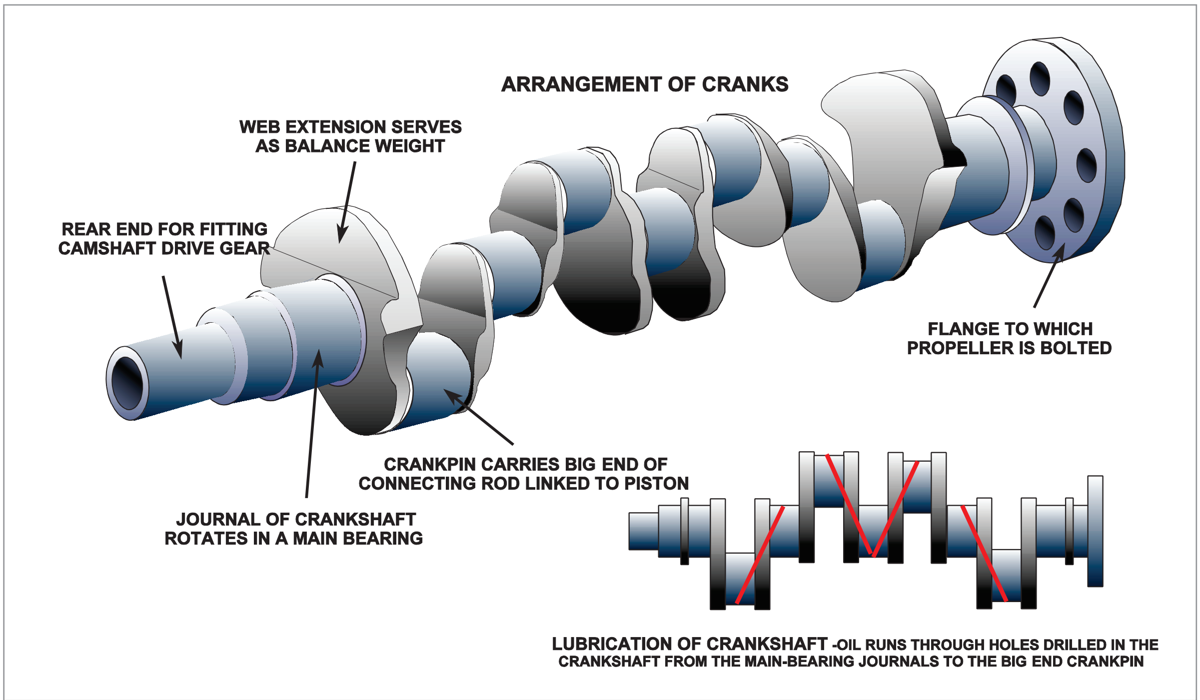


Figure 2.12 A four cylinder crankshaft

The **Journals**, the main part of the shaft, are supported by the main bearings in the crankcase.

The **Pistons** are attached by the **Connecting Rods** to the **Crank-pin.**

The crankshaft often has as many crank throws as there are pistons *(four throws for a four cylinder engine).* Oil-ways are drilled through the shaft to transfer the lubricating oil onto the bearing surfaces. **Plain Bearings** are used to enable the high reciprocating loads to be carried. The oil-ways can also be used to carry oil for the operation of a variable pitch **Propeller.**

The crankshaft is accurately balanced to minimize vibration, however, when a shaft has to transmit a torque or twisting moment it must flex to some extent and spring back again when released. If the shaft must have a lot of kinks in it to provide the crank throws, the twisting moments are hard to resist and perceptible deflection may take place.

In the case of a radial engine, several cylinders may be connected to a single throw, and a horizontally opposed engine may have only two pistons connected to one crank-pin.

The repeated applications of force to which the crankshaft is subjected may set up oscillations as the shaft recovers its original shape between power impulses. At certain speeds the impulses may coincide with the natural vibration period of the shaft and give very rough running even in an engine which is in good mechanical balance. For these reasons the shafts should be as short as possible and adequately supported and counter-weighted to minimize these torsional effects. In any event, many engines have rpm ranges which are prohibited for prolonged use (Critical rpm) to prevent unnecessary vibration. This is indicated by a **Red Arc** on the rpm indicator.

It was previously stated that increasing the number of cylinders improves the power output and makes the engine run smoother. This is because there are more power strokes in the 720° of crankshaft rotation. This is called the **Firing Interval.** Four cylinders are generally regarded as the minimum number to give reasonable firing interval. The firing interval for any engine can be found by dividing 720° by the number of cylinders of the engine. i.e. 4 cylinder =180° and a 6 cylinder engine = 120°.

The crankshaft and cylinder arrangement will also determine the order in which the cylinders fire. This is called the **Firing Order** of the engine.

A typical four cylinder engine could have a firing order of **1-3-4-2.** The cylinders do not fire consecutively as this reduces the load and vibration on the crankshaft.

Note: *Lycoming firing order is 1-3-2-4.*

Connecting Rods

The connecting rods transmit the forces of combustion to the crankshaft; they convert the linear movement of the pistons into rotary movement of the crankshaft. A connecting rod is usually made of H section high tensile steel, to combine lightness with the strength necessary to withstand the compressive and tensile loads imposed as the piston changes direction. The rod is connected to the crank-pin of the crankshaft by a large circular bearing at the **Big End** of the rod.

The Pistons

Generally made of aluminium alloy, the piston forms a sliding plug in the cylinder and transmits the force of the expanding gases via the connecting rod to the crankshaft. Bosses are formed to house the **Gudgeon Pin** which fastens the piston to the **Small End** of the connecting rod. Circumferential grooves are machined in the piston to accommodate piston **Rings** which provide the means of preventing pressure leakage past the piston in one direction and oil leakage in the other.

A number of piston rings can be fitted to a piston. Their arrangement will vary from engine to engine, but will be similar to the following paragraphs, and *Figure 2.13*.

The **Compression Rings** prevent gas leakage into the crankcase. They are fitted into grooves cut into the upper portion of the piston. Gas passing down between the piston and the cylinder wall forces a compression ring down in its groove and outwards against the cylinder wall. A small amount of gas will pass the top ring; so a second (and sometimes a third) compression ring is fitted.

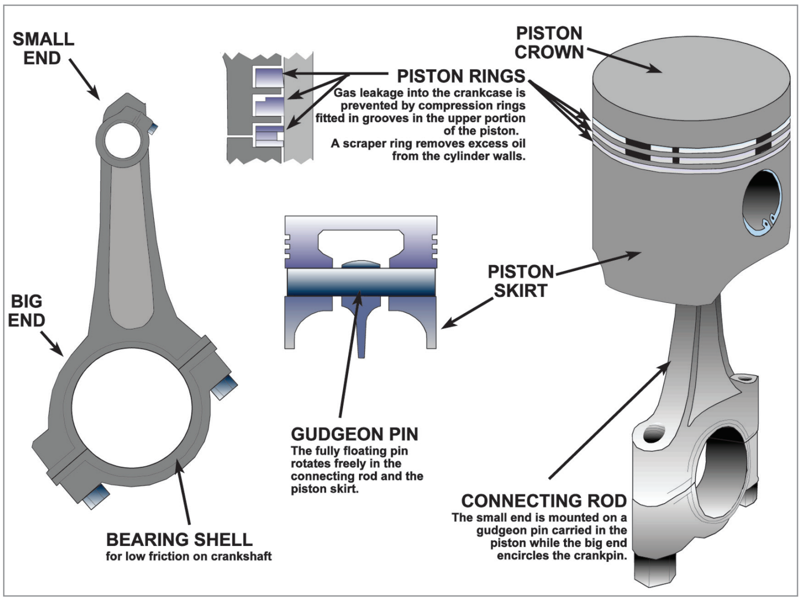


Figure 2.13 The piston and associated components

The **Scraper Rings** or **Oil Control Rings** prevent excess oil passing into the combustion chamber and spread the oil evenly around the cylinder bore. They are designed so that the bearing face is reduced in area and the bearing pressure consequently increased.

The rings are generally made of a special grade of cast iron; the rings are sprung against the cylinder walls.

Cast iron has the ability to retain its elasticity when heated. It also has self-lubricating qualities due to the graphitic content of the metal. This is desirable because during the power stroke the walls of the cylinder are exposed to the hot combustion gases, and the thin film of oil is burned away.

Piston rings which are worn or stuck in their grooves will cause excessive blue smoke (burning oil) to be ejected from the exhaust pipe.

Cylinder Barrel or Block

Made of alloy steel, the **Cylinder** resists the pressure of combustion and provides a working surface for the piston. The cylinders are usually secured to the crankcase by studs and nuts. One end of the cylinder is sealed by the **Cylinder Head**, the movable piston sealing the other end. *Figure 2.14*

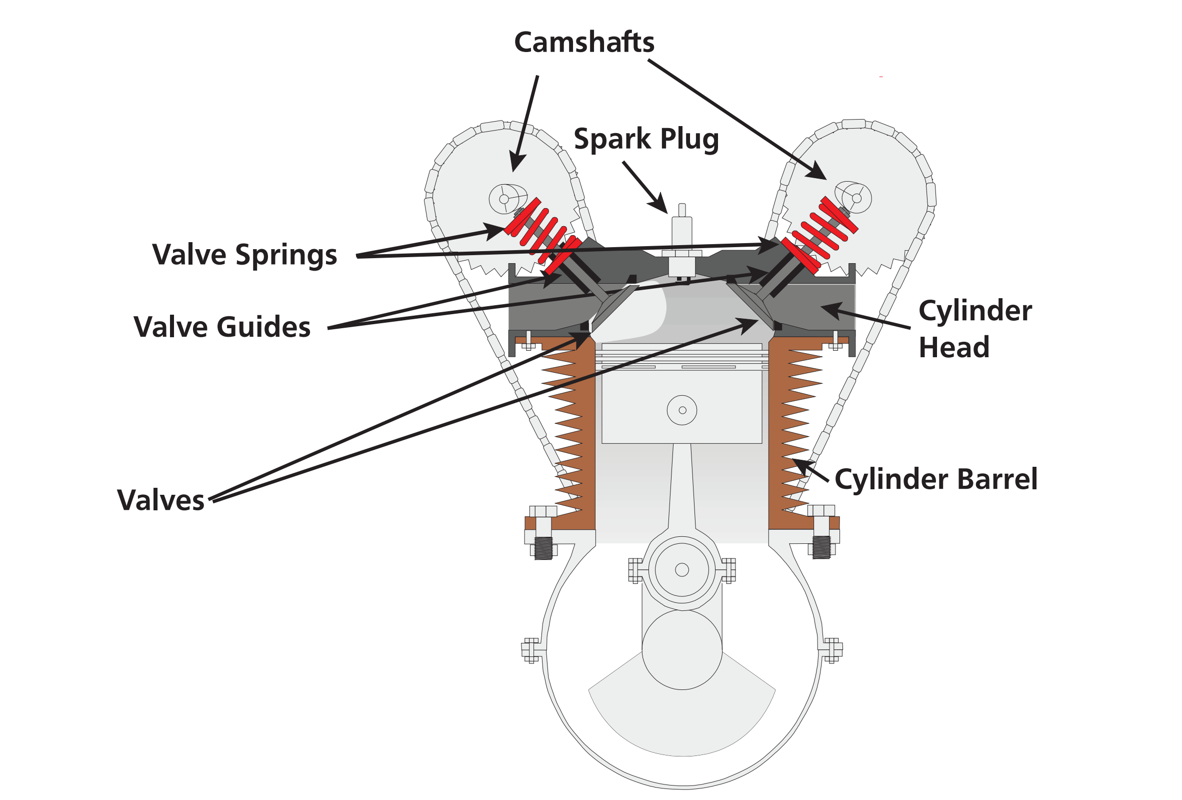


Figure 2.14

About 30% of the heat generated during combustion is transferred to the cylinders. To cool the cylinder there are two cooling methods used. **Liquid Cooling** has jacket around the cylinders to allow for the flow of a liquid around them and carry the heat away. **Air-cooled** engines, have fins machined onto the cylinder to increase the surface area in contact with air, which is used to dissipate the heat.

The Cylinder Head

The cylinder head is generally made of aluminium alloy to improve heat dissipation. It seals one end of the cylinder to provide a combustion chamber for the mixture. The cylinder head accommodates the **Valves, Valve Guides** and **Sparking Plugs**, and supports the valve **Rocker Arms**. **Valve Seats** are cut into the cylinder head, which form gas tight seals with the valves.

The cylinder head may be detachable but more commonly it is screwed and shrunk onto the cylinder.

Valve Guide - guides the valve in a straight path and keeps the valve concentric to its seat. Usually the valve guide is pressed into the cylinder head.

Valve Seat - ground to form a gas tight seal with the face of the valve, cut at various angles *(30° or 45°).*

Valves - inlet and exhaust valves open and close the passages for the induction and scavenging of the gases. The face of the valve is accurately machined to the same angle as the valve seat. The valve and seat are then lapped until a full contact is obtained. Exhaust valve stems are sometimes hollow and partly filled with sodium to assist in cooling. They may be flat, trumpet or mushroom shape.

Valve Springs - made of special spring steel, to ensure that the valves remain closed except when operated by the cams. The springs are of the helical coil type, the usual practice being for two springs to be fitted to each valve, one inside the other.

This provides a **Safety Factor** and helps to eliminate **Valve Bounce**. The springs are held compressed between the cylinder head and the valve spring cap, the latter being located on the valve stem by split collets.

Valve Operating Gear

The valve operating gear consists of a **Camshaft,** *Figure 2.15*, (or camshafts) driven from the crankshaft at **Half Crankshaft Speed** regardless of how many cylinders there are, or how they are arranged.

The camshaft is designed so as to have one **Cam Lobe** to control the opening of each valve. The camshaft is driven at half crankshaft speed because each valve is only required to open and close once per working cycle, that is to say, once every two revolutions of the crankshaft.

The angular position of the lobes on the camshaft of an aircraft engine is fixed, causing the amount of valve lead, valve lag and valve overlap to remain constant, irrespective of changing engine speed. The fact that the camshaft is driven by the crankshaft means that valve opening and closing angles are referred to with respect to **crankshaft** rotation, not camshaft rotation. *(See valve timing diagrams.)*

Valve Clearance

To ensure that the valves close fully, it is necessary for there to be a **Valve (or Tappet) Clearance**. This is a small gap measured between the **Rocker Pad** and the **Valve Tip.**

The valves are continuously heated by combustion and expand at a greater rate than the rest of the operating mechanism. As the engine heats up, the small gap, or valve clearance, shown in *Figure 2.15*, allows the valve to expand at its own rate.

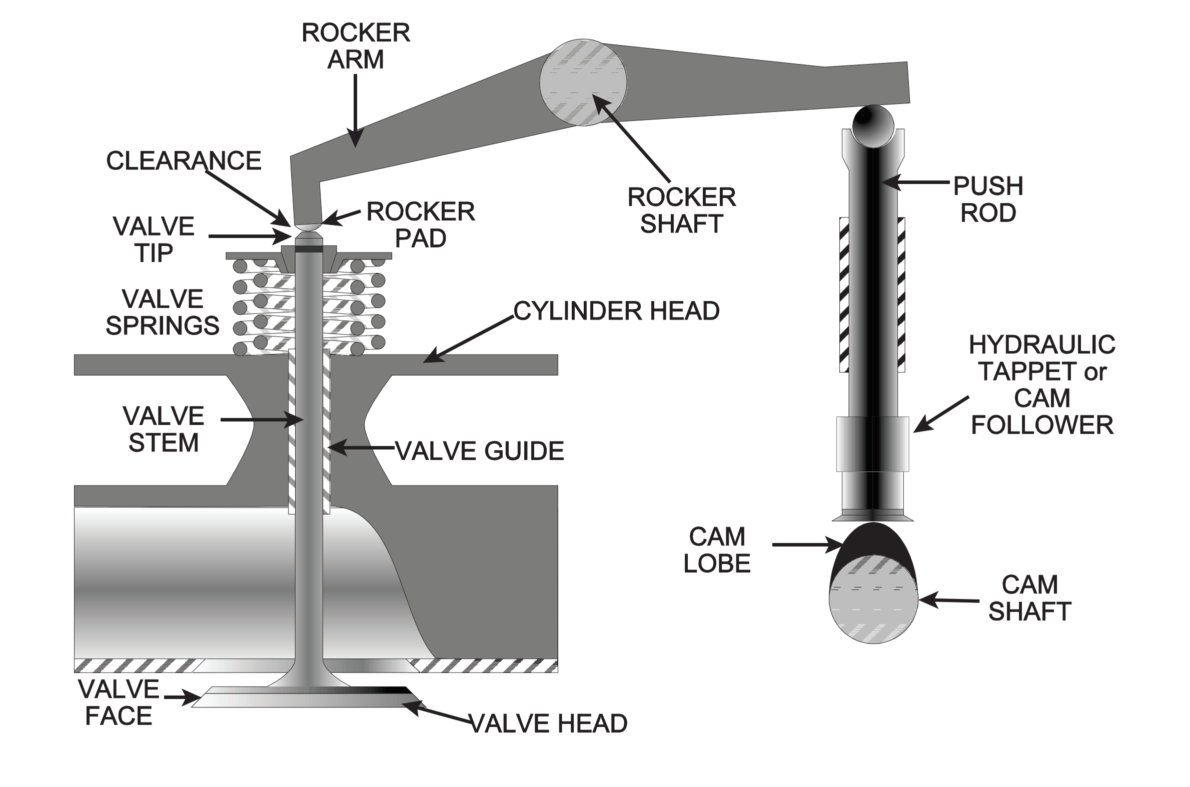


Figure 2.15 Valve clearance

The valve clearance becomes smaller but the valve still remains shut. The valve clearance is measured between the rocker pad and the valve tip by feeler gauges and there is provision made on the rocker arm for the clearance to be adjusted.

Excessive valve clearance will cause the valve to open late and close early. Too little clearance will have the opposite effect of causing the valves to open early and close late and may even prevent the valves closing at all, thereby producing an event called **Popping back into the Carburettor.** The same effect can be caused by an inlet valve which is sticking in its guide.

Some designs of engine use **Hydraulic Tappets.** These are self-adjusting and operate with no clearance and thus there is no tappet noise.

A hydraulic tappet is made in two main parts, one sliding within the other. Oil, which is supplied under pressure, causes the tappet to lengthen and take up any clearance when the engine is running.

The Sump

The sump is a casing attached to the base of the crankcase, it collects the lubricating oil after it has passed through the engine.

With some lubricating systems the sump also acts as the oil reservoir and all the oil is contained within it. A filter is housed in the sump to trap any debris in the oil, so preventing damage to the oil pumps.

The Carburettor

The **Carburettor** meters the air entering the engine and adds the required amount of fuel as a fine spray under all conditions of engine running. For an aircraft engine the correct mixture must be supplied regardless of altitude or attitude of the aircraft.

An **Injector** can be fitted instead of a carburettor on some engines. They are attached to the base of the crankcase, metal pipes connect the outlet from the carburettor or injector to the cylinders. This is called the **Induction Manifold.**

The waste gases after combustion are carried away from the cylinders by the **Exhaust System.** The exhaust consists of steel pipes connected to each of the cylinders. The pipes from each cylinder usually connect up and go into one or two pipes which then carry the hot gases outside the aircraft to atmosphere.

The Accessory Housing or Wheelcase

For the engine to operate supporting systems are needed, and they may need power to drive them. Oil Pumps, Fuel Pumps, Superchargers and Magneto Ignition systems are fitted to the **Accessory Housing** and driven via gears by the crankshaft.

The housing casing is bolted to the rear of the crankcase which encloses the gear train and provides mounting pads for the ancillary equipment, *Figure 2.16*. A **Starter Motor** can be connected to the housing to initially rotate the crankshaft and start the cycle of operation.

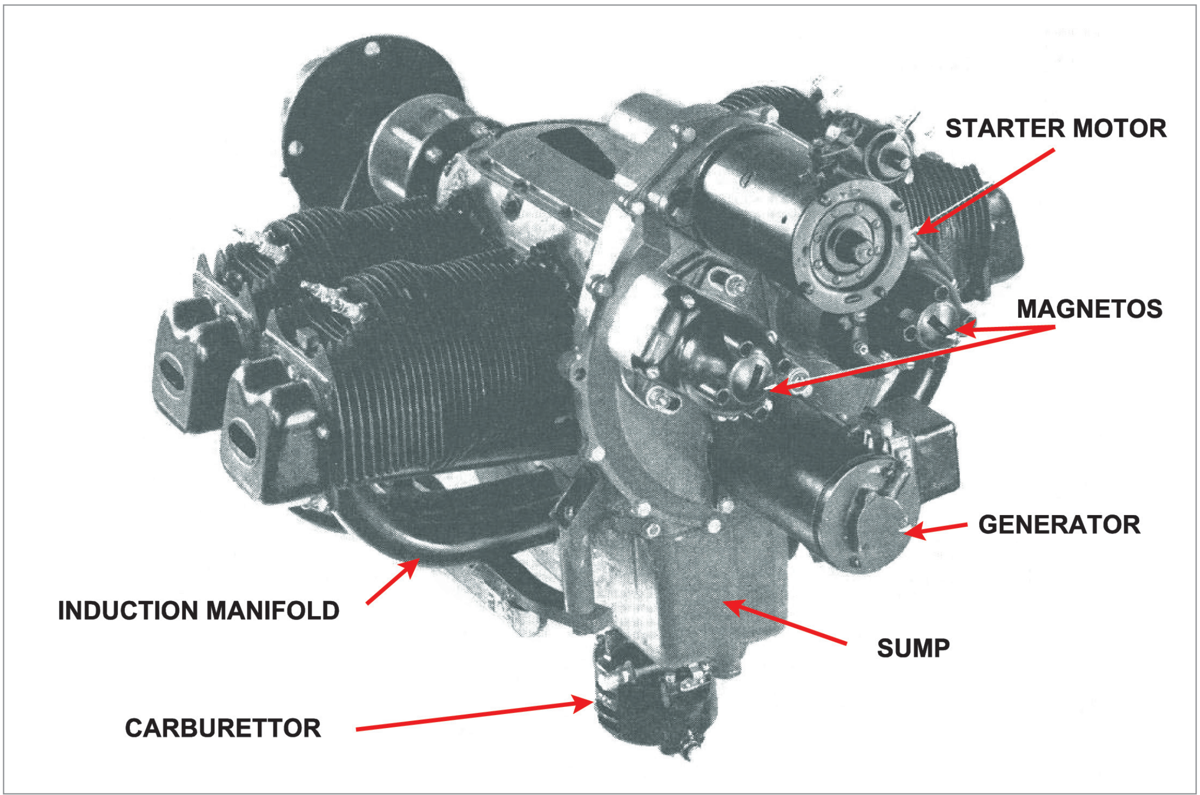


Figure 2.16 Accessory housing

The accessory housing can also provide the drive to power aircraft systems such as **Electrical Generation, Hydraulics** and **Pneumatic** systems.

Some engines may also have a **Gearbox** fitted between the crankshaft and the propeller. This is a **Reduction Gearbox** to reduce the speed of propeller rotation. For the propeller to operate efficiently a comparatively low speed is required. For the engine to develop its full power, it must turn at high speed. So that the engine and the propeller can both operate efficiently the reduction gearbox may be required. Two typical types of reduction gearing are **Spur Gear** and **Planetary Gears.** The lower powered engines have the propeller connected directly onto the crankshaft. These are called **Direct Drive** engines.

Aero-engines are classified by Cylinder Arrangement, Type of Drive, Direction of Rotation, Cylinder Capacity, Cooling Method, Fuel System Type and whether they are supercharge or normally aspirated.

An example of light aircraft engine is depicted below.

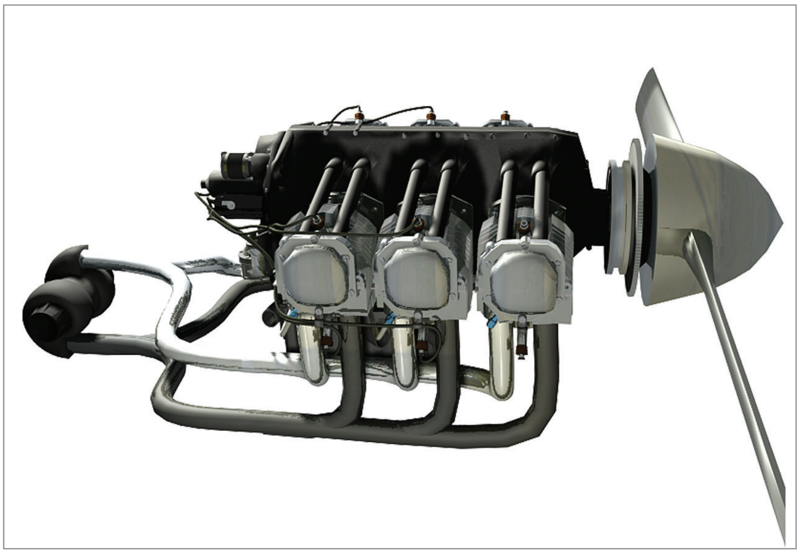


Figure 2.17

Figure 2.17 shows the Textron Lycoming model AEIO 540 L1B5. The model number is used to define the engine.

AE Aerobatic Engine.

I Injected Fuel System

O Horizontally opposed Cylinder Arrangement.

540 Cylinder displacement = 540 cubic inches.

L Left hand Rotation.

1B5 Modifications from basic model.

This type of model numbering system is used by most manufacturers. If the letters G and S were included it would imply the engine was geared and supercharged.

Questions

1. **The temperature of the gases within the cylinder of a four-stroke engine during the power stroke will:**

   a. be constant
   b. decrease
   c. increase
   d. follow Charles's Law

2. **The number of revolutions of the crankshaft required to complete a full cycle in a four-stroke engine is:**

   a. 6
   b. 4
   c. 2
   d. 8

3. **The inlet valve opens before TDC in the exhaust stroke to:**

   a. increase the pressure in the cylinder on completion of the induction stroke.
   b. reduce engine vibration
   c. allow the incoming mixture to mix with a certain proportion of the exhaust gases
   d. induce a greater amount of mixture into the cylinder

4. **The correct working cycle of a four-stroke engine is:**

   a. exhaust, power, induction, compression
   b. compression, power, exhaust, induction
   c. induction, power, compression, exhaust
   d. power, exhaust, compression, induction

5. **Valve overlap is incorporated in the valve timing of a piston engine to:**

   a. improve volumetric efficiency
   b. reduce wear on the big end bearings
   c. increase the engines compression ratio
   d. prevent a weak cut when the engine is accelerated rapidly

6. **With an increase in the rotational speed of a four-stroke engine, the valve overlap:**

   a. increases
   b. decreases
   c. remains constant
   d. increases up to ground idle and thereafter decreases

7. **In a normally aspirated engine, exhaust back pressure:**

   a. decreases as an aircraft climbs and thereby reduces the rate of decline of the engine power output
   b. increases as an aircraft climbs and thereby reduces the engine power output
   c. is affected by the power lever position
   d. decreases as an aircraft descends and thereby improves the engine power output

8. **When the spark ignites the mixture:**

a. the explosion pushes the piston down
b. the mixture changes from rich to weak forward of the flame front
c. complete combustion occurs within 8 to 10 microseconds
d. temperature and pressure increase within the cylinder

9. **If the volume of a quantity of gas is halved during compression:**

a. its pressure is approximately doubled
b. its temperature remains constant
c. its mass is approximately doubled
d. its pressure is approximately halved

10. **The term Indicated Mean Effective Pressure refers to:**

a. the maximum working pressure in the engine cylinder
b. the average pressure within the cylinder during the four cycles
c. the pressure achieved during compression
d. the minimum working pressure applied to the piston during the cycle

11. **The degrees of rotation to complete a full cycle on a nine cylinder engine will be:**

a. 180
b. 360
c. 720
d. 80

12. **The firing interval of a six cylinder horizontally opposed engine will be:**

a. 180
b. 120
c. 60
d. 360

13. **Which of the following statements would be correct for a double banked radial engine?**

a. There will always be an odd number of cylinders
b. Radial engines are generally liquid-cooled
c. The linear distance from TDC to BDC will accommodate two throws
d. Radial engines cannot suffer from hydraulicing

14. **On a four cylinder engine with a total volume of 9600 cc, bore area of 100 cm^2 and a crank throw of 10 cm, what would the Compression Ratio be?**

a. 7:1
b. 8:1
c. 24:1
d. 6:1

15. **With an increase in outside air temperature, specific fuel consumption will:**

    a. increase
    b. decrease
    c. stay the same
    d. stay the same for all temperatures up to and including 15°C and thereafter increase

16. **Combustion, in a four-stroke engine, theoretically occurs at:**

    a. a constant pressure
    b. a constant temperature
    c. a constant volume
    d. a constant velocity

17. **In a convergent duct:**

    a. the pressure and velocity increase, the temperature decreases
    b. the pressure and temperature decrease, the velocity increases
    c. the temperature and velocity increase, the pressure decreases
    d. the pressure and velocity remain constant, the temperature decreases

18. **During the compression stroke:**

    a. the temperature of the gases remains constant
    b. the volume of the gases increases
    c. the mass of the mixture decreases
    d. the mass of the mixture remains constant

19. **From Top Dead Centre (TDC) to Bottom Dead Centre (BDC) on the practical power stroke:**

    a. the temperature of the gases rises for a short time then decreases
    b. the pressure of the gases remains constant
    c. the temperature of the gases decreases from TDC to BDC
    d. the density of the gas remains constant

20. **In a divergent duct:**

    a. the velocity and temperature increase, the pressure decreases
    b. the temperature and pressure increase, the velocity decreases
    c. the temperature and pressure decrease, the velocity increases
    d. the velocity and temperature decrease, the pressure increases

21. **During the induction stroke:**

    a. the mixture becomes weaker
    b. the volume of the gases becomes smaller
    c. the temperature of the gases reduces
    d. the pressure of the gases increases

22. **Ideally, maximum pressure is attained within the cylinder:**

    a. when combustion is complete
    b. at the end of the compression stroke
    c. during the period of valve overlap
    d. when combustion temperature is at a minimum

23. **The power output of an internal combustion engine:**

    a. is proportional to the volume of mixture induced into the cylinder
    b. increases with increased humidity
    c. falls as the charge temperature falls
    d. is proportional to the weight of the mixture induced into the cylinder

24. **During the period of valve overlap:**

    a. the action of the exhaust gases flowing past the exhaust valve increases the pressure within the cylinder
    b. the temperature of the exhaust gases increases the mass of incoming mixture
    c. the action of the exhaust gases flowing out past the exhaust valve tends to reduce the pressure in the cylinder
    d. the crankshaft is moving past Bottom Dead Centre

25. **The power output of an internal combustion engine can be increased by:**

    a. increasing the area of the cylinder
    b. increasing the length of the stroke
    c. increasing the engine rpm
    d. all of the above

Engine Components

26. **Valve Overlap is:**

    a. the number of degrees of camshaft rotation during which the inlet and exhaust valves are open at the same time
    b. the number of degrees of crankshaft movement during which the inlet and exhaust valves are open at the same time
    c. the distance the piston travels while the inlet valve remains open after BDC
    d. the number of degrees of crankshaft rotation during which the inlet and exhaust valves are open at the same time around BDC

27. **The purpose of a valve spring is to:**

    a. close the valve
    b. cause a snap opening of the valve
    c. allow the valve timing to vary with changing rpm
    d. maintain the valve clearance within tolerance

28. **Excessive blue smoke from the exhaust of an engine that has been warmed up to normal operating temperature may indicate that:**

    a. the mixture is too rich
    b. the oil pressure relief valve has stuck in the open position
    c. the piston rings are worn or stuck in their grooves
    d. the oil pressure is too low

29. **The camshaft of a horizontally opposed four-stroke engine rotates at:**

    a. twice engine speed
    b. engine speed
    c. twice magneto speed
    d. half engine speed

30. **A reduction gear is fitted:**

    a. between the camshaft and the propeller
    b. between the pushrods and the valves
    c. between the crankshaft and propeller
    d. between the connecting rod and the crankshaft

31. **Prolonged use of low rpm could cause contamination of the:**

    a. oil filter
    b. spark plug
    c. carburretor
    d. oil pump

32. **If the Starter Engaged Light remains on after engine start, you should:**

    a. shut the engine down immediately
    b. ignore it if it remains on for longer than 30 seconds
    c. shut the engine down if the light remains on for more than 30 seconds
    d. shut the engine down if the light remains on for more than 60 seconds

33. **The crankshaft of typical in-line four cylinder aircraft engine:**

    a. rotates at half the speed of the camshaft
    b. will have the crank throws spaced 90 degrees apart
    c. allows a firing order of 1-3-4-2
    d. will not flex or twist

34. **Two valve springs are fitted to each valve:**

    a. to minimize camshaft wear
    b. to allow a greater cam rise
    c. to prevent valve rotation
    d. to reduce valve bounce

35. **Excessive valve clearance:**

    a. will prevent the valve closing completely
    b. is eliminated when the engine reaches working temperature
    c. will cause the valve to open early and close late
    d. will cause the valve to open late and close early

36. Valve lead occurs when:

a. the inlet valve opens before bottom dead centre
b. the exhaust valve opens before the inlet valve
c. the exhaust valve opens before top dead centre
d. the inlet valve opens before top dead centre and the exhaust valve opens before bottom dead centre

37. Insufficient tappet clearance at the inlet valve would cause:

a. the valve to open early and close late
b. the valve to open late and close early
c. the mixture in that cylinder to be weak
d. misfiring

38. The length of the stroke is:

a. equal to the length of the cylinder
b. determined by the size of the piston
c. equivalent to twice the crank throw
d. inversely proportional to the engine power output

39. Tappet clearance is measured between the:

a. push rod and the valve tip
b. valve tip and the rocker pad
c. valve spring and the rocker pad
d. valve tip and the rocker cover

40. The number of revolutions required to complete the induction and compression stroke in a six cylinder four-stroke engine is:

a. 1
b. 2
c. 6
d. 4

41. The purpose of a crankcase breather is to:

a. maintain the oil tank pressure at atmospheric
b. prevent distortion of the crankcase
c. allow the oil to breathe
d. prevent pressure building up inside the crankcase

42. Tappet clearance is provided in a piston engine to:

a. adjust the valve timing
b. allow for expansion of the valve gear as the engine warms up
c. allow for manufacturing tolerances
d. prevent valve bounce

43. **Piston rings are manufactured from cast iron:**

a. because it has a negative coefficient of expansion
b. to take advantage of its extreme malleability
c. because of its self-lubricating qualities
d. to take advantage of its brittleness

44. **The exhaust valves:**

a. are opened directly by the action of push rods which are in turn operated by cams on the crankshaft
b. are less affected by the heat of combustion than the inlet valves
c. are opened by the valve springs and closed by the rocker gear
d. sometimes have their stems partly filled with sodium to assist cooling

45. **Hydraulic valve tappets are used on some engines to:**

a. eliminate valve bounce
b. eliminate constant valve adjustment and checks
c. give a more positive closing action
d. give a more positive opening action

Terms and Definitions

46. **The swept volume of a cylinder is:**

a. the area of the bore × the stroke
b. the area of the cylinder cross section × the cylinder length
c. half of the clearance volume
d. the total volume + the piston volume

47. **The thermal efficiency of a piston engine can be increased by:**

a. increasing the rpm
b. increasing the combustion chamber volume
c. advancing the ignition point into the direction of rotation
d. increasing the compression ratio

48. **A normally aspirated engine is one which:**

a. has four cylinders
b. is not supercharged
c. is never air-cooled
d. is all of the above

49. **The Compression Ratio of an engine may be defined as the:**

a. swept volume + clearance volume ÷ swept volume
b. swept volume + clearance volume ÷ clearance volume
c. total volume - clearance volume ÷ clearance volume
d. swept volume ÷ (swept volume + clearance volume)

50. **An engine has a total volume of 2100 cm^3 and a swept volume of 1800 cm^3. Its compression ratio is:**

a. 7:6
b. 6:1
c. 7:1
d. 6:7

51. **Volumetric efficiency may be defined as:**

a. the ratio of the volume of the mixture drawn into the cylinder during normal engine working, to the volume of the mixture which would be required to fill the cylinder under normal temperatures and pressures
b. the ratio of the volume of air and the volume of fuel drawn into the cylinder
c. the ratio of the volume of one of the cylinders to the volume of all of the cylinders in the engine
d. the efficiency with which the air and fuel mix together in the cylinder

52. **The ratio of the power produced by an engine to the power available in the fuel is known as the:**

a. specific fuel consumption
b. indicated horsepower
c. volumetric efficiency
d. thermal efficiency

53. **Specific Fuel Consumption (SFC)**

a. is the inability of the internal combustion engine to use any fuel other than that specified by the manufacturer
b. becomes greater as the efficiency of the engine improves
c. is the weight of fuel used by an engine per unit horsepower per unit time
d. increases in proportion to the thermal efficiency

54. **Brake Horsepower is:**

a. theoretical power in the cylinder
b. useful power at the propeller
c. power lost in the engine
d. power required to slow the aircraft down

55. **A method of improving Volumetric Efficiency is:**

a. valve overlap
b. the use of carburettor heat
c. weakening the mixture
d. to make the mixture richer

Answers

1	2	3	4	5	6	7	8	9	10	11	12
b	c	d	b	a	c	a	d	a	b	c	b

13	14	15	16	17	18	19	20	21	22	23	24
c	d	a	c	b	d	a	b	c	a	d	c

25	26	27	28	29	30	31	32	33	34	35	36
d	b	a	c	d	c	b	a	c	d	d	d

37	38	39	40	41	42	43	44	45	46	47	48
a	c	b	a	d	b	c	d	b	a	d	b

49	50	51	52	53	54	55
b	c	a	d	c	b	a

Chapter

3

Piston Engines - Lubrication

Function of the Lubrication System

The components that make up a piston engine are subjected to high loads, high temperatures, and high speeds. The component parts are generally made of metals, and as the moving parts of the engine slide against each other, there is a resistance to their movement. This is called **Friction.**

The friction will increase as the load, temperature and speed increases, the movement of the components also produces **Wear** which is the loss or destruction of the metal components. Both friction and wear can be reduced by preventing the moving surfaces coming into contact by separating them with a material/substance which has lower frictional properties than the component parts. This is referred to as a **Lubricant.**

A lubricant can come in many forms. Greases, powders and some solid materials. However it is in the form of **Oils** with which this chapter will concentrate on. The oil can be forced between the moving parts, called **Pressure Lubrication** or the components can be **Splash Lubricated.**

The **Primary** task of the lubrication system of the engine is to **Reduce Friction** and component **Wear,** it also has a number of secondary functions. Of these perhaps the most important is the task of **Cooling.** The flow of oil through the engine helps to dissipate the heat away from the internal components of the engine.

As the oil flows through the engine it also carries away the by-products of the combustion process and **cleans** the engine. The internal metal components are protected against **Corrosion** by the oil, which also acts a **Hydraulic Medium** reducing the shock loads between crankshaft and bearing and so reducing vibration. The oil can provide the power source for the operation of a hydraulic variable pitch propeller.

The oil system can be used to give an indication of the power being developed by the engine, and its condition. The oil system's use as an **Indicating Medium** is of great importance to the pilot as it can give an early warning of mechanical failure or loss of power.

It should be remembered that an increase in friction will cause an increase in Friction Horsepower, and therefore a reduction in the Brake Horse Power developed by the engine.

The **Reduction in Friction and Wear** by the lubricant is of prime importance, but the secondary functions of **Cooling, Cleaning, Protection, Hydraulic** and **Indicating Mediums** should not be ignored.

The Wet and Dry Sump Lubricating Systems

There are two lubrication systems in common use, these are the **Wet Sump** and **Dry Sump** systems. The system used is normally dependant on the power output of the engine, and role of the aircraft. The principle of lubrication of the engine is the same whichever system is used, the principle difference between the two systems being the method used to store the supply of oil.

Most light, non-aerobatic aircraft engines use the **Wet Sump** system. In this system the oil is stored in the bottom or sump of the engine. This simplifies construction but has a number of disadvantages:

a) Lubrication difficulties arise during manoeuvres. The oil enters the crankcase, is flung around by the revolving shafts with possible over-oiling of the engine, inverted flight being particularly hazardous.

b) The temperature of the oil is more difficult to control as it is stored within the hot engine casing.

c) The oil becomes contaminated and oxidizes more easily because of the continual contact of the oil with hot engine.

d) The oil supply is limited by the sump capacity.

The **Dry Sump** system overcomes the above problems by storing the oil in a remotely mounted **Tank.**

As previously stated the principle of oil supply is the same for both systems. A **Pressure Pump** circulates the oil through the engine, and so lubricates the moving parts. In a dry sump system, **Scavenge Pumps** then return the oil to the tank to prevent the engine sumps flooding.

The arrangement of the oil systems in different aircraft engines varies widely, however the functions of all such systems are the same. A study of one system will clarify the general operation and maintenance requirements of other systems.

The principal units in a typical reciprocating engine oil system includes an **Oil Tank** (dry sump), **Oil Filters, Pressure** and **Scavenge Pump, Oil Cooler** (radiator), an **Oil Pressure** and **Oil Temperature Gauge**, plus the necessary interconnecting oil lines, which are all shown in the *Figure 3.1* This shows a dry sump system, for a wet sump system the oil tank is not used, and there is a single pump, the pressure pump.

The following paragraphs state the function of the main components of the system.

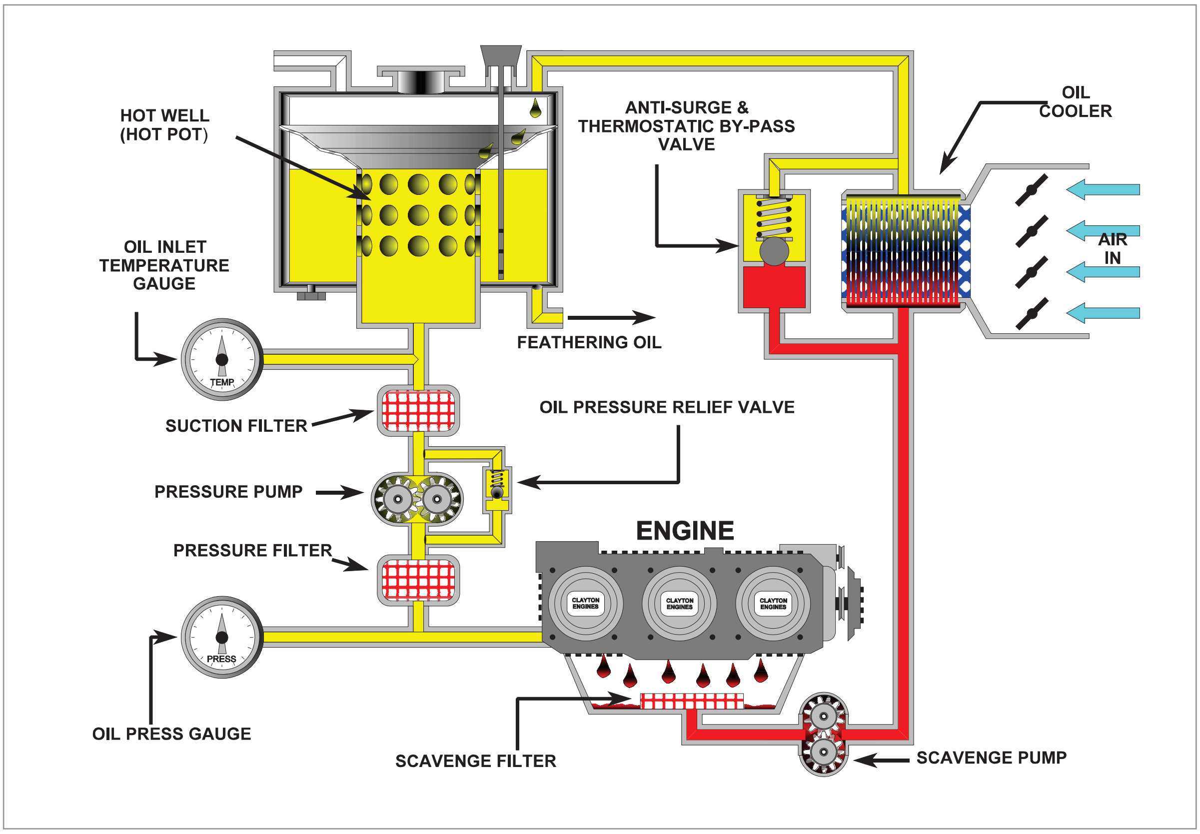


Figure 3.1 Dry sump lubrication

The Oil Tank

Oil tanks are made of sheet metal, suitably baffled and strengthened internally to prevent damage due to the oil surging during manoeuvres.

The tank is placed wherever possible at a higher level than the engine to give a gravity feed to the pressure pump, and forms a reservoir of oil large enough for the engine's requirements, plus an air space. The air space allows for:

a) The increased oil return when starting the engine. When the engine is stopped after a previous run, the walls of the crankcase are saturated with oil which will drain into the sump. The oil will remain there until the engine is started, when the scavenge pump will return it to the tank.

b) The expansion of the oil, and therefore its greater volume as the oil absorbs heat from the bearings

c) 'Frothing' due to aeration of the oil.

d) The displacement of oil from the variable pitch propeller and other automatic controlling devices.

The **hot pot** (hot well) forms a separate compartment within the tank. Its purpose is to reduce the time taken to raise the temperature of the oil when starting the engine from cold by restricting the quantity of oil in circulation when the oil is cold and viscous.

The hot pot consists of a cylinder of metal fitted above the oil outlet to the engine, thus the oil must be inside the hot pot to be able to reach the pressure pump. When starting, the level of oil in the hot pot drops, uncovering a ring of small diameter ports. These ports offer a great resistance to the flow of cold thick oil so that very little passes to the inside of the hot pot. The oil is returned from the engine to the inside of the hot pot and is recirculated.

As the hot oil is returned to the tank some of its heat raises the temperature of the walls of the hot pot. The oil in the immediate vicinity is heated and thins so that the ports offer less resistance to the flow of the thinner oil, and progressively more and more oil is brought into circulation. The oil is filtered by the suction filter before passing to the pressure pump.

When feathering propellers are fitted, the lower ring of feed ports to the hot pot are placed above the bottom of the tank, this provides a feathering reserve of oil even if the main tank has been emptied through the normal outlet, as would occur if the main feed pipeline was to develop a leak or completely fail.

The scavenge oil returning to the tank is passed by an internal pipeline over a de-aerator plate to the inside of the hot pot. The plate separates the air from the oil to reduce frothing. The tank is vented through the crankcase breather to prevent oil losses during excessive frothing conditions.

The Suction Filter

A coarse wire mesh filter is fitted between the tank and pressure pump. It is designed to remove large solid particles from the oil before it enters the pressure pump and so prevent damage.

The Pressure Pump

The pump consists of two deep toothed spur gears rotating in a close fitting pump casing driven via the accessory housing. Oil is carried either side of the casing in the space between the gear teeth, and is made to flow. The outlet side of the pump is enclosed and restriction to flow is given from the engine components to be lubricated. This gives a rise in system pressure.

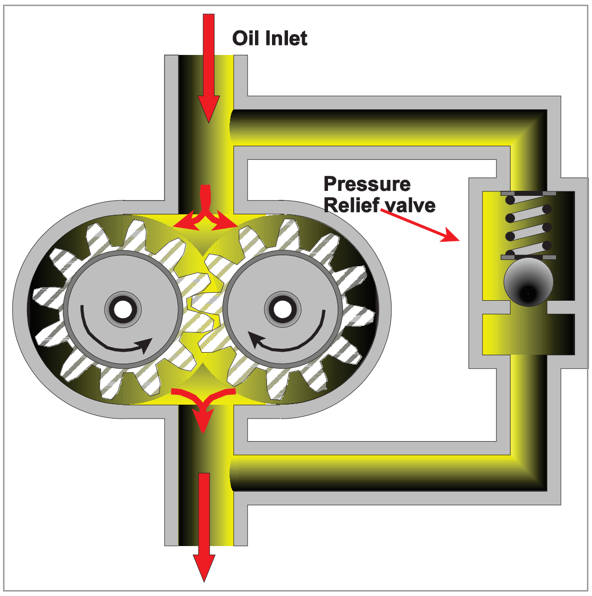


Figure 3.2 Spur gear pump

The actual oil pressure obtained will depend on the **Speed of the Pump,** the **Temperature of the Oil** and the **Resistance offered by the Components.**

The capacity of the pump must be such that it will supply a minimum oil pressure under its most adverse running conditions of low turning speed and high inlet oil temperature. As a consequence of this, under normal running conditions the increased flow would tend to cause a dangerously high oil pressure.

Very high pressures are prevented by a **Pressure Relief Valve** (PRV) across the inlet and outlet connections which limits maximum pressure in the system. When the pressure reaches a predetermined figure, the valve opens and sufficient oil is returned to the inlet side of the pump to limit the maximum oil pressure.

In operation the engine will have range of operating pressure related to engine speed from idle to maximum rpm.

The Check Valve

(Non-return Valves, or One-way Valves)

The oil tank may be at a higher level than the pressure pump to provide a gravity feed. When the engine is stopped and the oil is hot and thin, there is sufficient pressure from the gravity feed to force the oil through the clearances in the pressure pump so that the oil tank would drain into the crankcase and the engine would be flooded with oil. This feature of dry-sump operation is sometimes referred to as over-oiling. To prevent this a check valve is fitted. This consists of either an lightly sprung loaded valve, or electrically-operated shut off valve (SOV) which will hold back the oil until the engine is started.

The Pressure Filter

The pressure filter is fitted downstream of the pressure pump before the oil enters the engine and is designed to remove very small solid particles before the oil passes to the bearing surfaces. A spring loaded relief valve is fitted to bypass the filter element when the oil is cold, or if the element becomes blocked. It will also protect the engine if the pressure pump breaks up.

The Scavenge Pump

The **Scavenge Pump** returns the oil by pumping it from the sump back to the tank. When the engine is stopped the oil in the crankcase will drain into the sump. As the engine is started there will be a quantity of oil, which, if the pumps were the same size, would not be removed. Therefore, to maintain a dry sump it is necessary for the scavenge pump to be of a larger capacity than the pressure pump. In practice the scavenge pump capacity is **25% - 50%** larger than that of the pressure pump.

Oil Cooler

The use of oil for cooling the internal components of the engine has already been emphasized. If the oil itself gets too hot, it could fail as a lubricant. To prevent its temperature rising too high a cooler is introduced in to the system.

The oil cooler consists of a matrix or tube block, which spreads the oil in a thin film and subjects it to cooling air. The matrix is built up of round tubes, the ends of which are expanded and shaped to form hexagons to form a surface for soldering the tubes together. The matrix itself is bonded into the oil cooler jacket by soldering the flats of the tubes to the inner shell of the cooler jacket.

When starting the engine from cold, the cooler matrix will be full of cold thick oil, and to force the oil through the small oilways of the cooler would require a very high pressure. To prevent damage to the cooler an **Anti-surge Valve** is fitted to by-pass the matrix when the oil is cold.

The temperature of the oil is affected by three factors:

a) The amount of heat generated in the engine (power).

b) The temperature of the cooling air.

c) The rate at which air flows through the cooler.

In some light aircraft the flow of air through the cooler is simply dependant on the forward speed of the aircraft in flight, and the airflow from the propeller whilst the aircraft is on the ground. In certain conditions of flight, where high power is used with low forward speed e.g. a climb, care must be taken to prevent overheating the oil. The flight manual will recommend climb speeds that should ensure adequate cooling.

Higher powered aircraft will be fitted with shutters behind the cooler to control the flow of air through the cooler. This would be closed at start up to allow the engine oil temperature to rise quickly (cold oil increases internal friction), and then be opened to maintain the temperature. In flight the shutters will close off again as the temperature of the air reduces at altitude. Control of the shutters can be manual or automatic.

Diesel engine lubrication systems are typically 'Wet-Sump' and would definitely include an oil cooler because of the need to dissipate the additional heat generated by the diesel engine.

Lubrication Monitoring Instruments

The importance of maintaining the correct **Oil Temperature** has been explained in the paragraphs above. The other parameters of the oil system monitored are **Pressure** and **Quantity.**

The temperature of the oil in a piston engine is measured at the inlet to the engine pressure pump. Most aircraft use an electrical sensor to indicate the temperature to a flight deck gauge. Temperatures in the region of 85°C would be considered normal.

Oil pressure is sensed at the outlet side of the engine driven pressure pump. The pressure will depend on the size and loading of the engine, 50-100 psi being a typical value. The sensor can be electrical or a direct reading mechanical system. Both temperature and pressure sensing systems are covered in the Engine Instruments, Book 5.

It is mandatory that oil temperature and pressure are indicated on the flight deck. Oil quantity may be displayed. If not displayed there will be a facility for checking the quantity prior to flight, either by the use of a dip stick or sight glass.

Correct oil temperature and pressure during engine operation are perhaps the most important indicators the pilot has of engine condition. Indications outside of operating limits could be indicative of impending engine failure.

Viscosity

The varying load, power and outside air temperatures that aircraft engines operate at require oils with differing properties. Thickness of the oil is a very important factor, and is known as the oil's **Viscosity or Grade.** Viscosity is defined as the measure of a fluid's internal friction, or its resistance to flow. A liquid that flows freely has a low viscosity (thin oil) and one which is sluggish has a high viscosity (thick oil). The viscosity of an oil will change with changes in **Temperature.** An increase in temperature will **Reduce** viscosity and vice versa.

The engine's operating temperature will vary considerably from the time when it is started from cold, to running at high power for long periods of time. The oil's viscosity must stay within required limits to do its job, this range of temperature is termed its **Viscosity Index.**

Viscosity Grade Numbering

There are various standards employed to determine the viscosity or thickness of oils. They all provide a datum by which differing oils can be compared. These methods measure the time taken for a fixed quantity of oil at a given temperature to flow through an orifice or jet of a given size.

There are two standards that are generally employed in aviation to indicate the viscosity of oils. These are the **Society of Automotive Engineers, (SAE)** and the **Saybolt Universal** systems. Both systems use numbers to indicate the viscosity.

The lower the viscosity number, the thinner the oil.

COMMERCIAL SAE NO.	SAYBOLT UNIVERSAL
30	60
40	80
50	100
60	120

It can be seen that the SAE number is half that of the Saybolt Universal system. Lighter loaded engines use a **Low Viscosity** or thin oil, whereas higher powered engines with higher loading would require a **High Viscosity** or thick oil. As previously stated the climate in which the engine operates also has an influence on the viscosity. For example a light aircraft operating within the UK during winter may use an 80 grade oil, and in summer it would use a 100 grade. The choice being dependent on the average ambient temperature.

The use of too high a viscosity oil at too low a temperature can cause problems during starting. There are in use oils that have two viscosity values - SAE 15W/50. These oils are called **Multi -grade Oils.** They would give the characteristics of low viscosity at low temperatures, and high viscosity at higher temperatures.

Types of Oil

The type of oil used in aircraft piston engines is normally mineral based. If the oil contains no additives it is called a **Straight oil**. To meet certain requirement of engine operation, additives can be added to the oil. These take the form of anti-oxidants, detergents and oiliness agents. These oils are called **Compound oils**.

The two oils are identified by the viscosity numbering system, and if a compound oil the addition of letters or lettering. A bottle or can containing a straight oil with a viscosity of 80, would have only the number 80 marked on it. A compound oil of the same viscosity may be marked AD 80 or W 80. The actual lettering varies with manufacturer. The letters AD stand for **Ashless Dispersant,** and is oil with specific qualities for cleaning.

Generally straight oil is only used when running in new engines, or for specific engine installations. As previously stated piston engines normally use mineral based oils, however some engine manufacturers have trialed and approved the use of **Semi-synthetic Oils** *(Figure 3.3)*.

Figure 3.3 Types of oil compound, multigrade and straight oil

Operational Considerations

Indications of oil pressure and temperature give the pilot a good idea of the mechanical integrity of the engine. Of course the pilot must then interpret these indications correctly.

On radial and inverted engines the pilot's knowledge of the lubrication system is required even before starting the engines. These engine can suffer from a problem called **Hydraulicing,** where oil accumulates in the lower cylinders between piston and cylinder head. As oil is incompressible damage to the engine could occur as the piston moves on the compression stroke. Prior to starting, these engines should be pulled through the cycle by use of the propeller, to ensure no hydraulic lock has occurred, (Confirm magnetos are OFF before turning engine).

On starting positive engine oil pressure should be indicated within a specified time. (Piper Warrior 30 seconds). If the engine is started from cold the oil pressure could be excessively high. This would be **Normal** as long as it drops to within its normal range as the engine warms up. Correct engine operating pressure and temperatures are dependent on each other. **High oil** temperature could give **low pressure.** The oil pressure should be within its operating range at the correct operating temperature.

Fluctuations in pressure could be the result of low oil levels, or system faults. Low pressure at normal temperature would indicate imminent engine failure, and a landing should be made as soon as possible.

A problem that can occur during starting in very cold weather is **Coring.** It is caused by the fact the cold viscous oil does not flow correctly through the engine. It should be remembered that an important task of the oil is to cool. The reduction in flow rate will not dissipate the heat being generated in the engine. The result is that the **Oil temperature rapidly rises,** but this is only locally at the point of sensing. The problem is that the majority of the oil is **Cold.** To overcome coring oil cooler flaps should be **Closed**, this will initially increase temperature but should improve flow particularly through the cooler, and then bring temperatures down.

It should be appreciated that as the oil is used to lubricate the moving parts of the engine, the oil will come in contact with the combustion gases. Sealing of the valves and pistons is not 100% and as a result some oil will be burnt and the engine will therefore have an oil consumption rate. Ignoring external leakage, oil consumption varies between engines. A light aircraft would use around 1 pint per hour. A consumption rate greater than this would indicate wear in the engine.

The oil contents should always be checked prior to flight. If the engine has a **Dry Sump** system, the contents should be checked **immediately** after the engine has stopped, (realistically within a few minutes of shutdown). This ensures that the tank contents are recorded accurately before the oil migrates under gravity down into the engine sump. Large piston engines have oil tanks fitted with a check valve which is underneath the oil tank and closes under spring pressure or by an electrically operated actuator on engine shutdown. The closing of the check valve prevents oil migration into the sump. The **Wet Sump** system is the opposite. A period of a least **15-20 minutes** should have elapsed before the contents are checked in a similar fashion to motor cars. In any event, the oil level is checked after a period of time.

Questions

1. **From the following list select the correct combination of statements.**

    The primary tasks of lubrication are to:

    1. reduce friction
    2. cool the engine
    3. clean the engine
    4. reduce component wear
    5. act as a hydraulic medium

    a. 1 and 3.
    b. 2 and 5.
    c. 1 and 4.
    d. 1 and 5.

2. **In a piston engine dry sump oil system, the oil temperature and pressure are sensed:**

    a. when the oil is leaving the sump.
    b. for the temperature when the oil is leaving the tank, and for the pressure when the oil is leaving the pressure pump.
    c. for the oil temperature when the oil is entering the tank and for the pressure when it is entering the pressure pump.
    d. at the same point.

3. **Oil returning to the oil tank is filtered by:**

    a. the oil pressure filter.
    b. the oil tank filter.
    c. a micron size multi-bore filters assembly.
    d. the scavenge filter.

4. **Engine oil pressure is:**

    a. low at idle rpm and high at high rpm.
    b. controlled by the oil cooler.
    c. substantially decreased when the oil pressure relief valve opens.
    d. relatively unaffected by engine speed.

5. **The purpose of the crankcase breather is to:**

    a. maintain the pressure in the oil tank at atmospheric pressure.
    b. ease the task of the oil scraper ring.
    c. prevent pressure building up inside the crankcase.
    d. prevent distortion of the crankcase.

6. **The most probably cause of small fluctuations in the oil pressure would be:**

    a. lack of oil.
    b. the pressure relief valve sticking.
    c. air in the oil tank.
    d. the scavenge pump working at a greater capacity than the pressure pump.

7. **The extra space in the oil tank is to cater for:**

   a. frothing and aeration of the oil as it passes through the engine.
   b. fire protection.
   c. the accommodation of extra oil contents on long duration flights.
   d. anti-surge action.

8. **The scavenge pump system in a lubrication system has:**

   a. a bypass in case of blockage.
   b. a smaller capacity than the pressure pump.
   c. a bifurcated tertiary drive system.
   d. a larger capacity than the pressure pump.

9. **In a "wet sump" oil system, the oil is contained in the:**

   a. engine and tank.
   b. tank and oil cooler.
   c. sump and tank.
   d. engine and sump.

10. **The oil contents of a piston engine (wet sump) are checked:**

   a. when the engine is running at idle power.
   b. as soon as possible after the engine is stopped because the oil will drain away from the sump.
   c. after approximately 15 minutes once the engine has stopped.
   d. when the oil has reached a specific temperature.

Answers

1	2	3	4	5	6	7	8	9	10
c	b	d	d	c	b	a	d	d	c

Chapter

4

Piston Engines - Cooling

The Reasons for Cooling

The piston engine is a heat engine, its purpose is to convert the energy released by the fuel into mechanical energy and so do useful work. In Chapter 2 it was stated that the thermal efficiency is at best only 25-28%. This means that over 70% of the heat energy released by the fuel is wasted. The exhaust gas is responsible for around 40%. Some of this energy can be recovered on some aircraft by driving a turbine driven supercharger (turbocharger).

The remaining 32% raises the temperature of the engine components, and if not controlled could lead to the following problems.

a) Structural failure of the engine components.

b) Over temperature of the oil, which could result in breakdown of its lubricating properties.

c) The fuel can ignite as it enters the cylinder, before the spark plug fires. This is called **Pre-ignition.**

d) The combustion process can become unstable even if the mixture has been ignited by the spark plug. This is called **Knocking or Detonation**.

Both pre-ignition and knocking result in a loss of engine power.

So far the problems of over heating have been discussed, but problems can also occur if the engine operates at too low a temperature.

a) High values of thermal efficiency require the engine to operate at high temperatures.

b) Low temperatures increase the internal friction of lubricants (high viscosity) this would increase Friction Horsepower and so reduce Brake Horsepower.

c) The ability of the liquid fuel to change its state to a gas is reduced, which affects the fuel mixture and combustion.

To operate efficiently, the engine must operate at the **Highest Temperatures Consistent with Safe Operation.** Allowances for changes in the ambient and internal temperatures require a **Cooling System** to control and maintain these temperatures.

Liquid and Air-cooled Systems

The cylinder arrangements of different engines has already been covered in Chapter 2. It was stated that the cylinder arrangement was dependant on the power required and type of cooling system used. The two types are **Liquid Cooling** and **Air Cooling.**

The liquid cooling system *(Figure 4.1)* dissipates the heat from the engine by pumping a mixture of **Water** and **Glycol** (anti-freeze) through passages built into the cylinders and cylinder heads. The liquid is then passed through an **Air-cooled Radiator** mounted in slip stream of the propeller. This ensures that there is an airflow through the radiator even with the aircraft stationary on the ground.

An engine driven **Pump** circulates the liquid through the engine, and temperature is controlled by a **Thermostat.** The liquid is stored in a reservoir called a **Header Tank.** Pipes carry the liquid from the header tank to the engine, and then from the engine to the radiator and back to the header tank. Air flowing through the radiator dissipates the heat from the coolant to the air.

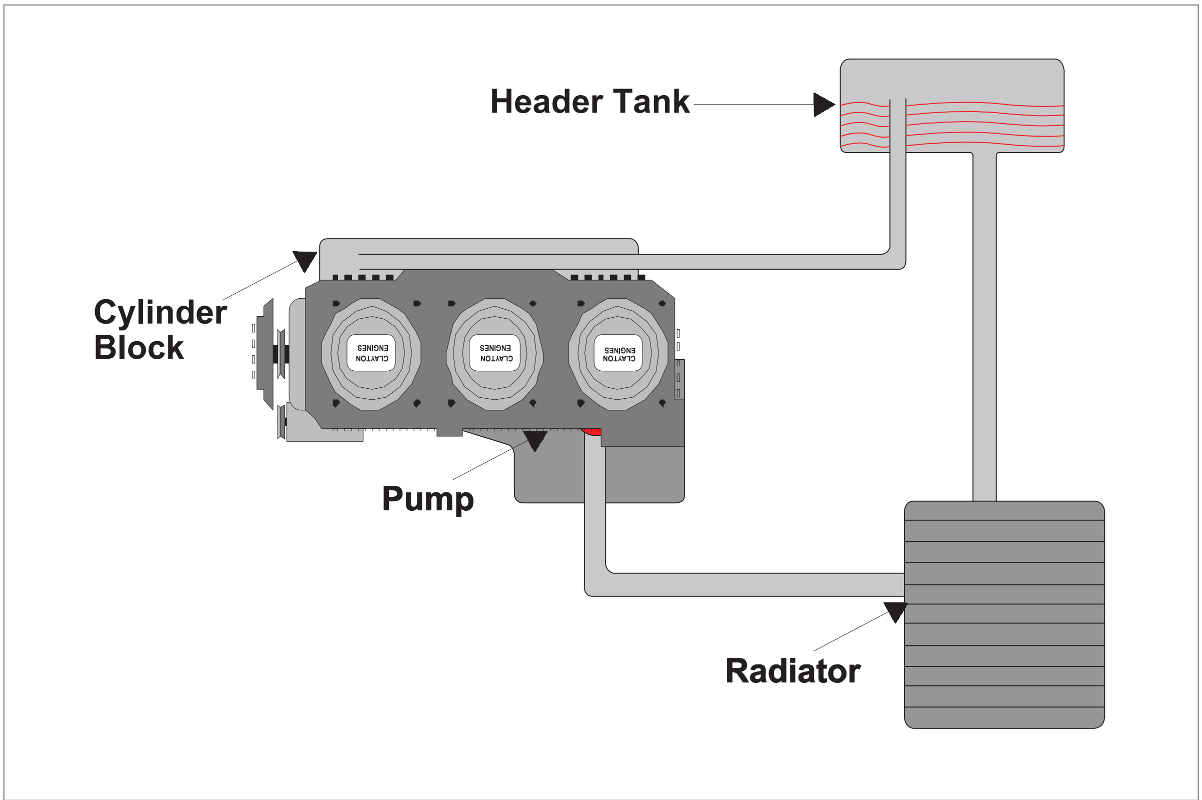


Figure 4.1 Liquid cooling system.

The air-cooled engine uses the cooling air from the **Propeller Slipstream** and the **Aircraft's Forward Speed** to transfer the heat generated in the engine directly to the air. The engine is **Cowled** to reduce drag and control the flow of air around the engine to ensure equal cooling and so prevent overcooling at the front of the engine. The rate of flow can be altered on some aircraft by a variable **Cowl Flap or Gills** at the rear of the engine cowling.

Air Cooling

The air-cooled engine has few moving parts, and its simplicity make it virtually maintenance free. It is lighter in weight than a similar powered liquid-cooled engine, and for these reasons it is the **preferred** choice for aero piston engines.

It should be appreciated however that liquid cooling is more efficient, it gives better control of engine temperature and produces less drag on the aircraft. For these reasons liquid cooling is used on high speed aircraft using very powerful engines.

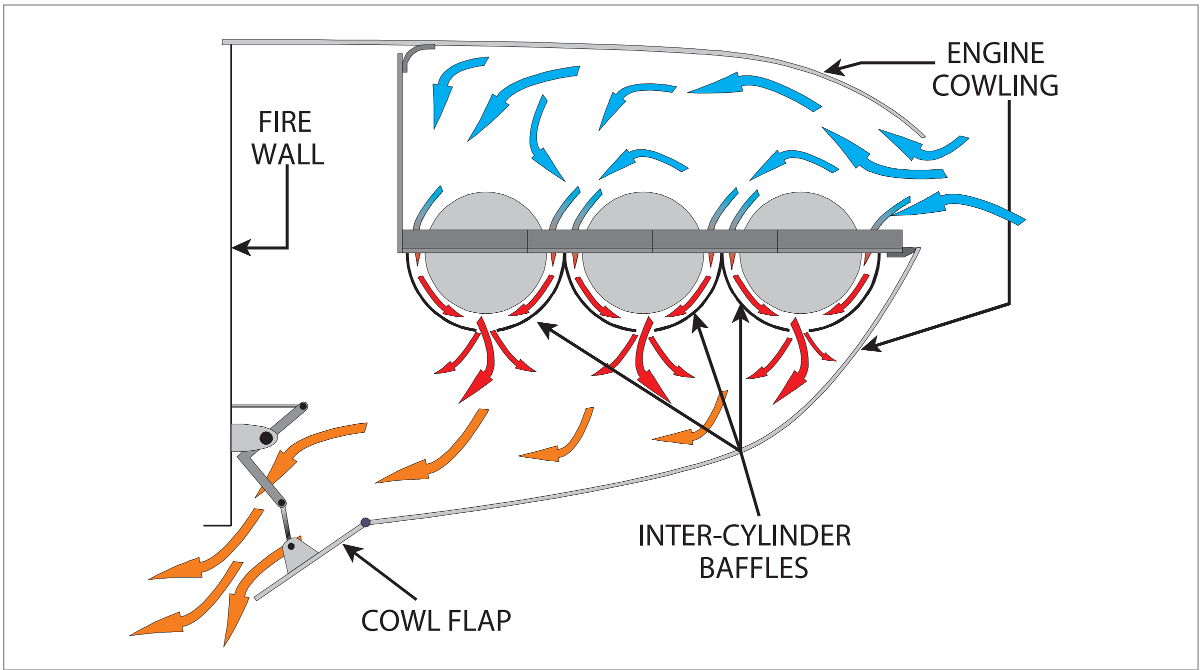


Figure 4.2 Cooling airflow in a six cylinder horizontally opposed engine.

The main factors governing the efficiency of an air-cooled system are:

Air Temperature
The ambient air temperature can vary widely with changes in climatic conditions and altitude. Dissipation of the heat will be more rapid as the air temperature decreases.

Speed of the Airflow
The speed of the airflow passing over the cylinders is governed by the slipstream and will vary with the speed of the aircraft. Consequently, care must be taken when ground running to prevent overheating. On some installations, a fan is fitted behind the propeller to obtain a more uniform speed of airflow.

Cooling Fins
The walls of the cylinder are finned to increase the cooling area. However, the pitch of the fins must be such that a large fin area can be obtained but the fins must not be so close that the resistance to the airflow builds up pressure which would tend to decrease the flow and increase drag. An average pitch for fins is about five to the inch. The fins are thin in section and may be extended to increase fin area at local hot spots to try to produce an even temperature throughout the component, e.g. around the exhaust ports on cylinders.

Baffles

Baffles *(see Figure 4.2)* are directional air guides to direct the airflow completely around the cylinder. They must always be close fitting and provide a seal with the cowlings, so that all the cooling airflow is over the cylinders. Care is taken to ensure that an even cross-sectional area is maintained, so that the airflow does not slow down and cause drag.

Engine Construction

Where possible, engine components are made of materials with a high heat conductivity, aluminium alloys are in common use. Cylinder heads are sometimes made of steel, and to obtain a better heat flow, there is a heavy deposit of copper on the combustion chamber face.

Cowlings, Cowl Flaps and Gills

Cowlings must be close fitting without dents or projections to disturb the airflow. Any disturbance to the designed flow will not only increase drag but also decrease cooling. With the cowl flaps or gills open, the airflow over the engine nacelle causes a pressure drop at the cooling air outlet, thus making it easier for the heated air to flow and maintain a high speed over the engine. As the air flows over the cylinders it absorbs heat and expands and, given a suitable gill opening, increases its speed. Any increase in speed through the engine will create a reactive force, tending to reduce the total engine drag.

The heat from the engine is not always transferred straight to the atmosphere. It can be used for heating the cabin of the aircraft, and directed when selected to supply hot air to remove ice from the carburettor.

The Cylinder Head Temperature Gauge

On some aircraft the pilot can monitor the temperature of the engine by the use of a **Cylinder Head Temperature Gauge.** The gauge uses a sensor which is fitted to the engines cylinder heads. If only one sensor is fitted it will be fitted to the **Hottest Cylinder.** This is usually one of the rearmost cylinders. The sensor is a **Thermocouple.** The principle of operation of a thermocouple is covered in depth in the electrical and instrument objectives. It is suffice to say that the sensor produces a **Voltage** which is directly proportional to its temperature. The cockpit indication is displayed by a sensitive moving coil meter called a **Galvanometer.** The scale reads temperature and not voltage.

Operational Procedures

The cooling arrangements for a particular engine are designed to ensure satisfactory cooling during flight, when the forward speed of the aircraft should give an adequate flow of cool air. This can however sometimes not be the case. During a climb, high power is used which generates high temperature in the engine. Forward speed is reduced and airflow to the engine is reduced. The pilot should be aware of the possibility of overheating. Climbing at best rate of climb speed (V_Y) is preferable to prolonged use of best angle of climb speed (V_X).

Descending can also cause problems. Engine power is reduced and there is less heat generated in the engine. If the aircraft is placed into a dive this will increases the flow of air over the engine and it will be overcooled. The sudden change in temperature could cause what is know as **Thermal Shock.**

This can cause components to fracture, and is a common problem on the cylinders of engines. Better control of temperature is possible if cowl flaps or gills are fitted, but these are only fitted to more complex aircraft. On simple light aircraft the pilot controls the cooling airflow by airspeed.

At high power settings such as take-off when the engine is generating a lot of heat, and at low airspeeds when the cooling flow is minimal, the cowl flaps should be selected open to increase flow rate of air and so increase cooling. This means that at take-off the cowl flaps would increase drag. In descent the cowl flaps are closed to reduce cooling. In the cruise at altitude the cowl flaps could be partially closed to maintain the engine temperature, as the cooling air temperature falls improving its efficiency.

High power settings should normally be limited on the ground as only the propeller slipstream is available to give a cooling flow. This is not always sufficient and overheating can occur. Cylinder head and oil temperatures should be closely monitored during ground running. It should not be forgotten that the internal parts of the engine like the pistons, valves etc, are cooled by the lubricating system.

Cylinder head temperature is also affected by mixture strength. This is covered in Chapter 7. The highest cylinder head temperatures are when lean mixture is selected for economy or endurance cruise.

Prior to shutdown the engine should be run at approximately 1000 - 1200 rpm to prevent plugs fouling. The engine will have cooled and stabilized during the taxi. Shutting down whilst the engine is very hot can result in uneven cooling and possible damage.

Modern aero-diesels tend to be liquid-cooled or utilize a combined liquid/air cooling system. It is well known that liquid cooling is more effective as it provides a more uniform and controlled cooling of the engine, allowing tighter tolerances in the construction of the moving parts. Arguably the liquid system has the disadvantages of possible leakage and extra weight but these are outweighed by the advantages.

Questions

1. **The most efficient method for cooling a piston engine is to use .... However, the most common method of cooling is to use .... because of the .... involved.**

a.	air cooling	liquid cooling	reduced costs
b.	liquid cooling	air cooling	reduced costs
c.	fuel cooling	air cooling	reduced costs
d.	liquid cooling	fuel cooling	reduced costs

2. **At take-off cowl flaps should be selected:**

a. fully closed to decrease drag
b. open
c. partially closed
d. fully closed to increase drag

3. **A typical piston engine has a maximum thermal efficiency of:**

a. 70%
b. 80%
c. 90%
d. 30%

4. **In a four cylinder in-line engine air-cooled, (No. 1, 2, 3, 4 from the front) the coolest cylinder while running will be:**

a. 1
b. 2
c. 3
d. 4

5. **The device utilized to measure temperature on a piston engine is:**

a. thermometer
b. barometer
c. thermocouple
d. thermostat

6. **The temperature measuring device fitted in a four cylinder inline engine, (No. 1, 2, 3, 4 from the front), would normally be fitted to which cylinder?**

a. 1
b. 2
c. 3
d. 4

Answers

1	2	3	4	5	6
b	b	d	a	c	d

Chapter

5

Piston Engines - Ignition

The Dual Ignition System

All aero piston engines are fitted with dual ignition, that is to say, two electrically independent ignition systems.

Each engine cylinder has two sparking plugs fed by two separate magnetos. This reduces the risk of engine failure caused by faulty ignition and increases the power output of the engine by igniting the cylinder charge at two points (reducing combustion time).

Magnetos

Magnetos are **self-contained engine-driven electrical generators.** They produce a series of extra high tension (EHT) electrical sparks at the sparking plugs, in the correct firing sequence, for ignition of the petrol and air mixture.

The magneto combines the principles of the permanent magnet generator **(PMG)** and the step-up transformer in order to generate the EHT voltage necessary to break down the gap between the sparking plug electrodes.

A small magnetic field in the magneto **primary coil,** which consists of a few hundred turns of thick wire, is made to collapse at regulated intervals by the opening of a pair of cam-operated **contact breaker points.**

As the primary magnetic field collapses, the lines of magnetic force cut thousands of turns of very thin wire which comprise the **secondary coil,** and this induces within it an EHT voltage.

This is an example of electromagnetic induction. The induced EHT voltage is taken to a rotary switch called the **distributor** which distributes it to the sparking plugs in the correct firing sequence. The cam-operated contact breaker points and the distributor rotor are geared together so that the spark will appear at the sparking plug as the contact breaker points just open. The contact breaker cam and distributor rotor rotate at half engine speed.

The Capacitor (Condenser)

The prime function of the capacitor is to prevent burning or arcing across the contact breaker points, and to assist in creating the extra high voltage in the secondary coil by causing a rapid change of flux (magnetic field) in the primary coil. This increases the efficiency of the magneto.

The capacitor is fitted in parallel with the contact breaker points and the magneto control switch. The magneto relies for its operation on the rapid collapse of flux in the primary coil and this is caused by the contact breaker points interrupting the current flow through that coil.

With a capacitor across the points, the voltage that appears as the points open charges up the capacitor, and only a small weak spark appears at the breaker points and current in the primary coil ceases to flow allowing a very rapid collapse in primary flux.

The capacitor therefore stops arcing at the contact breaker points, and allows a rapid collapse of primary flux.

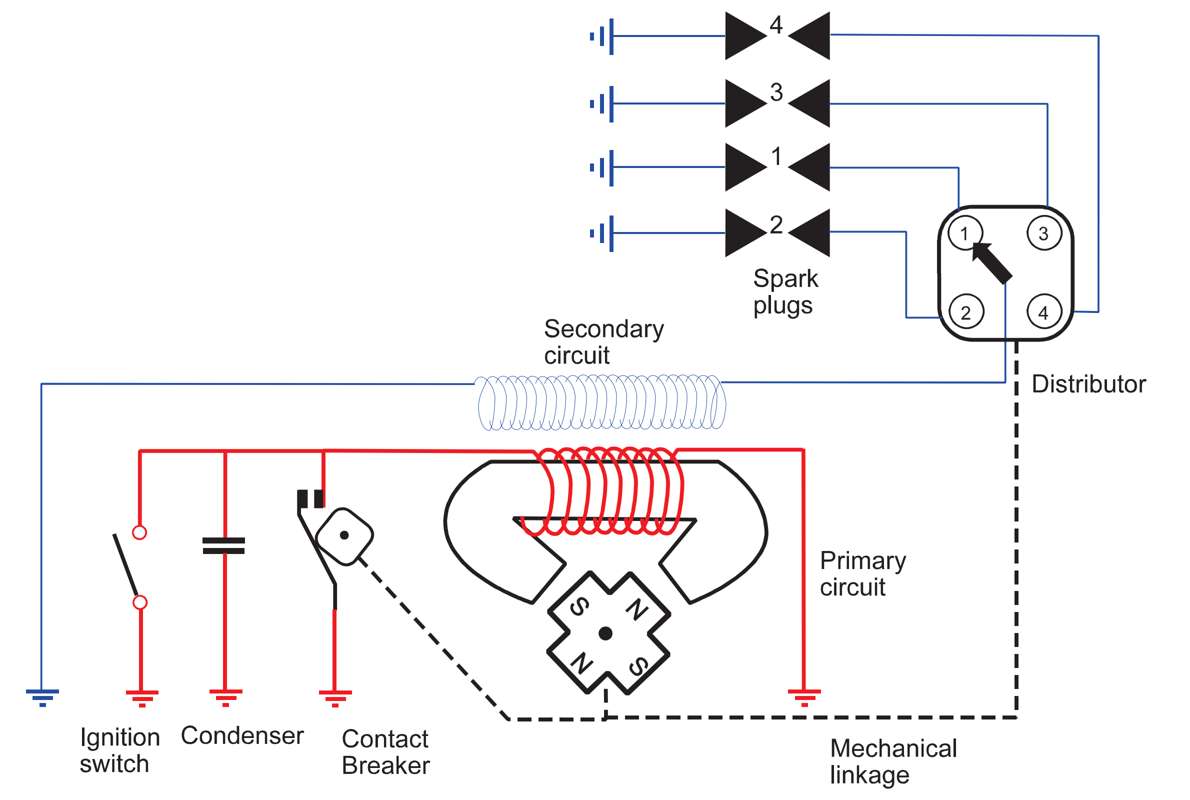


Figure 5.1 Magneto Circuit

The Ignition Switch

The ignition switch provides complete control of the engine's magneto circuit, the magneto being made inoperative by **earthing the primary circuit.**

In the 'OFF' position the switch is closed and this short-circuits the contact breaker points, which therefore no longer make and break the primary circuit. In the 'ON' position the switch is open and the primary circuit is controlled by the action of the contact breaker.

The Grounding Wire

As described above, the grounding wire is used to switch off the magneto. If the grounding wire breaks when the engine is running there will be no apparent changes in the engine's performance. If the grounding wire breaks and touches the engine-body or airframe then this is the equivalent of grounding the primary circuit, and the magneto is switched off. Hence the requirement for magneto checks listed below.

Magneto Checks

The **Dead Cut Check** is carried out at **slow running.** This check ensures that the pilot has control of the ignition before carrying out further ignition checks at higher engine speeds. **RPM MUST DROP BUT ENGINE MUST NOT STOP WHILE SWITCHING ONE MAGNETO OFF AT A TIME.**

Consider the situation which would exist with an engine running with the pilot unaware that only one magneto was working. If that live magneto was switched 'OFF' during a high rpm magneto check the engine would die.

The automatic reaction of the pilot would be to switch the ignition switch quickly back to 'BOTH'. The engine suddenly bursting into life with the throttle still at the check position would set up a high torque reaction between the airframe and engine, possibly causing extensive damage.

The **Live Magneto Check** is not normally required, as evidence of a live magneto is usually found at the Dead Cut Check simply by observing a change in rpm as the switch is operated.

The **Magneto rpm Drop Check** is carried out at approximately 75% of the maximum engine speed. This checks that the magneto and sparking plugs are functioning correctly.

As each magneto is switched off in turn, a check for a drop in rpm is made and this drop must be within the limits laid down by the manufacturers. The fall in rpm is due to the increased time taken for the mixture to burn in the cylinders, as a magneto, and consequently a plug in each cylinder is switched off.

Auxiliary Starting Devices

During starting, most aero-engines are cranked at about 25 rpm, and at this speed the magneto will not produce a spark with adequate energy for ignition of the petrol/air mixture.

It is necessary therefore, to ease starting, to employ auxiliary methods of spark augmentation.

These take the form of:

The **High Tension (HT) Booster Coil** which supplies a succession of high voltage electrical impulses to the trailing, starting, or retarded brush (electrode) of the main distributor rotor (shower of sparks system). It is switched 'ON' for the starting and 'OFF' after start-up.

The **Low Tension (LT) Booster Coil** supplies a low voltage to the magneto primary during the starting sequence, this augmentation of the primary permitting normal operation of the magneto. This system requires a Battery supply and is connected to the Primary (typically left) Magneto. When switched on, and the Starter engaged, the Booster Coil feeds a high voltage directly to the distributor rotor trailing-arm providing a retarded spark which avoids kick-back during the starting cycle. It is switched 'ON' for starting and 'OFF' after start-up.

The **Impulse Coupling.** This is a mechanical device which uses a spring to temporarily increase the speed of rotation of the magneto giving a large retarded spark during the starting cycle. No action by the pilot is necessary.

Magneto and Distributor Venting

Since magneto and distributor assemblies are subjected to sudden changes in temperature, the problems of condensation and moisture are considered in the design of these units.

Moisture in any form is a good conductor of electricity; and if absorbed by the nonconducting material in the magneto, such as distributor blocks, rotor arms, or coil cases, it can create a stray electrical conducting path.

The high-voltage current that normally arcs across the air gaps of the distributor can flash across a wet insulating surface to ground, or the high-voltage current can be misdirected to some spark plug other than the one that should be firing. This condition is called 'flashover' and usually results in cylinder misfiring.

Waxing

For this reason coils, condensers, distributors and distributor rotors are waxed so that moisture on such units will stand in separate beads and not form a complete circuit for flashover.

Flashover can lead to carbon tracking, which appears as a fine pencil-like line on the unit across which flashover occurs.

The carbon trail results from the electric spark burning dirt particles which contain hydrocarbon materials.

The water in the hydrocarbon material is evaporated during flashover, leaving carbon to form a conducting path for current. When moisture is no longer present, the spark will continue to follow the track to the ground.

Magnetos cannot be hermetically sealed to prevent moisture from entering a unit because the magneto is subject to pressure and temperature changes in altitude.

Diesel engine ignition

Unlike the conventional spark-ignition engine, the diesel does not require an ignition-system at all, thus saving on complexity and weight. The diesel is classified as a compression-ignition engine where ignition of the fuel/air mixture is a function of the rise of temperature of the air due to compression.

Much higher compression-ratios occur in the diesel, ratios of 25:1 are not uncommon. At these compression-ratios the fuel self-ignites thereby eliminating the need for a spark-generating system.

For cold starting, diesel engines usually employ a system of glow-plugs or pre-heaters which provide initial localized heating to the combustion-chamber area. Once started the fuel is injected into a zone where the temperatures are higher than the flash-point of the fuel due to high compression ratios, and ignition effectively by detonation becomes continuous.

Questions

1. The spark appears at the plug electrodes when:

a. the contact breaker closes
b. the contact breaker opens
c. the contact breaker stays open
d. the magneto switch is made

2. The ignition switch is fitted in:

a. the primary coil circuit
b. the secondary coil circuit
c. the engine starter motor circuit
d. the battery circuit

3. When the ignition switch is placed in the 'ON' position it:

a. isolates the breaker points
b. makes the engine starter motor circuit
c. 'Earths' or 'grounds' the secondary winding
d. breaks the primary to earth circuit

4. The purpose of a condenser as fitted in a magneto is:

a. to assist in the rapid collapse of the primary current and prevent arcing at the contact breaker points
b. to prevent the rapid collapse of the primary circuit and arcing at the points
c. to reduce the high tension voltage of the secondary circuit
d. to earth the primary circuit

5. The engine is checked for dead cut at:

a. a power check
b. slow running
c. cruising rpm
d. full throttle

6. The distributor directs:

a. voltage from the primary winding to the spark plug
b. voltage from the secondary winding to the primary winding
c. voltage from the magneto secondary winding to the spark plug
d. voltage from the secondary winding to the contact breaker

7. To obtain a spark across the gap between two electrodes:

a. the circuit must have high EMF
b. the circuit must have high ohms
c. the circuit must have high current flow
d. the circuit must have an impulse union

8. **The purpose of an ignition switch is:**

   a. to control the primary circuit of the magneto
   b. to prevent condensation
   c. to connect the secondary coil to the distributor
   d. to connect the battery to the magneto

9. **In a complex engine as rpm increases the ignition timing may be:**

   a. advanced
   b. retarded
   c. not altered
   d. only retarded

10. **An impulse starter is a device to assist in starting an engine which uses:**

   a. a leaf spring
   b. a coil spring to increase temporarily the speed of rotation of the magneto
   c. a special starting battery which provides a sudden impulse of electricity to the plugs
   d. an explosive inserted in a special tube

Answers

1	2	3	4	5	6	7	8	9	10
b	a	d	a	b	c	a	a	a	b

Chapter

6

Piston Engines - Fuel

Types of Fuel

The preferred fuel currently used in aircraft piston engines is derived from mineral oil. The fuel is a blend of **Hydrogen & Carbon**. Jet and diesel fuels are also derived from the oil. The differing types of fuel are produced by a process called cracking. Aircraft piston engines use a **Gasoline** fuel known as **AVGAS**.

Equipment used for the dispensing of AVGAS is colour coded **Red** to prevent cross-contamination with other fuels.

Manufacturing Specifications and Grades

So that aviation gasoline will fulfil these requirements, it is manufactured to conform with exacting **specifications** that are issued by the Directorate of Engine Research and Development (DERD). The specification number for gasoline is DERD 2485.

Fuel **'grades'** lie within a specification and therefore carry a blanket DERD number followed by a grade not prefixed by the DERD notification.

The most popular grades of AVGAS readily available today are:

Grade	Performance No.	Colour	Specific Gravity (Density)	Lead Content
AVGAS 100LL	100/130	Blue	0.72	Low Lead
AVGAS 100	100/130	Green	0.72	High Lead
AVGAS 80	80/87	Red	0.72	Very Low Lead

Note: *although AVGAS 100 and AVGAS 100LL have the same 100/130 performance No. they are however easily distinguished by their colour.*

Some Aviation Authorities do allow the use of car petrol for some aircraft. This is generally referred to as **MOGAS** (motor gasoline). Within the UK, aircraft authorized for the use of MOGAS is laid down in Airworthiness Notices number 98 and 98a.

Because of its higher volatility carburettor icing and vapour locking is much more likely. Information on the use of MOGAS can also be found in CAA Safety Sense leaflet no. 4a.

Calorific Value

The **Calorific Value** of a fuel is a measure of the amount of heat that will be released during combustion, and is measured in British Thermal Units (BTU) per pound. This varies with the chemical composition of the fuel, those with a high hydrogen content being superior. The calorific value is related to specific gravity. The higher the specific gravity the higher the calorific value.

Volatility

A volatile liquid is one which is capable of changing readily from the liquid to the vapour state by the application of heat, or by contact with a gas into which it can evaporate.

Fuel is added to the air at the carburettor, the efficiency with which the fuel mixes with the air is largely determined by the volatility of the fuel.

However, the time involved is so small that some of the fuel remains in the form of minute droplets, the evaporation of which occurs in the induction system.

High Volatility

A liquid boils when its vapour pressure is greater than the atmospheric pressure acting on the surface of the liquid. This means that, as the atmospheric pressure reduces with altitude, the fuel vaporizes at a lower temperature. This is generally referred to as '**low pressure boiling**'.

Stability

A number of the hydro-carbon compounds which are present in gasoline have a considerable attraction for the oxygen in the air. When they come into contact with air, they oxidize and undergo chemical changes to form heavy resinous gummy compounds and corrosive bodies. It is essential that these potentially unstable hydro-carbons are not allowed to oxidize, this is prevented by the addition of oxidation inhibitors.

Sulphur Content

Sulphur and sulphur compounds, when burnt in air, form sulphur-dioxide. This combines with the moisture content of the exhaust products to form a sulphurous acid which is extremely corrosive to the exhaust system. It is important that the sulphur content is kept as small as possible, in aviation gasoline the maximum amount of sulphur permitted is 0.001%.

The Combustion Process

Combustion is a **controlled** rate of burning, it is not an 'explosion'. The mixture induced into the cylinders consists of **gasoline vapour** (**84.2**% **carbon** and **15.8**% **hydrogen** by weight) and **air** (**78**% **nitrogen**, **21**% **oxygen** and **1**% **other inert gases**). When combustion has been completed, the hydrogen in the fuel will have combined with the oxygen in the air to form H_2O which is water vapour, and the carbon in the fuel will combine with the oxygen in the air to form CO_2 - carbon dioxide. The nitrogen and other gases play no active part in the combustion process, but they do form the bulk of the gas that is heated and expanded to create pressure energy. The nitrogen also slows down the rate of combustion, without nitrogen, combustion would be an explosion with far too rapid a temperature and pressure rise to be harnessed to do useful work.

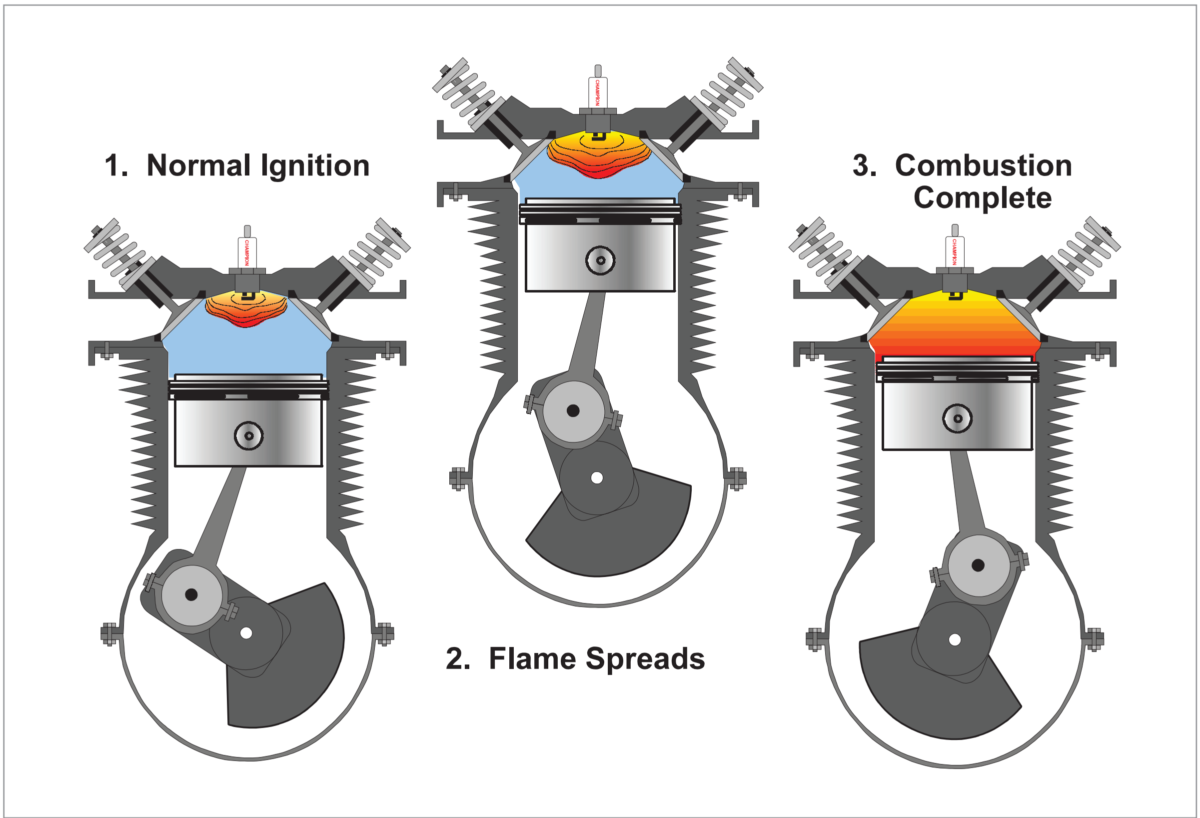


Figure 6.1 Normal combustion.

Flame Rate

When normal combustion takes place, the compressed charge is ignited by the spark and burns rapidly and steadily with a flame speed of **60-80 ft.** per second, giving a steady and smooth temperature and pressure rise in the combustion chamber.

Maximum pressure will be generated when combustion has been completed, and ideally this should occur when the crank is at **8° - 10°** after top dead centre (ATDC) where, because of the ineffective crank angle, the volume of the combustion chamber is still at a minimum. Should maximum pressure conditions obtain in advance of this (i.e. at, or before TDC) the engine would tend to run backwards.

Variable Ignition Timing

As combustion takes a short period of time, in order for combustion to be completed when the piston is at **8° - 10°** ATDC, the spark must occur before the piston reaches TDC. The flame rate remains reasonably constant, but the engine speed varies considerably, therefore at low engine speeds it is necessary for the ignition to be retarded to prevent the maximum pressure building up before the piston reaches TDC. As the engine speed increases, both the flame rate and the time required for complete combustion remain constant, but because of the increased piston speed, it is necessary to advance the ignition so that the maximum pressure still occurs at the right time, i.e. **8° - 10°** ATDC.

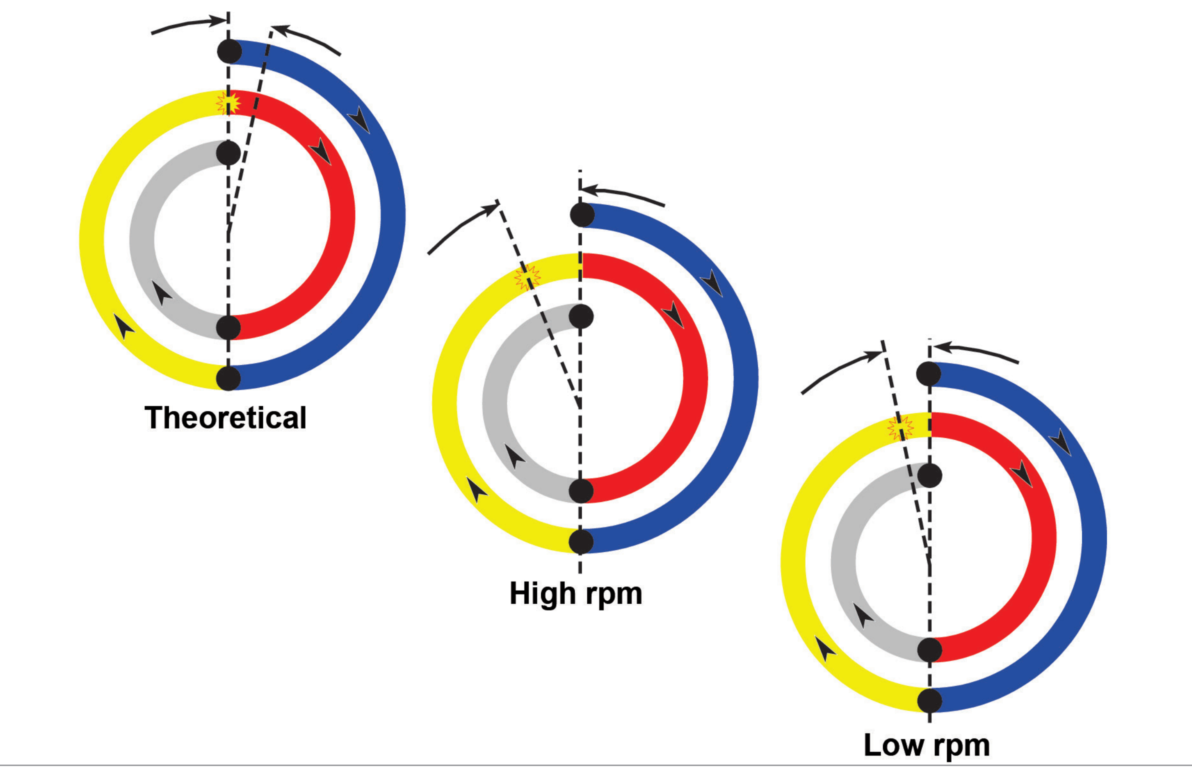


Figure 6.2 Moving the ignition point to the optimum position for idling rpm & high speed running.

Variations in Flame Rate

The flame rate does vary slightly, for instance the mixture will burn faster if it is made richer or the pressure in the cylinders increase. It is necessary to increase the mixture strength of all aircraft engines when they are producing high power to ensure stable combustion. Therefore, the increased flame rate which results from the action of selecting a rich mixture shortens the time required for combustion so that, to obtain full power, it is necessary to retard the ignition slightly, or alternatively not to make any further advance of the ignition.

Anti-detonation Properties

The higher that the pressure of the fuel/air mixture can be raised before combustion, the higher will be the pressure of the burning gases. Consequently, the greater will be the power output and thermal efficiency of the engine. The compression pressure is governed by the compression ratio of the engine and is limited by the tendency of the fuel to detonate, or knock.

Detonation (Knocking)

Detonation occurs after ignition and is unstable combustion. During normal combustion, the flame travels smoothly and steadily through the mixture as the advancing flame front heats the gases immediately ahead of it, so that they in turn burn.

Progressively there is more and more heat concentrated in the flame front, which is brought to bear on the remaining unburnt portion of the mixture, termed **end gas**, and its temperature is raised.

In addition, the burnt gases have expanded so that the end gas is subjected to an increasing pressure.

Ultimately there is sufficient pressure and heat available to bring all the end gas to the point of combustion at the same instant, and it explodes. The flame rate increases to 1000 ft per second, with a degree of violence which will depend on the amount of end gas that remains.

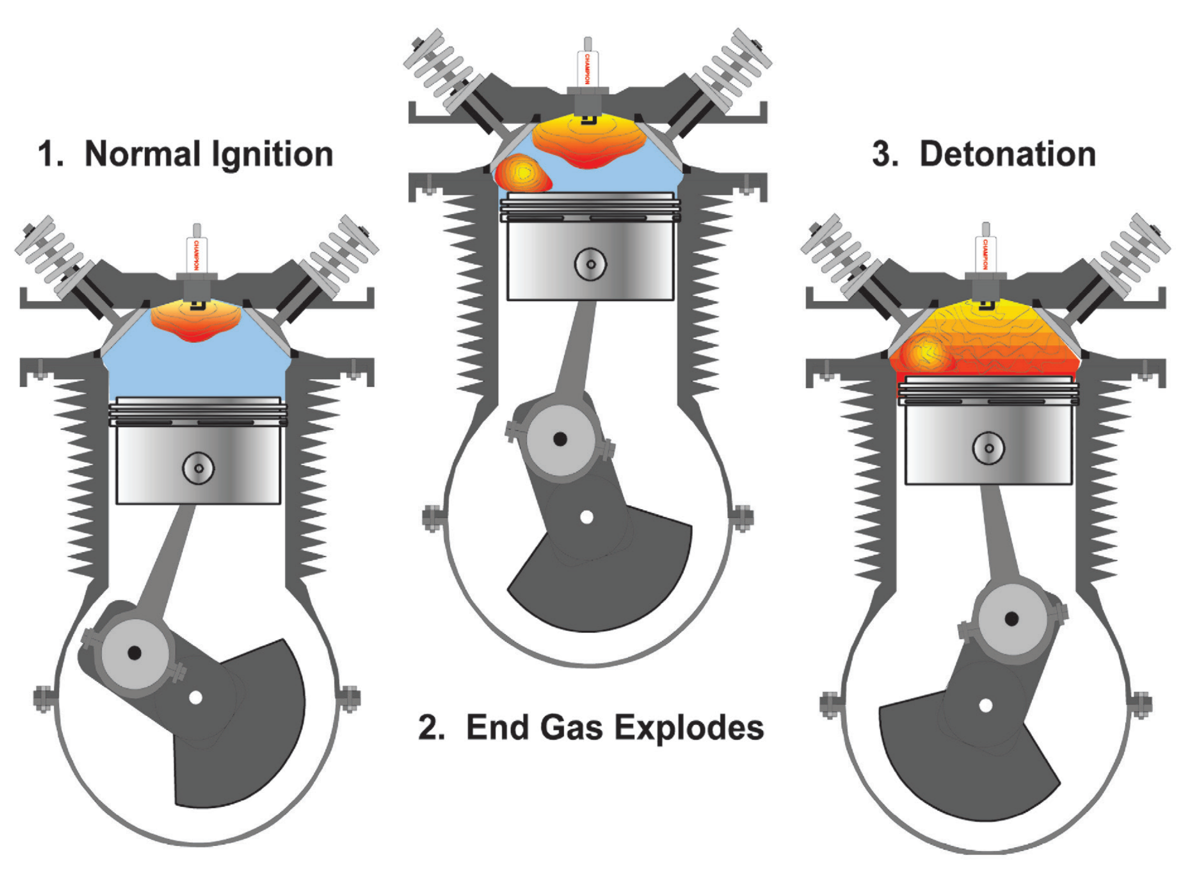


Figure 6.3

The Effects of Detonation

The explosion of the end gas can cause the piston crown to burn, and eventually to collapse, overheating of the combustion chamber can also occur. This may cause the valves to split and distort and possibly burn the sparking plug electrodes.

There is also a sudden rise in pressure as detonation occurs, which applies a shock loading to the engine component parts, which may cause mechanical damage.

Finally, because the maximum pressure is generated before the piston is in the correct position to utilize it, the piston has to overcome a high back pressure and power is lost.

Detonation and Diesel Engines

Detonation in a diesel engine is quite normal. The diesel is sometimes referred to as the ‘detonation-ignition’ engine. Diesels are constructed to withstand the additional pressures generated and therefore are generally heavier.

The Causes of Detonation

Any condition that heats the charge before combustion will aggravate matters in the end gas, pre-heating the air before it enters the engine (the use of 'hot-air' to overcome carburettor icing) or over-compression in the supercharger may well give rise to excessive temperatures. Once burning has started the process should not be prolonged.

Detonation may be caused by one or a combination of the following:

a) **Incorrect mixture strength**

The greater the amount of fuel for a given amount of air, the greater the power obtainable without detonation. If the power output is high, then the mixture must be rich.

b) **High charge temperature**

Anything that raises the temperature or the pressure of the charge unduly before burning, e.g. carburettor heating (at high power), overheated cylinders, high boost with very low rpm.

c) **Incorrect ignition timing**

If the spark is too far advanced the charge ignites too early, giving higher temperatures.

d) **Cooling**

If the combustion chamber surfaces are coated with carbon, or coke as it is commonly called, heat from the flame will not dissipate rapidly, resulting in high cylinder head temperatures.

e) **Cylinder head design**

The greater the time taken for the flame front to travel through the combustion chamber, and the higher the charge temperature, the greater the risk of detonation. Design features which would directly affect these would be for example: the size of combustion chambers, the positions of the spark plugs and the valves, the compression ratio and effective cooling.

f) **Use of incorrect fuel.**

See the Fuel Quality Control section on the opposite page.

The Recognition and Prevention of Detonation

Detonation is spontaneous combustion, and can be recognized by its metallic knocking sound or **pinking** which is caused by the violent vibrating pressure waves striking the walls of the combustion chamber. Much damage may be done under high power circumstances, particularly in an aircraft, where because of the noise created by the propeller, the detonation may go unnoticed until it is too late.

Detonation may be controlled by:

a) **A compact combustion chamber** helps in this respect by reducing the distance that the flame front has to travel, also the time taken to burn the charge can be reduced by initiating flame fronts from **two sparking plugs**.

b) **If possible the flame should be started from the vicinity of some hot spot** such as the exhaust valve, so that the end gas is pushed away from the hotter parts of the combustion chamber, and compressed into a cooler part.

c) Running conditions can also assist in delaying the onset of detonation, for example, the same power may be obtained at a **higher engine speed** by using a finer propeller pitch. This enables a smaller throttle opening to be used, which helps in two ways, the smaller throttle opening reduces the cylinder pressure and the higher running speed cuts down the time available.

d) In short, anything which can reduce **temperature, pressure or time** will be instrumental in reducing, or at the very best preventing its creation.

Fuel Quality Control

One of the easiest way of controlling detonation is by improving the quality of the fuel. There are two chemically pure fuels, **Iso-octane** and **Normal Heptane**, which are employed as **reference fuels** when determining the anti-detonation qualities of a fuel under laboratory conditions.

Iso-octane has very good combustion characteristics and shows little tendency to detonate when mixed with air and ignited at high temperatures, and is given a rating of 100.

Normal Heptane detonates very readily and has a rating of 0.

The combustion characteristics of any blend of fuel can be compared with those of the two reference fuels by using each in turn under standardized conditions in a special single-cylinder engine.

The engine is run using the fuel under test and then compared to a blend of the two reference fuels to produce the same degree of detonation in the engine. If the blend of the reference fuels is 95% iso-octane and 5% normal heptane, then the fuel under test would be given an **octane rating** of 95. The octane rating is, therefore, a measure of the fuel's **Anti-knock value.**

The original tests were based on an air/fuel ratio which gave maximum detonation, but this condition is not truly representative of the working range of the engine. Maximum detonation occurs with economical mixtures used for cruising but, for take-off and climbing, rich mixtures are used.

It is important to know how the fuel will behave under these varying mixture strengths, and so aviation fuel has two ratings. This is sometimes referred to as the performance number or performance index.

As an example, AVGAS 100LL is a 100 octane fuel with a perf number of 100/130, the lower figure is the weak mixture detonation point and the higher figure the rich mixture detonation point. It follows that if an engine is designed to use a certain grade of fuel, then a lower grade should never be used, as this would cause detonation.

If at any time the correct octane rating is not available, then a higher octane rating must be used.

Fuel Additives

Detonation can be avoided by putting small quantities of additives into the fuel, the principal one used being **Tetra Ethyl-lead** (TEL). The action of TEL is to reduce the formation of peroxides which would otherwise encourage detonation.

In the course of time, fuels with better combustion characteristics than iso-octane were produced and, to rate these, comparisons are made with iso-octane doped with TEL. As the percentage rating of the iso-octane can no longer apply, an alternative scale for rating these fuels, which have a high resistance to detonation, is provided by a range of **performance numbers.**

A rating above 100, e.g. 100/130 grade gasoline is a performance number, although in practice the fuel would still be referred to as a 100 octane fuel.

The Advantages of High Octane (Anti-detonation) Ratings

Better quality fuel permits:

a) Increased compression ratios with an increase in thermal efficiency, better fuel consumption, and an increase in engine power.

b) Increased induction pressure and greatly increased power from a given engine by the use of a supercharger.

The power output of an engine is directly proportional to the weight of mixture burned in unit time, increased induction pressure will increase this weight. (Although basically the quantity or 'weight of charge ' induced will still depend upon the position of the throttle butterfly).

Pre-ignition

Pre-ignition, (also known as 'Running-on') is the ignition of the charge **before the spark occurs** at the sparking plug. This is usually caused by a local 'hot-spot' in the combustion chamber, such as incandescent carbon or very hot sparking plug points, with consequent rough running, running-on, and loss of power.

Thermal Efficiency

The heat produced by the burning of one gallon of fuel is capable of producing a lot of work if the heat is fully utilized and none wasted, but in practice a considerable amount of work is lost in the form of heat to the cylinder walls and the piston crowns. The exhaust gases also remove heat as their temperature is still high when they are expelled from the cylinder during the exhaust stroke.

Additional work is absorbed in overcoming the internal friction of the engine.

The net result is that, under the best conditions, rather less than 30% of the heat value of the fuel is converted into useful work at the propeller shaft.

If the fuel is very volatile, not only will there be **excessive losses by evaporation** in the aircraft's fuel tanks, but the fuel will tend to boil and vaporize at the depression (inlet) side of the fuel pump, causing **cavitation** (bubbles forming in the fuel around the pump impeller) and **vapour**

locks to form. The tendency for **carburettor icing** under certain atmospheric conditions is also enhanced.

Diesel Engine Fuel

Diesel aero-engines use a fuel known as Aviation Turbine Gasoline or AVTUR.

AVTUR (paraffin) is widely available, less of a fire-hazard, less volatile and therefore a safer fuel option operationally than AVGAS.

Aviation fuel is sold and delivered to the aircraft in units of volume (US gallons, imperial gallons or litres). AVTUR is more dense then AVGAS (with an SG of 0.8) and so contains more energy per unit volume than AVGAS (with an SG of 0.72). Therefore, for a given fuel load on board an aircraft, the range would be greater if AVTUR was used, as opposed to AVGAS.

Questions

1. **If the specific gravity of a fuel is known to be 0.7, 100 imperial gallons of it will weigh:**

   a. 700 lb
   b. 70 lb
   c. 7000 lb
   d. 7100 lb

2. **A fuel grade which is used in typical aircraft engines is:**

   a. DTD. 585/100
   b. DERD 2479
   c. AVGAS 100
   d. DERD 2484

3. **The "anti-knock" value of a fuel is its:**

   a. degree of resistance to pre-ignition
   b. resistance to adiabatic combustion
   c. ability to oppose burning
   d. resistance to detonation

4. **The differences between AVGAS 100 and AVGAS 100LL are:**

	Colour	Anti-knock value
a.	same	same
b.	same	different
c.	different	same
d.	different	different

5. **The octane rating of a fuel is determined by comparison with mixtures of:**

   a. methane and orthodentine
   b. heptane and iso-octane
   c. methane and iso-octane
   d. heptane and orthodentine

6. **In the internal combustion engine, detonation occurs due to:**

   a. the use of too high an rpm with too little manifold pressure
   b. the use of the wrong grade of oil
   c. the cylinder temperatures and pressures being too low
   d. excessive combustion temperatures and pressures

7. **The calorific value of a fuel is the:**

   a. kinetic energy contained within it
   b. heat energy in the fuel
   c. heat energy required to raise the temperature of the fuel to its boiling point
   d. heat energy required to raise the temperature of the fuel to its boiling point from absolute zero

8. The octane rating of a particular grade of fuel is given as 100/130, this indicates that:

a. it will act as both 100 octane and 130 octane fuel at take-off power settings
b. with a rich mixture it will act as 100 octanes, and with a weak mixture it will act as 130 octanes
c. its anti-knock qualities are identical to iso-octane
d. with a weak mixture it will act as 100 octane, and with a rich mixture it will act as a 130 octane fuel

9. Tetra-ethyl lead is added to some aviation fuel to:

a. decrease its octane rating
b. decrease the risk of detonation
c. increase its calorific value
d. increase its specific gravity

10. If the vent pipe of an aircraft's fuel tank becomes blocked, it will cause:

a. the pressure in the tank to fall when fuel is used
b. the pressure in the tank to rise when fuel is used
c. the evaporation rate of the fuel to decrease as fuel is used from the tank
d. the fuel pressure at the carburettor to rise

11. Detonation is liable to occur in the cylinders:

a. with an over rich mixture at idle power
b. with a weak mixture and high cylinder head temperature
c. with a rich mixture at high power settings
d. at very low engine speed

12. Pre-ignition refers to the condition when:

a. a rich mixture is ignited by the spark plug
b. the spark plug ignites the mixture too early
c. the mixture is ignited by abnormal conditions within the cylinder before the normal ignition point
d. the mixture burns in the inlet manifold

13. An exhaust gas temperature gauge is powered by:

a. 12 V DC
b. 115 V AC
c. 28 V DC
d. A thermocouple which generates its own voltage.

14. Flame Rate is the term used to describe the speed at which:

a. the mixture burns within the cylinder
b. the combustion pressure rises within the cylinder
c. peroxide forms within the cylinder
d. fulminates form with the cylinder

15. **The colour of 100/130 grade low lead fuel is:**

    a. green
    b. blue
    c. red
    d. straw yellow

16. **Diesel fuel (AVTUR) is:**

    a. lighter per unit volume than AVGAS
    b. heavier per unit volume than AVGAS
    c. more likely to ignite when exposed to a naked flame.
    d. has less energy per unit volume than AVGAS.

Answers

1	2	3	4	5	6	7	8	9	10	11	12
a	c	d	c	b	d	b	d	b	a	b	c

13	14	15	16
d	a	b	b

Chapter

7

Piston Engines - Mixture

The Chemically Correct Ratio

Although air and fuel vapour will burn when mixed in proportions ranging between **8 : 1** (rich) and **20 : 1** (weak), complete combustion only occurs with an air/fuel ratio of **15 : 1 by weight.** This is the **chemically correct ratio,** at this ratio all of the oxygen in the air combines with all of the hydrogen and carbon in the fuel.

The chemically correct mixture does not give the best results, because the temperature of combustion is so high that power can be lost through **detonation**.

The Practical Mixture Ratio

Although the chemically correct mixture strength would theoretically produce the highest temperature and therefore power, in practice mixing and distribution are less than perfect and this results in some regions being richer and others being weaker than the optimum strength. This variation may exist between one cylinder and another.

A slightly rich mixture does not have much effect on power since all the oxygen is still consumed and the excess of fuel simply serves to slightly reduce the effective volumetric efficiency, in fact its cooling effect can be to some extent beneficial.

Weak mixtures, however, rapidly reduce power since some of the inspired oxygen is not being utilized, and this power reduction is much greater than that resulting from slight richness. It is, therefore, quite common to run engines (when maximum power rather than best fuel economy is the objective) at somewhat richer than chemically-correct mixtures (e.g. about **12.5 : 1**) to ensure that no cylinder is left running at severely reduced power from being unduly weak.

Problems Caused by Weak Mixtures

A mixture which is weaker than the chemically correct ratio, besides burning at lower temperatures, also burns at a slower rate (because of the greater proportion of nitrogen in the cylinder). Power output thus decreases as the mixture is weakened, but, because of the increase in efficiency resulting from cooler burning, the fall in power is proportionally less than the decrease in fuel consumption. Thus the Specific Fuel Consumption (SFC), decreases as the mixture strength is weakened below **15 : 1**.

For economical cruising at moderate power, air/fuel ratios of **18 : 1** may be used, an advance in the ignition timing being necessary to allow for the slower rate of combustion.

With extremely weak mixtures, the gases may still be burning when the exhaust valve opens, exposing the valve to high temperatures which may cause the valve to crack or distort. As the inlet valve opens, the heat of the exhaust gases is still so high that it may ignite the mixture in the induction system, and **'popping back'** occurs through the induction manifold.

This slow burning also causes overheating, as a certain amount of the heat is not converted into work by expansion and has to be dissipated by the cooling system. The mixture requirement is, therefore, dependent upon engine speed and power output. A typical air/fuel mixture curve is shown in *Figure 7.1*, next page.

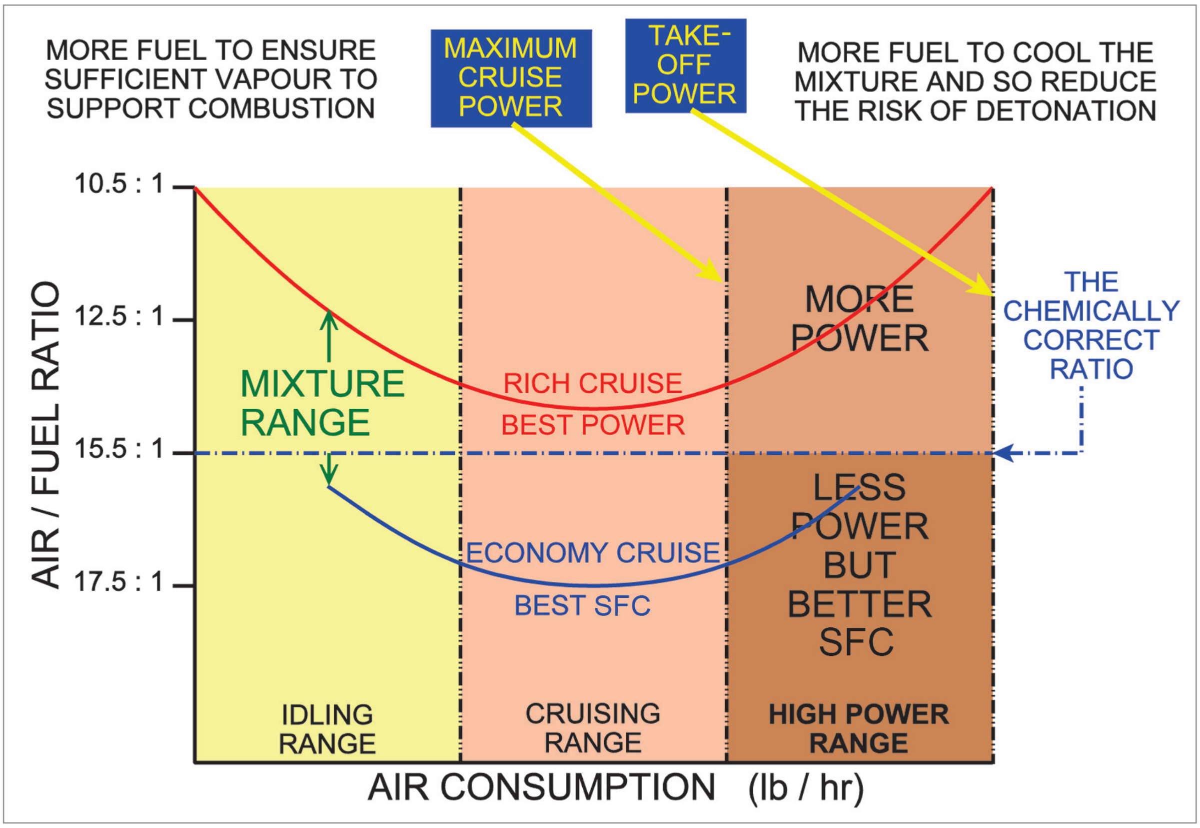


Figure 7.1 A typical air/fuel mixture curve.

Slow Running and Starting

A rich mixture is required for starting and slow running because:

a) Fuel will only burn when it has vaporized and is mixed with air. When starting, the engine is cold and there is little heat to assist the vaporizing process, therefore only the lightest fractions of the fuel will vaporize and this may show as white smoke at the exhaust. White smoke may be apparent due to the fact that water is a product of combustion leaving condensation inside the exhaust, and also that the engine is breathing in cold moist air. The white smoke will gradually disappear as the engine reaches normal running temperature. To make sure that there is sufficient fuel vapour in the cylinders to support combustion a rich mixture is required.

b) The exhaust valve is given a certain amount of lag so that full advantage can be taken of the considerable inertia of the gases at normal engine speeds, to obtain efficient scavenging of the burnt gases, and to give impetus to the incoming charge. As engine speed reduces, the gas velocity falls and more of the burnt gases remain in the cylinder, whilst at still lower speeds there is the tendency for exhaust gases to be sucked back into the cylinder by the descending piston before the exhaust valve closes. The consequent dilution of the induction gases is such that, to maintain smooth running, a rich mixture is required.

Take-off Power

When full power is selected for take-off, the mixture must be further enriched to about **10 : 1.** Apart from the cooling effect, the excess fuel is wasted, for there is insufficient oxygen available for it to burn completely. The higher power results from a greater weight of charge induced in a given time, and not because of mixture enrichment. In practice, excess fuel vapour is not scavenged as vapour, the oxygen is shared out to some extent, so that carbon monoxide (CO) is produced during combustion as well as carbon dioxide (CO_2). With very rich mixtures some of the carbon fails to combine with oxygen at all and is exhausted as **black smoke.**

Climbing Power

The engine power output is a product of engine speed and the mean effective pressure in the cylinders during the working cycle, higher power outputs involve increases in both of these factors. As the speed and the pressure increase, there is also an increase in the temperature of the gases and, therefore, their tendency to detonate. When higher power is required for climbing, the mixture is enriched to about **11:1**. The extra fuel, in vaporizing, cools the mixture and reduces the tendency to detonate.

Cruise Power

During cruising conditions only moderate power is required from the engine, the mixture can be leaned to around **18:1** allowing the minimum expenditure of fuel to achieve economy.

The Exhaust Gas Temperature Gauge

As the mixture control is moved from fully rich to a weaker setting, the air fuel ratio approaches the chemically correct value of approximately **15:1**. At this ratio all the air and fuel are consumed and the heat released by combustion is at its **maximum.** More heat means more power. Rpm will rise (fixed pitch propeller), airspeed will increase as more power is produced. Both these indications can be used to adjust mixture, but a more accurate method is to indicate the change in exhaust gas temperature as the mixture is varied.

The **Exhaust Gas Temperature Gauge** (EGT) consists of a **Thermocouple** fitted into the exhaust pipe of the hottest cylinder. A thermocouple produces a voltage directly proportional to its temperature. The voltage is indicated by a gauge calibrated to show temperature. The mixture control should always be moved slowly. If moved toward lean the temperature will peak at the ratio of **15:1**. It should be remembered that this ratio **IS NOT USED** as detonation can occur. On reaching the peak EGT the mixture control would then be moved towards rich and the temperature would drop. A temperature drop would be specified in the aircraft's flight manual which would give the rich cruise setting.

Weakening the mixture beyond the chemically correct value will lower EGT and raise CHT and ***excessive*** weakening will lower both. Again the flight manual will specify the temperature drop required to set the economy cruise ratios. Mixture is normally only adjusted at cruise power settings. It should be returned to **Fully Rich** whenever the power is changed. *(Figure 7.2, next page.)*

Diesel Engines

Diesel engines generally run lean. This is because the air supply is not throttled and is fed unrestricted into the cylinder as a function of fuel delivery. Problems such as detonation do not feature as with conventional piston engines although running temperatures are generally higher requiring a reliable and effective cooling system. There is also no mixture lever as aero-diesels operate with a 'single-lever' concept similar to some turboprops.

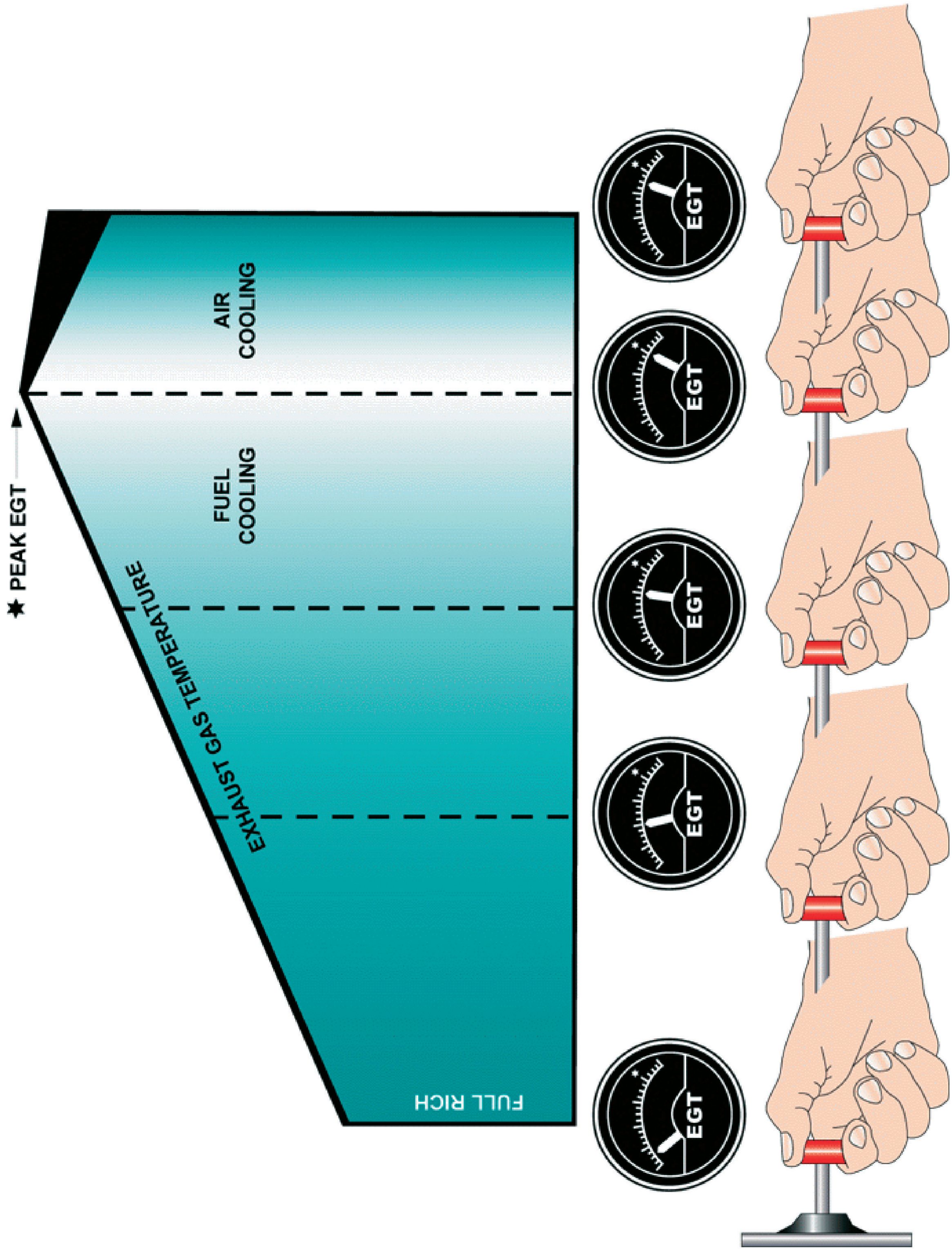


Figure 7.2 EGT changes with mixture leaning.

Questions

1. Weakening the mixture below the best fuel/air ratio will cause the engine power to:

a. decrease
b. increase initially, but decrease below take off power
c. increase
d. be unaffected by altitude increase

2. For maximum endurance the mixture control should be set to:

a. weak
b. the chemically correct state
c. between rich and weak
d. rich

3. An air/fuel ratio of 9:1 would be considered:

a. chemically correct
b. extravagant
c. rich
d. weak

4. Because of the reduction in the density of the atmosphere associated with an increase in altitude:

a. the mixture control must be moved towards the weak position
b. the throttle must close progressively to maintain the best air/fuel ratio.
c. the mixture must be progressively richened to compensate for the power loss
d. the octane rating of the fuel must be increased

5. A chemically correct mixture is:

a. 15:1 (fuel : air)
b. 15:1 (air : fuel)
c. 13:1 (fuel : air)
d. 13:1 (air : fuel)

6. While weakening the mixture from the chemically correct mixture the EGT will .... and the cylinder head temperature will .... with a .... in thermal efficiency.

a.	increase	increase	decrease
b.	decrease	increase	decrease
c.	decrease	increase	increase
d.	increase	increase	increase

7. Which of the following mixtures theoretically would produce the maximum rpm?

a. 14:1 (air : fuel)
b. 14:1 (fuel : air)
c. 15:1 (fuel : air)
d. 15:1 (air : fuel)

8. **A weak mixture is used for which of the following?**

   a. Take-off
   b. Climbing
   c. Engine starting
   d. Cruising

9. **While using a weak mixture which of the following would be an incorrect statement?**

   a. The charge would be cooled due to a larger proportion of nitrogen in the cylinder
   b. The charge would burn slower due to a larger proportion of nitrogen in the cylinder
   c. The ignition may have to be advanced
   d. The ignition may have to be retarded

10. **While using a rich mixture which of the following would be a correct statement?**

   a. The charge would burn slower
   b. All of the fuel would be used during combustion
   c. All of the oxygen would be used during combustion
   d. Cylinder head temperature increases while richening further

Answers

1	2	3	4	5	6	7	8	9	10
a	a	c	a	b	b	d	d	d	c

Chapter

8

Piston Engines - Carburettors

The Basic Requirements of a Carburettor

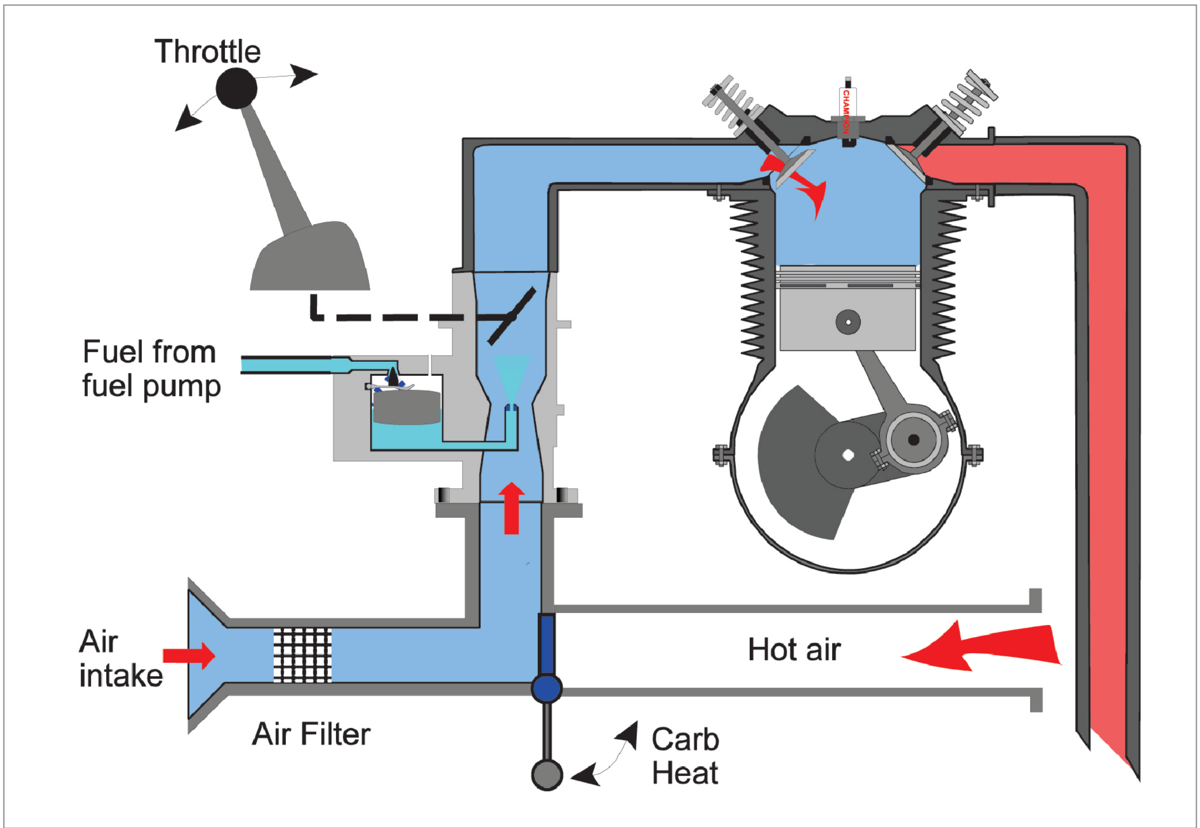


Figure 8.1 General layout.

The carburation system must:

a) Control the air/fuel ratio in response to throttle setting, at all selected power outputs from slow-running to full throttle, and during acceleration and deceleration.

b) It must function at all altitudes and temperatures in the operating range.

c) It must provide for ease of starting and may incorporate a means of shutting off the fuel to stop the engine.

The float chamber carburettor is the cheapest and simplest arrangement and is used on many light aircraft, however it is very prone to carburettor icing, and may be affected by flight manoeuvres. The injection carburettor is a more sophisticated device and meters fuel more precisely, thus providing a more accurate air/fuel ratio, it is also less affected by flight manoeuvres, and is less prone to icing.

The direct injection system provides the best fuel distribution and is reputed to be the most economical, it is unaffected by flight manoeuvres and is relatively free from icing.

Any of these systems may be fitted with a manual mixture control, by means of which the most economical cruising mixture may be obtained. However, in order to assist the pilot in selecting the best mixture, some aircraft are fitted with fuel flowmeters/pressure gauges or exhaust gas temperature gauges.

Diesel engines do not have carburettors but do have an inlet-system to allow air to be induced towards the cylinders incorporating an air filter. The air supply is not 'throttled'.

The Simple Float Chamber Carburettor

This carburettor employs two basic principles, those of the ‘U’ tube and the Venturi.

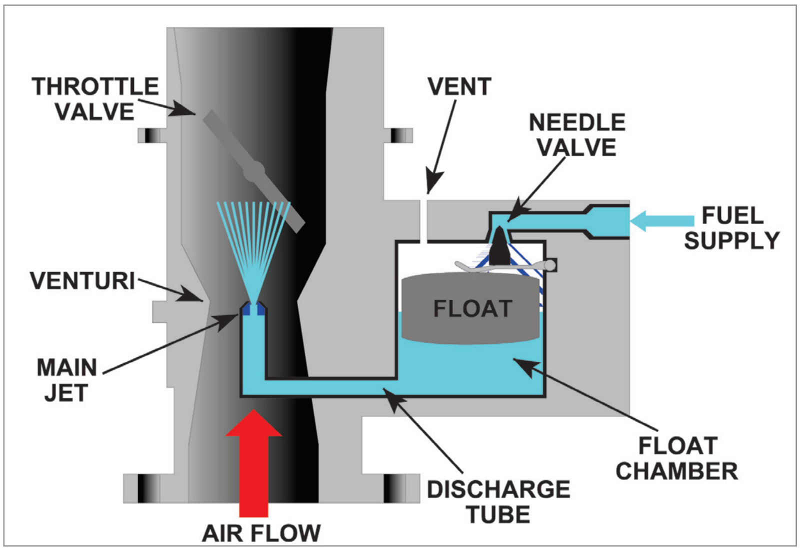


Figure 8.2 A simple float chamber carburettor.

The ‘U’ Tube Principle

If a tube is bent into the shape of a ‘U’ and then filled with liquid, the level in either leg will be the same, provided that the pressure acting on the tube is the same. If the pressure difference is created across the ‘U’ tube it will cause the liquid to flow. In practice one leg of the ‘U’ tube is opened out to form a small tank, a constant level being maintained by a float and valve mechanism regulating the flow of fuel from a fuel pump (or pumps) delivering a supply from the main aircraft tanks. *See Figure 8.1.*

The Venturi Principle

Bernoulli’s Theorem states that the total energy per unit mass along any one streamline in a moving fluid is constant.

The fluid possesses energy because of its pressure, temperature and velocity, if one of these changes one or both of the others must also change to maintain the same overall energy.

As the air passes through the restriction of the Venturi its velocity increases, causing a drop in pressure and temperature. The pressure drop at the throat of the Venturi is proportional to the mass airflow, and is used to make fuel flow from the float chamber by placing one leg of the ‘U’ tube in the Venturi.

In a float chamber carburettor such as that shown in *Figure 8.2*, airflow to the engine is controlled by a throttle valve, and fuel flow is controlled by metering jets.

Engine suction provides a flow of air from the air intake through a Venturi in the carburettor to the induction manifold. This air speeds up as it passes through the Venturi, and a drop in pressure occurs at this point. Within the induction manifold however, pressure rises as the throttle is opened.

Fuel is contained in a float chamber, which is supplied by gravity, or an electrical booster pump, or by an engine-driven fuel pump, and a constant level is maintained in the chamber by the float and needle-valve.

Where fuel pumps are used, a fuel pressure gauge is included in the system to provide an indication of pump operation. Air intake or atmospheric air pressure acts on the fuel in the float chamber, which is connected to a fuel discharge tube located in the throat of the Venturi.

The difference in pressure between the float chamber and the throat of the Venturi provides the force necessary to discharge fuel into the airstream. As airflow through the Venturi increases so the pressure drop increases, and a higher pressure differential acts on the fuel to increase its flow in proportion to the airflow. The size of the main jet in the discharge tube determines the quantity of fuel which is discharged at any particular pressure differential, and therefore controls the mixture strength. The simple carburettor illustrated in *Figure 8.2* contains all the basic components necessary to provide a suitable air/fuel mixture over a limited operating range.

Modifications to the Simple Carburettor

The Pressure Balance Duct

To maintain the correct rate of discharge of fuel through the main jet, the pressure in the float chamber and the air intake must be equal. Admitting atmospheric pressure in the float chamber by means of a drilling in the float chamber cover plate is not a satisfactory method of ensuring equalized pressure across the carburettor because, due to manoeuvres and the speed of the aircraft, the changes in pressure localized around the air intake would not be readily transmitted to the float chamber.

Equalized pressure conditions can only be obtained by connecting the float chamber directly to the air intake by a duct which is called the pressure balance duct. This duct also supplies air to the diffuser and is used in some carburettors to provide altitude mixture control. This mechanism is shown in *Figure 8.3.*

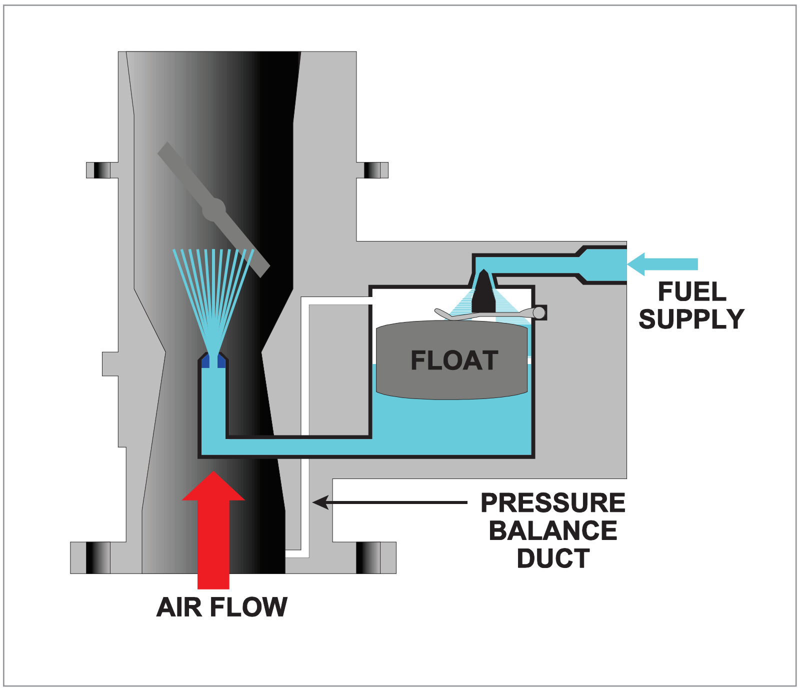


Figure 8.3 The pressure balance duct.

The Diffuser

As engine speed and airflow through the Venturi increase, the proportion of fuel to air rises as a result of the different flow characteristics of the two fluids. This causes the mixture to become richer.

To overcome this effect, some carburettors are fitted with a diffuser such as is illustrated in *Figure 8.4*. As engine speed is progressively increased above idling, the fuel level in the diffuser well drops, and progressively uncovers more air holes. These holes allow more air into the discharge tube, and by reducing the pressure differential prevent enrichment of the air/fuel mixture. The process of drawing both air and fuel through the discharge tube also has the effect of vaporizing the fuel more readily, particularly at low engine speeds.

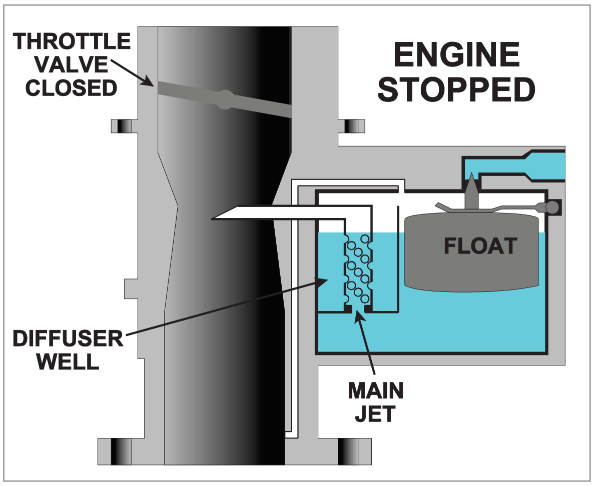


Figure 8.4 A diffuser well fitted in a carburettor float chamber.

The Principle of the Air Bleed Diffuser

A suction applied to a tube immersed in a liquid is sufficient to raise a column of liquid to a certain height up the tube. Should a small hole be made in the tube, under the same condition bubbles of air will enter the tube and the liquid will be drawn up the tube in smaller drops rather than a continuous stream. In other words, the liquid will be "diffused" or made to intermingle with the air. Air "bleeds" into the tube and reduces the forces acting on the fuel, retarding the flow of liquid through the tube. This is shown diagrammatically in *Figure 8.5*.

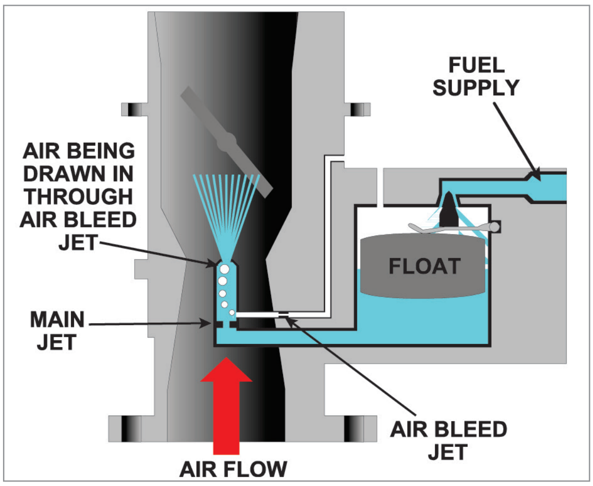


Figure 8.5 The air bleed diffuser.

Slow Running Systems

At low engine speeds, the volume of air passing into the engine is so small that the depression in the choke tube is insufficient to draw fuel through the main jet. Above the throttle valve there exists a considerable depression and this is utilized to affect a second source of fuel supply for slow-running conditions.

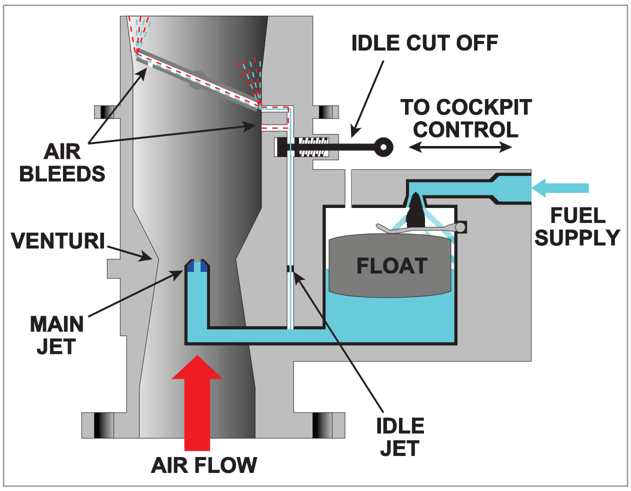


Figure 8.6 The slow running jet.

A slow running fuel passage with its own jet leads from the float chamber to an outlet at the lip of the throttle valve, shown in *Figure 8.6.* The strong depression at this point gives the necessary pressure difference to create a fuel flow.

The size of the slow running jet is such that it will provide the rich mixture required for slow running conditions. An air bleed, opening into the choke tube below the throttle valve, assists atomization. The purpose of the transverse passage drilled through the throttle valve is to evenly distribute the mixture over the area of the induction manifold. A small hole is drilled into the transverse passage from the choke tube side, and acts as an air bleed to draw some of the fuel through the throttle valve to mix with the air passing to the engine.

As the throttle is opened, the depression at the lip of the throttle valve decreases and the depression in the choke tube increases to the point where the main jet starts to deliver fuel and the flow through the slow running system slows down. Carburettors must be carefully tuned in order to obtain a smooth progressive change over between the slow running and the main system to prevent ‘flat spots’.

Note: *A flat spot is a period of poor response to throttle opening caused by a temporary weak mixture, it normally makes itself felt as a hesitation during engine acceleration.*

A cut-off valve is usually incorporated in the slow running passage, and is used when stopping the engine. When the cut-off is operated the valve moves over to block the passage to the slow running delivery, the mixture being delivered to the engine becomes progressively weaker until it will not support combustion and the engine stops.

This prevents any possibility of the engine continuing to run erratically due to pre-ignition, and also prevents fuel condensing in the cylinders which would tend to wash the oil from the cylinder walls, causing lack of lubrication when the engine is next started.

The cut-off may be a separate control or it may be incorporated in the mixture control lever.

Mixture Control

As altitude increases, the weight of air drawn into the cylinder decreases because the air density decreases. For a given intake velocity, the pressure drop in the Venturi will decrease as ambient density decreases. However, the fuel flow due to the pressure drop will not decrease by the same amount and so the mixture will become richer. This progressive richness with increased altitude is unacceptable for economic operation.

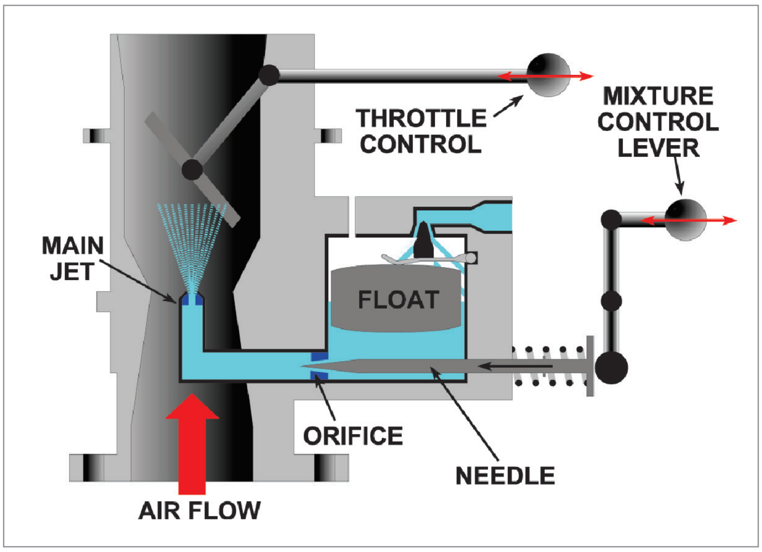


Figure 8.7 A needle type mixture control.

Needle Type

With a needle type mixture control, such as that illustrated in *Figure 8.7*, a cockpit lever is connected to a needle valve in the float chamber. Movement of the cockpit lever raises or lowers the needle and varies fuel flow through an orifice to the main jet. The position of the needle therefore controls the mixture strength, and in the fully-down position will block fuel flow to the main jet, thus providing a means of stopping the engine.

The smallest orifice in the whole fuel system is the fuel jet. To prevent any blockage of the jets by dirt or debris, a fuel strainer can be fitted just before them in the fuel line.

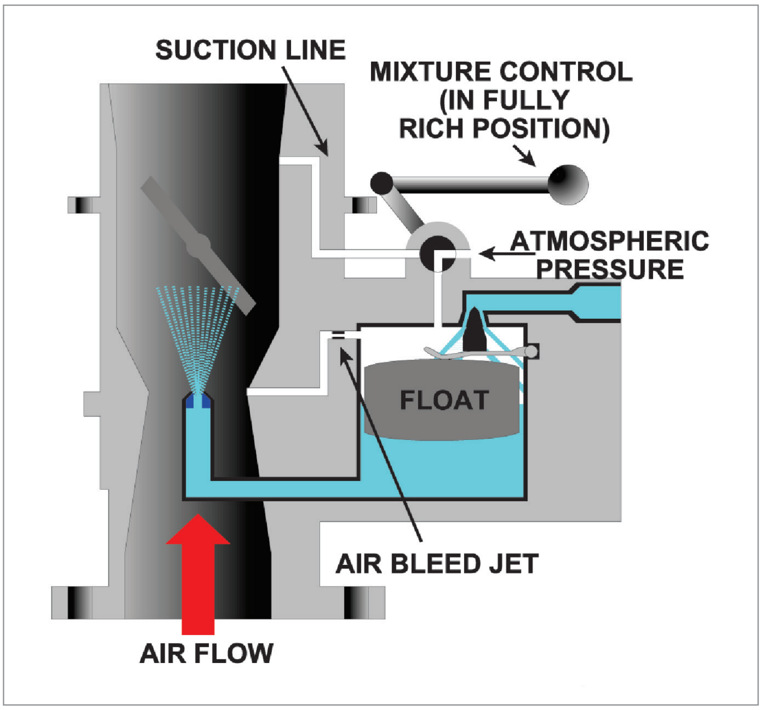


Figure 8.8 An air bleed mixture control.

Air Bleed

The Air Bleed Mixture Control shown in *Figure 8.8* operates by controlling the air pressure in the float chamber, thus varying the pressure differential acting on the fuel.

A small air bleed between the float chamber and the Venturi tends to reduce air pressure in the float chamber, and a valve connected to a cockpit lever controls the flow of air into the float chamber. When this valve is fully open the air pressure is greatest, and the mixture is fully rich, as the valve is closed the air pressure decreases, thus reducing the flow of fuel and weakening the mixture. In the carburettor illustrated the valve also includes a pipe connection to the engine side of the throttle valve, when this pipe is connected to the float chamber by moving the cockpit control to the 'idle cut-off' position, float chamber air pressure is reduced and fuel ceases to flow, thus stopping the engine.

Power Enrichment

At power settings above the cruising range, a richer mixture is required to prevent detonation. This rich mixture may be provided by an additional fuel supply, or by setting the carburettor to provide a rich mixture for high power and then bleeding off float chamber pressure to reduce fuel flow for cruising.

Power Enrichment or Economizer Jet.

Illustrated in *Figure 8.9* is a carburettor with an additional needle valve, which may be known as a power enrichment jet, or economizer jet. The needle valve, which is connected to the throttle control, is fully closed at all throttle settings below that required to give maximum cruising power at sea level, but as the throttle is opened above this setting the needle valve opens progressively until, at full throttle, it is fully open. On some engines the power jet is operated independently of the throttle, by means of a sealed bellows which is actuated by manifold pressure. In this way high-power enrichment is related to engine power rather than to throttle position.

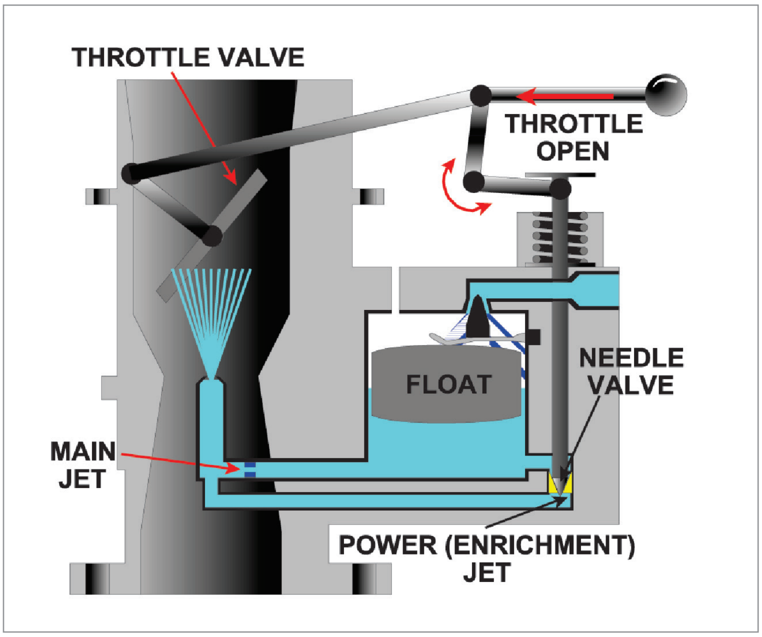


Figure 8.9 The 'Power', 'Enrichment' or 'Economizer' jet.

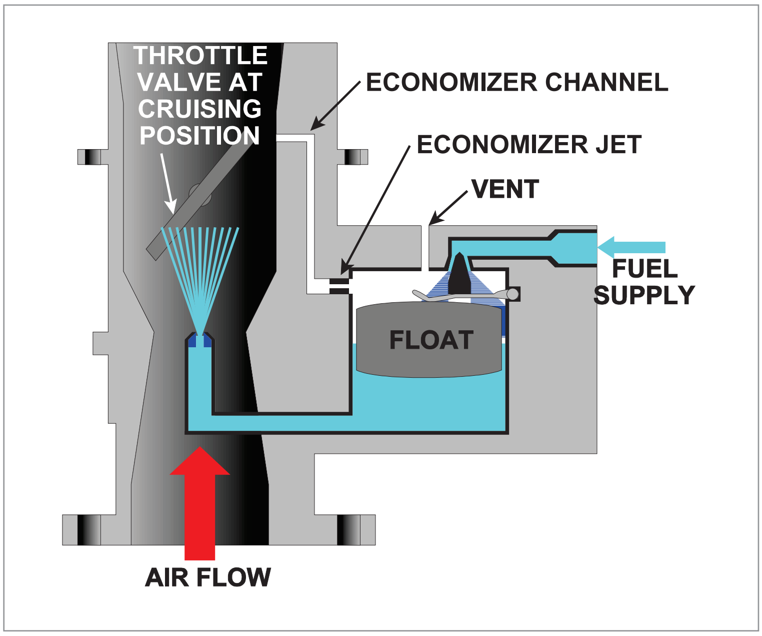


Figure 8.10 The Back Suction Economizer.

The Back Suction Economizer

An air-operated economizer (known as a back-suction economizer) is illustrated in *Figure 8.10*. When the throttle valve is at a high power setting, the pressure of air flowing past the valve is only slightly below atmospheric pressure, and will have little effect on air pressure in the float chamber, thus a rich mixture will be provided.

As the throttle is closed to the cruising position, air flowing past the throttle valve creates a suction, which is applied to the float chamber through the economizer channel and air jet. The reduced float chamber pressure reduces fuel flow through the main jet to provide the economical mixture required for cruising.

The Accelerator Pump

If the throttle valve is opened quickly, airflow responds almost immediately and a larger volume of air flows through the carburettor. The fuel metering system however, responds less quickly to the changing conditions, and a temporary weakening of the mixture will occur, known as a **flat spot** (or at worst causing a **'weak cut'**) before fuel flow again matches airflow. This condition is overcome by fitting an accelerator pump which is linked directly to the throttle, and forces fuel into the Venturi whenever the throttle is opened, this type of accelerator pump is illustrated in *Figure 8.11.*

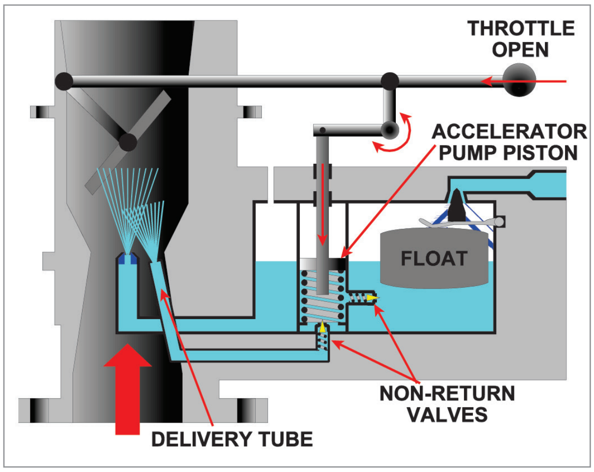


Figure 8.11 An accelerator pump.

In some pumps a controlled bleed past the pump piston allows the throttle to be opened slowly without passing fuel to the engine, in other pumps an additional delayed-action plunger is incorporated to supply an additional quantity of fuel to the engine for a few seconds after throttle movement has ceased.

Priming

Normally a priming pump would supply fuel to the induction manifold, close to the inlet valve. In the absence of such a device, it is permissible on some aircraft to prime the engine by pumping the throttle (exercising the accelerator pump) several times.

This practice must be discouraged in any other circumstance because it increases the chance of carburettor fires.

A simple, light aircraft fuel system is shown here. The fuel tanks are rigid tanks fitted in the wings and filled by the overwing method. The fuel is drawn from the tanks by a mechanical or electrical fuel pump through a tank selector and filter before being delivered to the carburettor (gear or vane type).

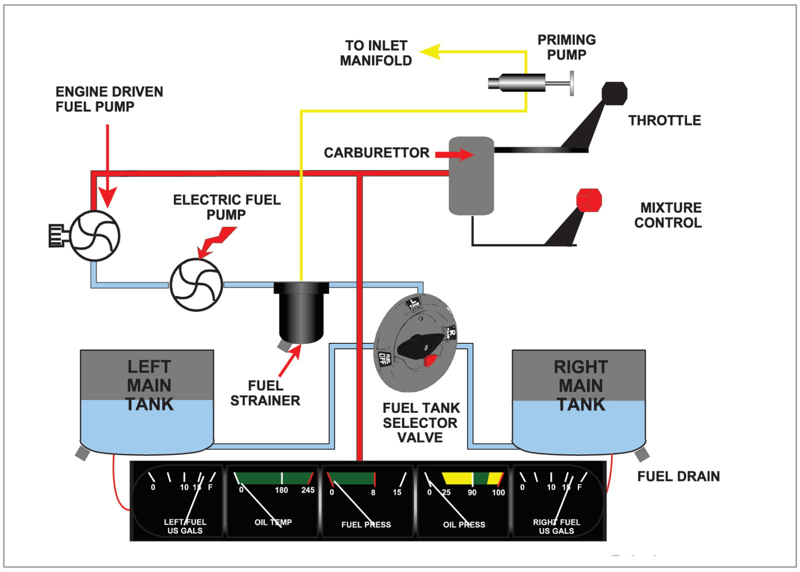


Figure 8.12 Single-engine light aircraft fuel system & engine priming system.

Engine priming is achieved by use of a priming pump which takes fuel from the filter housing and delivers it to the inlet manifold. The fuel system is monitored for contents and pressure and the fuel drains allow any water to be removed before flight.

Questions

1. **The pressure in the induction manifold of a normally aspirated engine:**

   a. remains constant as the throttle is opened
   b. decreases as the throttle is opened
   c. initially increases as the throttle is opened but decreases after approximately the half open position
   d. increases as the throttle is opened

2. **The purpose of an accelerator pump is to:**

   a. assist in the atomization of the fuel before it leaves the discharge nozzle
   b. prevent a rich cut when the throttle lever is advanced rapidly
   c. prevent dissociation and detonation
   d. prevent a weak cut when the throttle lever is advanced rapidly

3. **The fuel flow to a piston engine will vary according to:**

   a. the rpm and the throttle position only
   b. the rpm, the throttle position and the mixture setting
   c. the rpm and the mixture setting only
   d. the rpm only

4. **The primary function of a diffuser in a carburettor is to:**

   a. control the mixture strength over part of the engine speed range
   b. vent air from the float chamber
   c. emulsify the fuel during engine acceleration
   d. enable adjustment of the engine slow running speed

5. **The Venturi in the carburettor choke tube creates:**

   a. a positive pressure over the discharge nozzle
   b. a depression over the fuel discharge nozzle
   c. a positive pressure at the throttle valve
   d. a decrease in the velocity of the air entering the engine

6. **The fuel priming pump supplies fuel directly to:**

   a. the throttle butterfly valve
   b. the exhaust manifold
   c. the induction manifold
   d. the inside of the combustion chamber in the region of the spark plug

7. **A weak mixture would be indicated by:**

   a. a drop in engine speed
   b. white smoke in the exhaust manifold
   c. detonation and black smoke from the exhaust
   d. an increase in engine speed with black smoke from the exhaust

8. **The presence of an engine driven fuel pump on an engine fitted with a carburettor:**

a. dispenses with the need for a carburettor float chamber
b. ensures a positive flow of fuel to the discharge nozzles
c. ensures a positive flow of fuel to the carburettor float chamber
d. dispenses with the need for a fuel priming system

9. **It would normally be considered dangerous to pump the throttle lever when starting an engine because:**

a. it could increase the risk of fire in the carburettor air intake
b. it would prevent the engine starting
c. the engine would start too rapidly
d. it would richen the mixture to the point where spontaneous combustion would occur in the combustion chamber

10. **A typical air/fuel ratio for normal engine operation would be:**

a. 15 parts of air to one of fuel by weight
b. 20 parts of air to one of fuel by volume
c. 15 parts of air to one of fuel by volume
d. 12 parts of air to one of fuel by weight

11. **Excessive cylinder head temperatures are caused by:**

a. the prolonged use of weak mixtures
b. the ignition timing being too far advanced
c. the prolonged use of rich mixture
d. the ignition being too far retarded

12. **The mixture supplied by the carburettor to the engine is said to be weak when:**

a. the proportion of air in the mixture is insufficient to allow full combustion of the fuel
b. the proportion of air in the mixture is greater than that needed for full combustion of the fuel
c. a grade of fuel lower than that specified for the engine is used
d. there is insufficient power in the engine for take off

13. **In an attempt to maintain the correct air/fuel ratio while climbing into the decreased density air of higher altitude:**

a. the valve timing can be changed
b. an accelerator pump can be fitted
c. a mixture control is used
d. a diffuser is fitted

14. **The greater the weight of combustible mixture in the cylinders:**

a. the weaker is the mixture
b. the more the power decreases
c. the lower the cylinder head temperature will be
d. the greater the power developed by the engine

15. **A rich mixture is supplied to the cylinders at take-off and climb:**

a. to give greater thermal efficiency
b. to cool the charge temperature and prevent detonation
c. to increase the volumetric efficiency
d. to give excess power

16. **A fuel strainer should be fitted:**

a. in the inlet manifold
b. at the air intake
c. before the main jet
d. after the main jet

17. **The correct air/fuel ratio for an engine running at idle is:**

a. weak
b. chemically correct
c. 16:1
d. rich

18. **The method of priming an engine not fitted with a priming pump is to:**

a. activate the mixture control lever several times
b. turn the engine over several times on the starter motor before selecting the ignition on
c. pump the throttle several times
d. position the throttle lever midway between open and close

19. **A possible cause of the engine backfiring could be:**

a. an exhaust valve sticking open
b. a broken push rod
c. a blocked float chamber
d. a sticking inlet valve

20. **An overly rich mixture at slow running could be caused by:**

a. the priming pump being left open
b. low fuel pressure
c. the float chamber level being too low
d. a partially blocked main jet

Answers

1	2	3	4	5	6	7	8	9	10	11	12
d	d	b	a	b	c	a	c	a	d	a	b

13	14	15	16	17	18	19	20
c	d	b	c	d	c	a	a

Chapter 9

Piston Engines - Icing

Engine Icing

The problems of engine icing, particularly engines fitted with carburettors, have been known for some years, but still accidents occur in which induction system icing has been the cause, despite modern fuel metering devices.

Atmospheric conditions, particularly of high humidity (more than 50% Relative Humidity (RH) and temperatures ranging from **-7°C** (20°F) to as high as **+33°C** (90°F), may cause icing in the induction system of all types of piston engine. *Figure 9.1* shows the range of temperatures at which icing can affect the engine at different power settings.

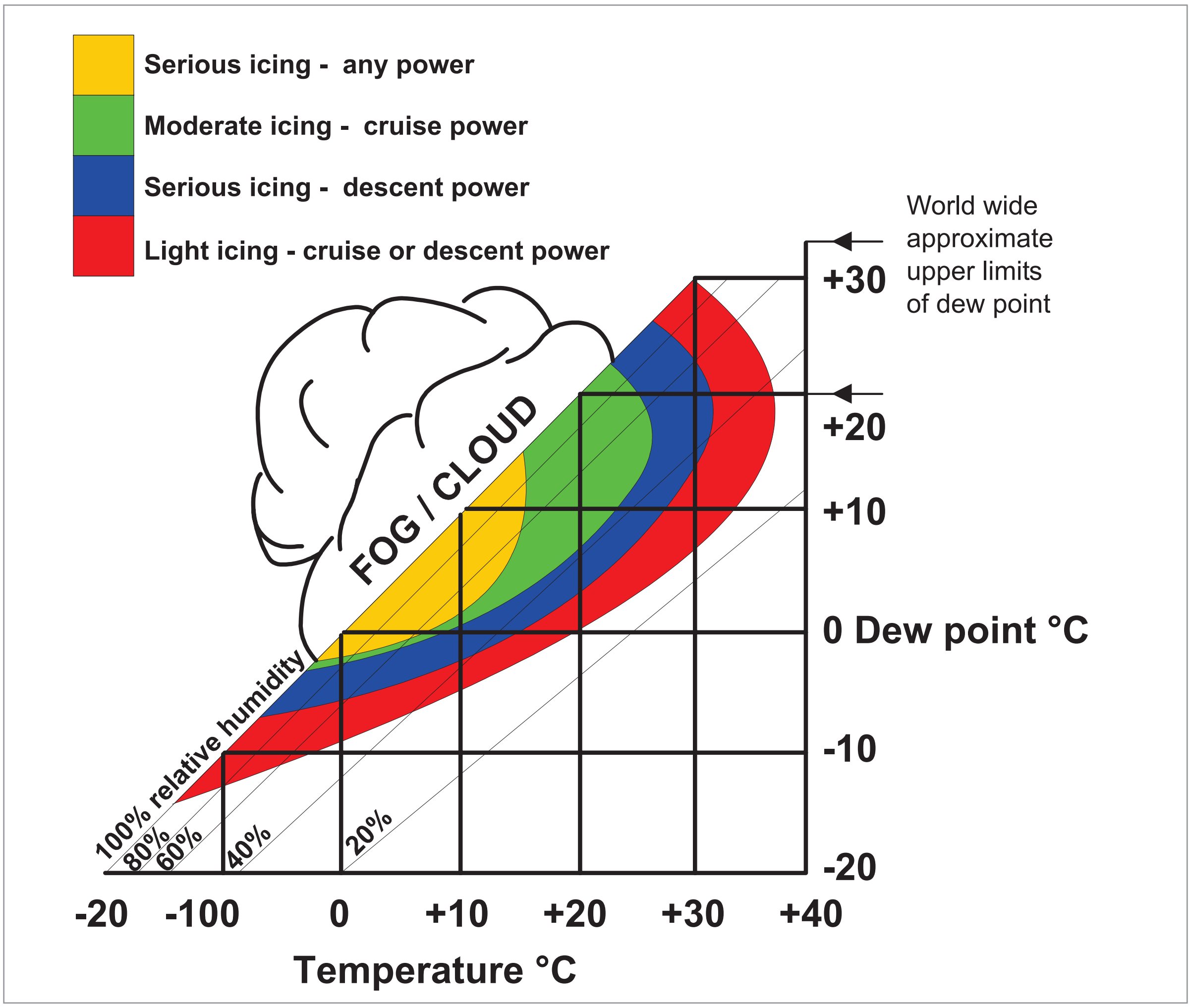


Figure 9.1

This temperature range and humidity occur throughout the year in the areas of the United Kingdom and Europe, and therefore pilots should be constantly aware of the possibilities of icing and take the corrective action necessary before such problems arise and the situation becomes irretrievable.

Once an engine stops due to induction icing it is most unlikely that it may be restarted in time to prevent an accident - therefore recognition and correction is vital.

All pilots operating piston engined aircraft should understand the problems associated with each particular type, but they also need to know how the engine reacts once heat is applied to prevent induction icing.

Basically there are three forms of icing:

a) **Impact ice** which forms on the air filters and bends in the induction system.

b) **Refrigeration ice** (carburettor icing) which forms in float type carburettors as a result of the low temperatures caused by fuel vaporization and low pressure acting on moisture in the atmosphere.

c) **Fuel icing** which is caused by moisture in the fuel coming out of suspension and being frozen by the low temperatures in the carburettor. This tends to stick to the inlet manifold around the corners and reduce air/fuel flow into the engine.

Carburettor Icing

The indications of icing to the pilot of an aircraft fitted with a carburettor, if he has failed to anticipate the problem, would be a gradual drop in rpm which may be accompanied by engine rough running and vibration. In aircraft fitted with a constant speed propeller it would be indicated by a drop in manifold pressure or reduction of airspeed in level flight.

The problem is caused partly by the rapid cooling in the throat of the carburettor as heat is absorbed from the air during the vaporization of the fuel, and also by the low pressure area in the Venturi tube. *Figure 9.2* shows the build-up of icing in the induction system.

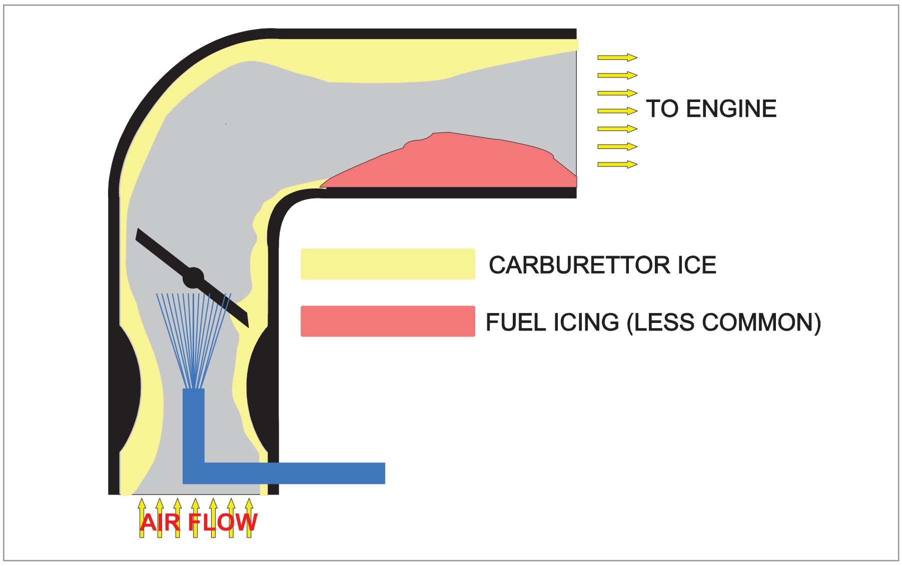


Figure 9.2

The result is that the temperature in this area of the carburettor drops as much as 22°C (70°F) below the temperature of the incoming air. If now the air contains a large amount of moisture this cooling process may be sufficient to cause ice to form in the area of the throttle "butterfly".

Here it will reduce the area of the induction intake and may prevent operation of the throttle plate, resulting in the loss of power, and if not corrected the ice may accumulate sufficiently to block the intake completely and stop the engine. At temperatures of -1°C (14°F) or below any moisture in the air will be already frozen and will pass through the carburettor and so heat should not be used.

Action to be Taken if Engine Icing is Suspected

When icing is suspected, the carburettor heat control should be selected to fully hot and left in the hot position for a sufficient length of time to clear the ice. This could take up to 1 minute, or longer depending on the severity.

Partial heat should not be used unless the aircraft is equipped with a carburettor air temperature gauge. The carburettor heat control provides heated air from around the exhaust pipe into the induction system which will melt the ice and which then passes through the engine as water. Engine roughness and further power loss may occur as the water passes into the cylinders and pilots should not be tempted to return the heat control to **OFF** (cold), thinking that the situation has become worse since applying heat.

Icing is also more likely during long periods of flight at reduced power, such as during a glide descent or letdown for approach and landing. Because the heat is derived from the engine, during long descents the engine temperatures will gradually cool, thus reducing the effectiveness of the hot air system.

Where icing conditions exist select full hot air before reducing power so that benefit is gained from the hot engine before the engine temperature starts to reduce.

To help maintain engine temperatures and provide a sufficient heat source to melt any ice, it is necessary to increase power periodically to a cruising setting at intervals of between **500** and **1000 ft** during the descent. Additionally this action prevents lead fouling of the spark plugs. Carburettor icing can occur during taxiing at small throttle settings or when the engine is at idle rpm. In these circumstances ensure that hot air is used before take-off to clear any ice, but select cold air before opening the throttle to full power and check that the correct take-off rpm /manifold pressure is obtained.

Under no circumstances should carburettor heat be used during take-off.

Engine Considerations

When using carburettor heat there are a number of factors which should be understood.

The application of hot air reduces the power output by approximately **15%** and also creates a richer mixture which may cause rough running.

Heat should not be applied at power settings greater than **80%** as there is a danger of detonation and engine damage. Intake icing should not occur at power settings involving a wide throttle butterfly opening.

The continuous use of carburettor heat should be avoided due to the change of mixture and increase of engine temperatures. Heat should be used only for a sufficient period of time to restore engine power to its original level. This will be noted by an increase of rpm or manifold pressure above the original setting when the control is returned to cold.

Do not use carburettor heat once clear of icing conditions, but check periodically that ice has not reformed.

Fuel Injected Engines

The fuel injected engine does not have the problems of ice forming at the Venturi, but other parts of the system may accumulate ice with a similar loss of power.

Fuel icing may gather at the bends in the system, impact icing may form at the impact sensing tubes, or on the air filters, particularly when flying in cloud at low temperatures. The alternate air system fitted to these engines should then be selected and the icing drill followed according to the aircraft check list.

Diesel Engines

Diesel engines do not suffer from icing in the same way as conventional piston engines. Firstly there is no ‘carburettor’ and therefore no Venturi to attract the refrigeration icing associated with float chamber carburettors.

Impact-icing at the air-inlet filter is overcome by the use of ‘ice-guards’ which effectively by-pass the filter when it becomes blocked with ice.

Problems of fuel-solidification known as ‘waxing’ where the fuel viscosity increased due to low temperatures is overcome by putting additives in the fuel or by using fuel-heaters in the fuel-lines or filters to ‘pre-heat’ the fuel.

Operational Procedures

The following points should be understood in the use of carburettor heat control.

Ground Operation

Use of the heat control on the ground should be kept to a minimum as the air is not filtered and may feed dust and dirt into the system causing additional wear on pistons and cylinders. A function check of the heater control should be made before take off. Rpm should drop approximately 100 rpm when heat is applied and return to the selected setting when turned OFF (cold).

Take-off

If icing is evident on the ground before take-off, use heat to clear the ice but return the control to OFF (cold) before applying take-off power. Check that normal take-off power is available.

Climb

Do not use carburettor heat during the climb or at power settings above 80% (approximately 2500 rpm).

Flight Operations

Be aware of conditions likely to cause carburettor icing - damp, cloudy, foggy or hazy days, or when flying close to cloud or in rain or drizzle.

Look out for an unaccountable loss of rpm/manifold pressure. Make frequent checks for icing by applying heat for a period of between **15** to **30** seconds, noting first the selected rpm then the drop of rpm as heat is applied.

Listen to the engine noise and check the outside air temperature. Should rpm increase whilst heat is applied, or the rpm return to a higher figure than original when re-selected to cold, then ice is present. Continue to use heat while flight in icing conditions continues.

Descents
Apply carburettor heat during glide descents or long periods of flight at reduced power (below 1800 rpm) remembering to warm/clear the engine for short periods every **500 - 1000 ft.**

Approach and Landing
The carburettor heat selector should remain at cold during approach and landing, except for a glide approach, but if icing conditions are known or suspected, full heat should be applied.

However the control must be returned to cold before applying power for a roller landing or carrying out an overshoot.

Caution
During hot/dry weather application of hot air may cause a rich cut in the engine, therefore use the carburettor heat control sensibly, not just as a matter of habit. Think about what you are doing and check the prevailing conditions.

Chapter 10

Piston Engines - Fuel Injection

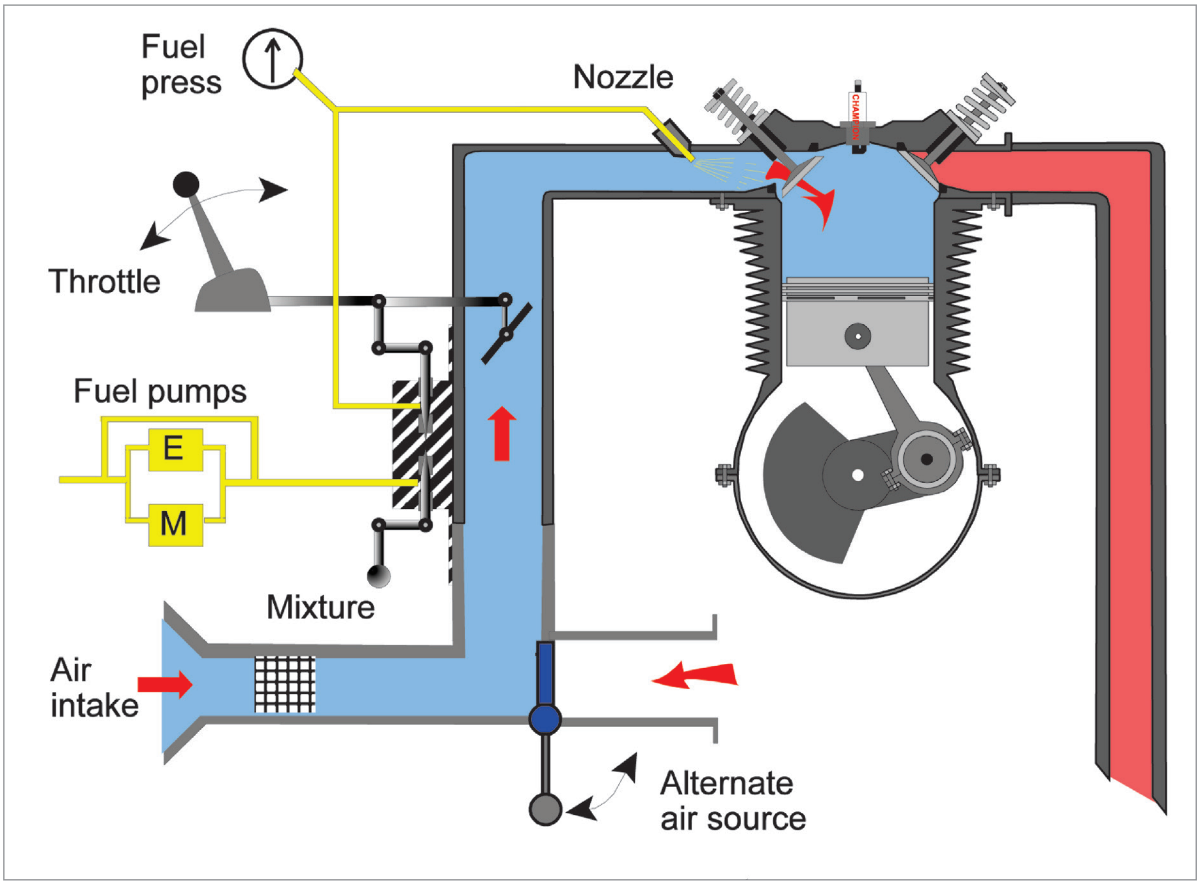


Figure 10.1 General arrangement.

Indirect Fuel Injection

Indirect fuel injection is often employed on aircraft piston engines, but is of the low-pressure, continuous-flow type. In the low-pressure, continuous-flow method, fuel is sprayed continuously into the induction pipe as close to the inlet valve as possible. The advantages claimed for the method are low operating pressure, good fuel distribution, freedom from icing problems and the ability to use a pump which does not have to be timed to the operating cycle.

Some fuel injection systems operate on a similar principle to the carburettor but inject fuel under pressure, into the intake.

In the indirect injection system, the air throttle metering valve varies the pressure of fuel according to engine speed.

Mixture strength is varied by a manually operated mixture control valve which adjusts the fuel pressure for altitude or operating conditions as necessary. Because of the method of operation of the injector, no special idling arrangements are required and a separate priming system for engine starting is unnecessary.

The main components in the system are a **fuel pump, a fuel/air control unit, a fuel manifold (distribution) valve, and discharge nozzles for each cylinder**.

In addition, a normal **throttle valve** controls airflow to the engine, and a **fuel pressure gauge** is fitted to enable mixture adjustments to be made. The system is illustrated in *Figure 10.2.*

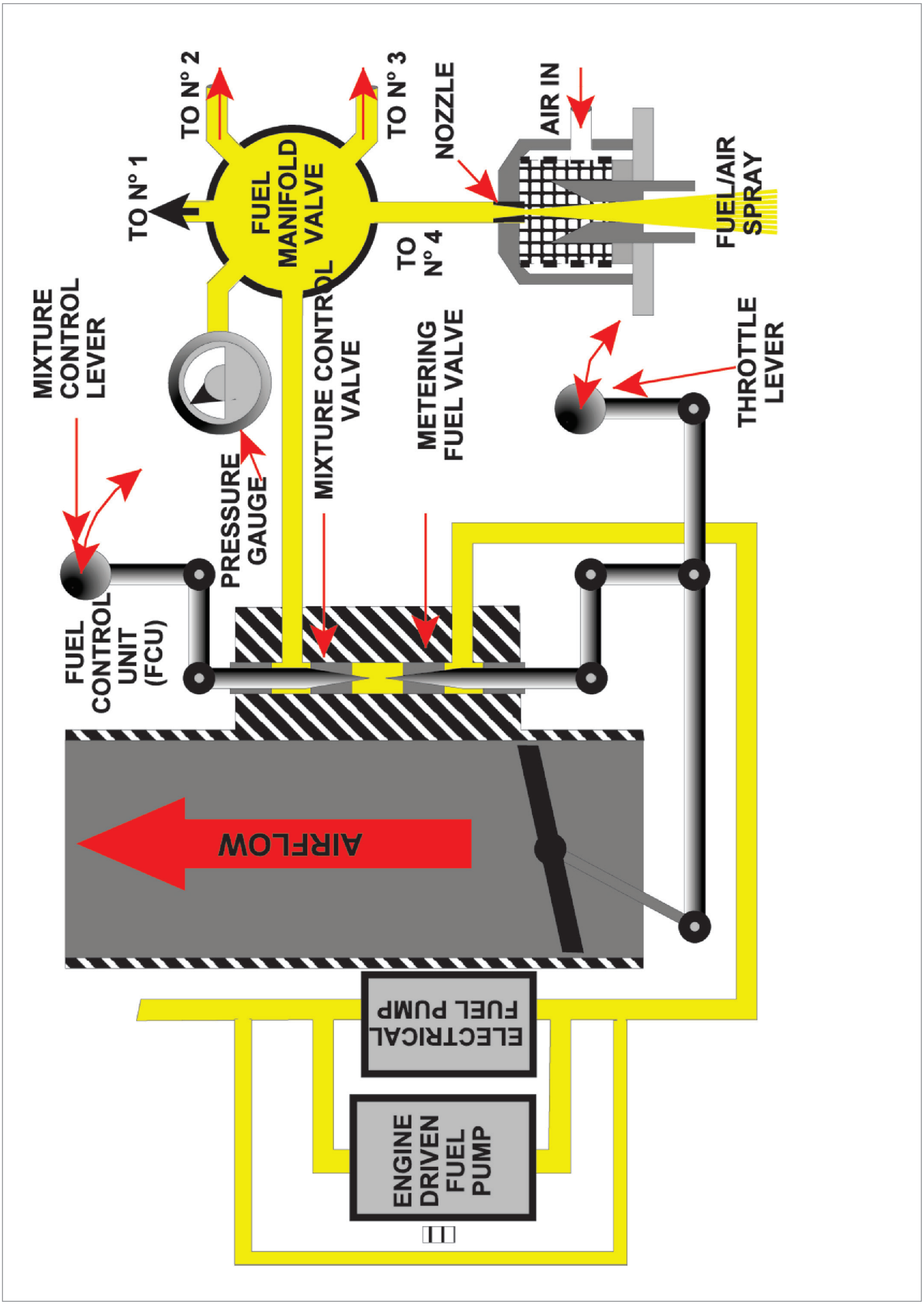


Figure 10.2 An indirect fuel injection system.

The Fuel Pumps

The pump supplies more fuel than is required by the engine, and a recirculation path is provided. Two pumps are provided, arranged in parallel, so that when the mechanical pump is not operating, fuel under positive pressure from the electrical pump can bypass the mechanical pump, so allowing the electrical pump to be used for engine priming and starting and in an emergency.

The Fuel/Air Control Unit

This unit is mounted on the intake manifold and contains three control elements:

a) **the air throttle assembly (throttle valve)**

b) **the throttle metering valve (metering fuel valve)**

c) **the mixture control valve**

The air throttle assembly contains the air throttle valve, which is connected to the pilot's throttle lever and controls airflow to the engine.

The intake manifold has **no Venturi** or other restrictions to airflow.

The fuel control unit is attached to the air throttle assembly, and controls fuel flow to the engine by means of two valves.

One valve, the **metering fuel valve**, is connected to the air throttle and controls fuel flow to the fuel manifold valve according to the position of the air throttle, thus fuel flow is proportioned to airflow and provides the correct air/fuel ratio.

The second valve, the **mixture control valve**, is connected to the pilot's mixture control lever, and bleeds off fuel pressure applied to the metering valve. Thus the air/fuel ratio can be varied from the basic setting of the metering valve, as required by operating conditions.

A fuel pressure gauge in the system indicates metered fuel pressure, and, by suitable calibration, enables the mixture to be adjusted according to altitude and power setting.

The Fuel Manifold Valve

This valve is located on the engine crankcase, and is the central point for distributing metered fuel to the engine. When the engine is stopped, all the outlet ports are closed, and no fuel can flow to the engine. As fuel pressure builds up (as a result of engine rotation or booster pump operation) all the ports to the discharge nozzles open simultaneously. A ball valve ensures that the ports are fully open before fuel starts to flow.

The Discharge Nozzle

A fuel discharge nozzle is located in each cylinder head, with its outlet directed into the inlet port. Nozzles are calibrated in several ranges, and are fitted to individual engines as a set, each nozzle in a set having the same calibration.

Diesel Engines

The fuel-supply system in terms of storage is similar to that of conventional aircraft. In a light aircraft the wing tanks (rigid) store the bulk of the fuel which is then sent utilizing the effects of gravity and ram air to a common strainer, selector-valve and then via water-traps, fuel heaters and filters to an engine-mounted delivery system.

Delivery to the cylinders may be performed in many ways. However the preferred system is known as 'common rail' where a high pressure supply (1800 bar/26 000 psi) is maintained locally and adjacent to the cylinders.

In electronic/computer-controlled dual-channel unit known as FADEC (Full Authority Digital Engine Control) opens electronically operated 'nozzles' at the appropriate time and duration according to demand.

Electronic or Common Rail Injection

An common rail systems, the distributor injection pump (old-style system) is replaced by a single extremely high pressure pump (2000 bar or 29 000 psi) that feeds a single storage manifold known as the Common Rail. The common rail distributes high pressure fuel to computer controlled injector valves. Each injector valve is activated by either a solenoid, or, more recently, by piezoelectric actuators.

In modern aircraft such as the DA40 both the timing and fuel quantity per injection is under the control of the FADEC. The FADEC receives data from various sources such as air temperature, air density and throttle position. The combination of the 'high-tech' injector-valves and computer control, leads to greater fuel efficiency and more effective power management.

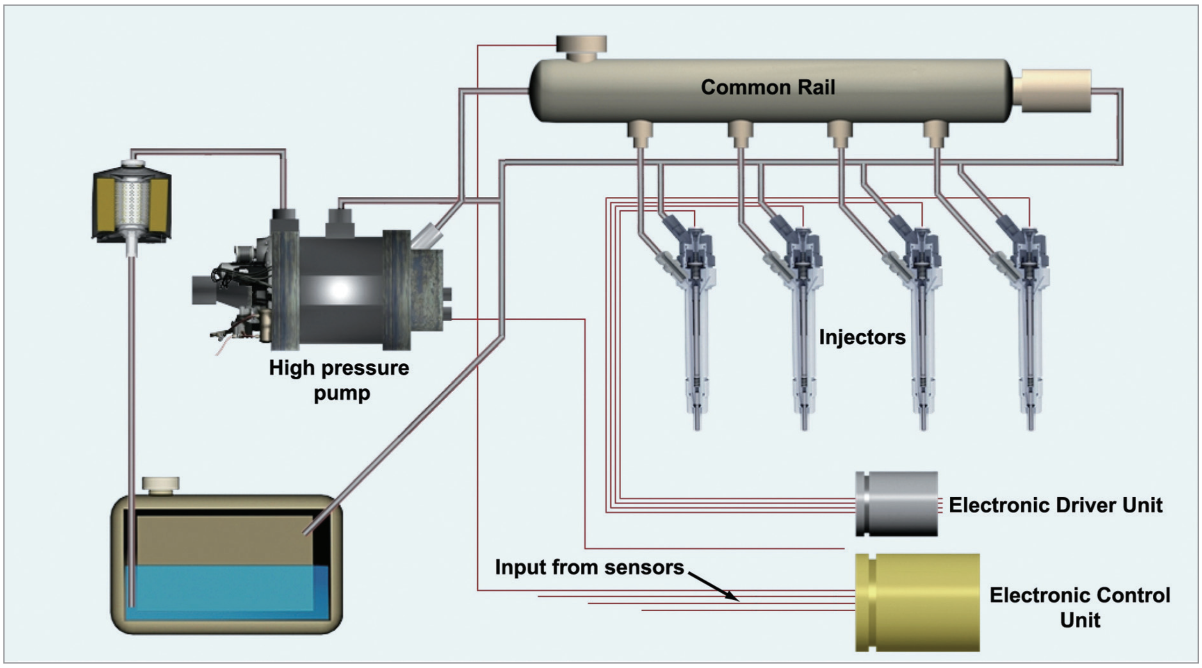


Figure 10.3 A common rail system.

Questions

1. The engine driven fuel pump supplies:

a. the exact amount of fuel required for all running conditions.
b. more fuel than is required by the engine; the excess fuel is recycled.
c. the exact amount of fuel required for all running and starting conditions.
d. more fuel than is required by the engine, the excess being used as priming fuel.

2. When an engine is fitted with a fuel injection system:

a. it does not require priming.
b. a separate priming system must be fitted.
c. a separate priming system is not required.
d. priming fuel originates from the excess supplied from the engine driven pump.

3. The mixture control on an engine fitted with fuel injection is:

a. automatic.
b. operated by a pneumatic plunger system.
c. hydro-pneumatically operated.
d. necessary.

4. In the intake of a fuel injected engine:

a. there will be a throttle valve but no Venturi.
b. neither a throttle valve nor a Venturi is required.
c. there will be a Venturi but no throttle valve.
d. both a throttle valve and a Venturi are required.

5. The discharge nozzle injects fuel:

a. continuously into the inlet manifold as close to the inlet valve as possible.
b. into the inlet manifold when the inlet valve opens.
c. into the combustion chamber during the compression stroke.
d. continuously into the combustion chamber during the induction stroke.

6. The Fuel Control Unit meters fuel to the discharge nozzles in proportion to:

a. the position of the throttle valve only.
b. the position of the mixture control lever only.
c. the positions of both the throttle lever and the mixture control lever.
d. the number of strokes applied to the priming pump.

7. The discharge nozzles of a fuel injected engine are matched to:

a. supply exactly the same amounts of fuel as each other.
b. the type of engine they are fitted to.
c. the octane rating of the fuel supply.
d. the engine they are fitted to and to the nozzles on the other cylinders.

8. **A fuel injected engine can be primed by:**

    a. a manual priming pump which delivers fuel to the discharge nozzles.
    b. an electric fuel pump delivering fuel to the discharge nozzles.
    c. the excess fuel delivered by the engine driven fuel pump.
    d. pumping the throttle lever while turning the engine over on the starter motor.

9. **The fuel manifold valve:**

    a. meters the amount of fuel delivered to the engine in proportion to the amount of air being delivered to the engine.
    b. distributes fuel to each cylinder in the correct firing order.
    c. distributes fuel continuously to all of the cylinders continuously.
    d. is kept entirely separate from the priming system.

10. **An engine which is fitted with fuel injection:**

    a. will never encounter hydraulicing.
    b. will not suffer from refrigeration icing.
    c. cannot be started by swinging the propeller.
    d. does not require priming.

11. **The Common Rail:**

    a. is, in effect, a reservoir of high pressure fuel
    b. is, in effect, a reservoir of low pressure fuel.
    c. is a device common to both the fuel and lubrication systems.
    d. is a device common to both the ignition and lubrication systems.

Answers

1	2	3	4	5	6	7	8	9	10	11
b	c	d	a	a	c	d	b	c	b	a

Chapter

11

Piston Engines - Performance and Power Augmentation

Engine Performance

In Chapter 2 it was stated that the power of the engine was dependent on the weight of charge induced. It can be seen that the **density** of the air, the **pressure** and **temperature** are greatest at sea level, decreasing in varying degrees with altitude increase. "Sea Level ISA." condition, then, can be said to be a temperature of +15°C, a pressure of 14.69 lb/in^2 (1013.25 mb or 29.92 in Hg) and a density of 1225 gm/cu.metre.

Sea level pressure can be said to be caused by the weight of air above a certain point on the Earth's surface, the decrease in density with altitude increase being due to the lessening of this weight. As the temperature in the atmosphere is radiated from the surface of the Earth, the greater the altitude (the further from the source of radiation) the lower the temperature.

Normal Temperature and Pressure (NTP)

The temperature scales used in aviation include the Centigrade, Celsius, Fahrenheit and Kelvin, and conversions between each are often required.

For convenience, the properties of a fluid are always assumed to be at a standard (termed **Normal Temperature and Pressure "NTP"**) unless otherwise stated.

In order that engine power output can be checked in any part of the World, regardless of ambient conditions, manufacturers specify a set of "standard" maximum power (rpm) figures which are obtained on a "standard" day according to Sea Level ISA conditions.

Density Altitude

Density altitude can be defined as the altitude in the standard atmosphere at which the prevailing density would occur, or alternatively, as the altitude in the standard atmosphere corresponding to the prevailing pressure and temperature. It is a convenient parameter in respect of engine performance figures.

It can be obtained by use of an airspeed correction chart or by navigational computer. A third (approximate) method is to add to the pressure altitude 118 feet for every degree Celsius that actual temperature exceeds the standard temperature. For example, suppose the elevation of an aerodrome is 5500 feet with a temperature of ISA plus 30 and a QNH of 1013 mb. Standard temperature at this altitude would be about +4°C, so the actual temperature is +34°C. Higher temperature means lower density and this lower density would be found at a level higher than 5500 feet in the standard atmosphere, in fact, at a density altitude of 30 × 118 = 3540 feet higher than pressure altitude. The density altitude (with which the engine performance is associated) would therefore be about 9040 feet. The answer can be checked on the computer by setting pressure altitude (5500 feet) against temperature (+34°C) in the Airspeed window and reading off Density Altitude (about 9000 feet) in its own window.

Superchargers and Turbochargers

The power output of an engine depends basically on the weight of mixture which can be burnt in the cylinders in a given time, and the weight of mixture which is drawn into each cylinder on the induction stroke depends on the temperature and pressure of the mixture in the induction manifold.

On a normally aspirated engine the pressure in the induction manifold at full throttle is slightly less than atmospheric pressure because of intake duct losses, and the manifold pressure decreases with any increase in altitude.

Power output therefore, decreases with altitude, although some of the loss is recovered in better scavenging of the cylinders as a result of reduced back pressure on the exhaust. In order to increase engine power for take-off and initial climb, and/or to maintain engine power at high altitude, the manifold pressure must be raised artificially, and this is done by **supercharging.**

Where a supercharger is used to increase sea level power, rather than to maintain normal power up to a high altitude, the engine will need to be strengthened in order to resist the higher combustion pressure. This is called a **Ground Boosted Supercharger.** *Figure 11.5.*

For superchargers capable of maintaining sea level values of power up to high altitude, a control system is necessary to prevent excessive pressure being generated within the engine at low altitude. These are called **Altitude Boosted Superchargers.** *Figure 11.5.*

Centrifugal Compressors are used in superchargers on aircraft engines and may be driven by either **internal** or **external** means, in some installations a combination of both may be used.

a) **Externally driven superchargers**, known as **turbosuperchargers** or **turbochargers,** are driven by a turbine which is rotated by the exhaust gases and **compress the air.**

b) **Internally driven superchargers** are driven by gearing from the engine crankshaft and **compress the mixture.**

The methods of operation and control of these two types are quite different, and are dealt with separately.

Centrifugal Compressors

Centrifugal compressors are used because they are comparatively light, are able to run at high speed, will handle large quantities of air, and are robust and reliable. A centrifugal compressor is made up of two components, the **impeller** which is rotated and accelerates the air and the **diffuser** which collects and directs the air into the manifold.

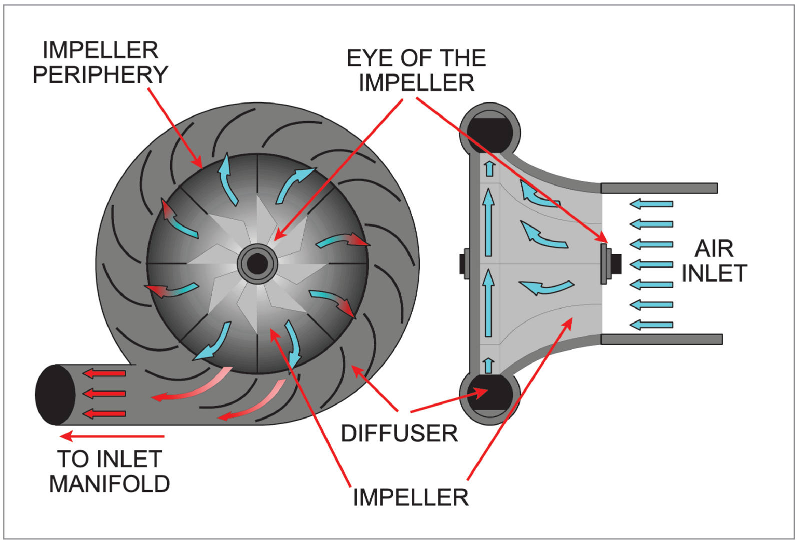


Figure 11.1 A centrifugal compressor.

Air is drawn into the impeller as it is rotated. The air is accelerated as it flows outwards between the vanes (converting mechanical energy into kinetic energy) and, as the cross-section of its path increases, some of this energy is converted into pressure energy.

The proportion of pressure gained in the **impeller depends on the impeller's diameter, speed of rotation** and the **shape of the vanes**.

The air leaves the impeller with considerable tangential and radial velocity and passes into the **diffuser**, which consists of a number of vanes fixed between the walls of the supercharger casing. The diffuser vanes form **divergent passages**, which **decrease the velocity** and **increase the pressure** of the air passing through them.

The action of compressing the air rapidly increases its temperature, and reduces some of the increase in density which results from the increased pressure, this loss of density may be partially recovered either by passing the air through an **intercooler** or by spraying the fuel into the eye of the impeller so that vaporization will reduce air temperature.

At a particular speed of rotation a centrifugal supercharger increases the pressure of air passing through the impeller in a definite ratio. Physical constraints limit the speed of rotation and size of an impeller, and so limit the pressure rise or **pressure ratio** and consequently, the power output or maximum operating altitude of the engine to which it is fitted.

Pressure ratios up to 3:1 are generally obtainable, and any further compression necessary would have to be obtained by fitting two compressors in series.

Manifold Pressure

Any engine with a supercharger will also be equipped with a variable pitch propeller controlled by a constant speed unit. The rpm of the engine is therefore controlled by the propeller pitch lever. To properly set the power and prevent the engine being **overboosted** the pilot must have an indication of the amount of pressure he/she is allowing into the cylinder with the throttle. This is known as **manifold pressure** (between the throttle valve and the inlet valve) and is indicated to the pilot on one of two gauges:

Boost Pressure

The pressure in the induction system relative to sea level standard pressure is called boost pressure, and is indicated by a gauge in the cockpit. The gauge is calibrated in pounds per square inch **above or below standard sea level atmospheric pressure** which is marked zero. Thus if the boost gauge is indicating -3 lb of boost the absolute pressure in the induction system would be 14.7 lb minus 3 lb which is equal to 11.7 lb. Similarly if there is +4 lb of boost indicated then the absolute pressure would equal 18.7 lb.

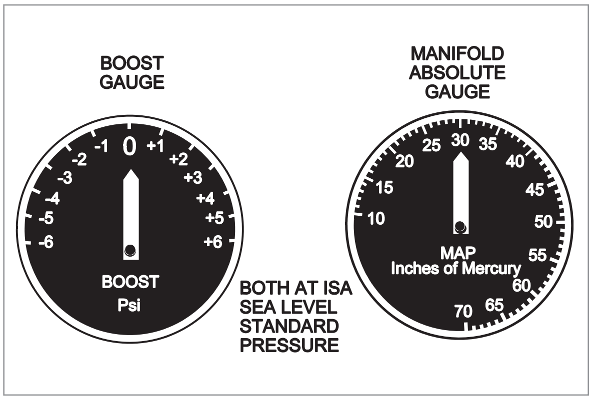


Figure 11.2 Manifold pressure indications.

Manifold Absolute Pressure

American practice is to use the term Manifold Absolute Pressure **(MAP)** for measuring the pressure in the induction system. The manifold gauge indicates the **absolute pressure** in inches of mercury **(Hg)**. When the atmospheric pressure is 14.7 lb it will support a column of Hg 29.92 inches high, therefore, a boost pressure of 0 lb is the equivalent of manifold pressure of 29.92 inches Hg.

To make a comparison between boost pressure and manifold absolute pressure it may be assumed that two inches of Hg is approximately equal to one pound of boost.

Externally Driven Superchargers (Turbochargers)

Externally driven **superchargers** are powered by the energy of the engine exhaust gases and are generally known as **turbosuperchargers** or **turbochargers.**

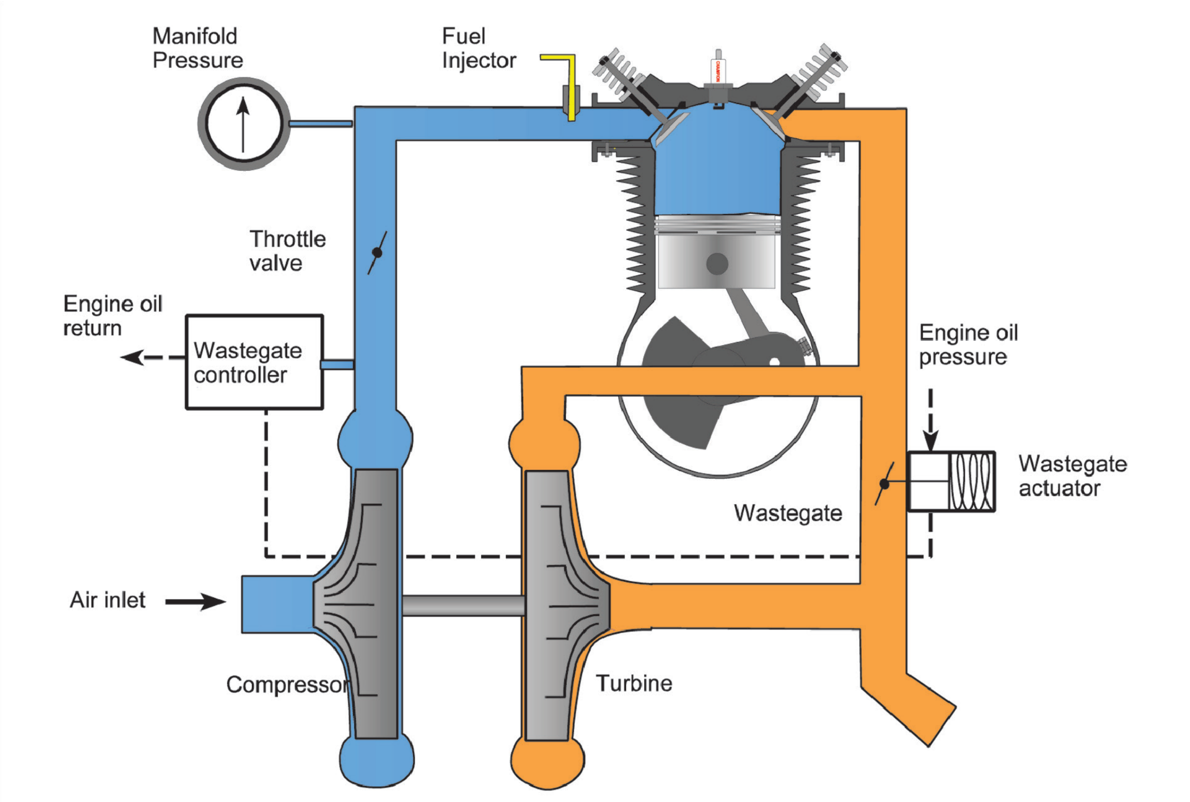


Figure 11.3 Turbocharger - general arrangement.

A **turbocharger** consists of a turbine wheel and an impeller fitted on a common rotor shaft, the bearings are lubricated by oil from the engine. The turbine is connected to the exhaust system and the compressor is connected to the intake system.

The turbocharger is not necessarily an integral part of the engine, but may be mounted on the engine or on the fire-proof bulkhead, and shielded from combustible fluid lines in the engine bay. Exhaust gases pass through nozzles and are guided onto vanes on the turbine wheel, causing it to rotate, the gases then pass between the vanes and are exhausted overboard. The more exhaust gases that are ***diverted*** over the turbine the faster it will go and therefore the faster the impeller will go and the greater will be the pressure ratio of the compressor.

The Wastegate

For any particular power output the turbocharger must deliver a constant mass of air to the engine in a given time, and, since the density of air decreases with altitude, the impeller rotates faster as the aircraft climbs to compensate for the reduction in density and maintain a selected manifold pressure.

Some form of control over compressor output must be provided, and this is done by varying the quantity of exhaust gas passing to the turbine to vary its speed and that of the compressor. A turbine bypass, in the form of an alternative exhaust duct, is fitted with a valve (known as a **wastegate**) which regulates the degree of opening through the bypass.

When the wastegate is fully open nearly all the exhaust gases pass directly to atmosphere, but as the wastegate closes gases are directed to the turbine, and the maximum rotor speed is achieved when the wastegate is fully closed, this will happen at what is termed the **critical altitude** for that engine and that turbocharger (the height above which maximum boost or manifold pressure can no longer be maintained) .

The wastegate may be controlled manually by the pilot, but in most turbocharger systems automatic controls are fitted to prevent **overboosting** the engine. In an automatic control system, the wastegate is mechanically connected to a **single acting actuator,** the position of which depends on the opposing forces of spring and engine oil pressure.

Spring force tends to open the wastegate and oil pressure tends to close it. Thus oil pressure in the actuator regulates the position of the wastegate according to engine requirements. Various types of controllers may be used to vary the wastegate actuator oil pressure: Absolute Pressure Controller (APC), Density Controller (DC), Differential Pressure Controller (DPC). We will concentrate on the Absolute Pressure Controller (APC) to begin with and then consider the others.

The Absolute Pressure Controller

Some simple turbocharger systems use a single controller, called an **Absolute Pressure Controller (APC)**, which is designed to prevent compressor outlet pressure from exceeding a specified maximum, this type of controller is illustrated in *Figure 11.4*.

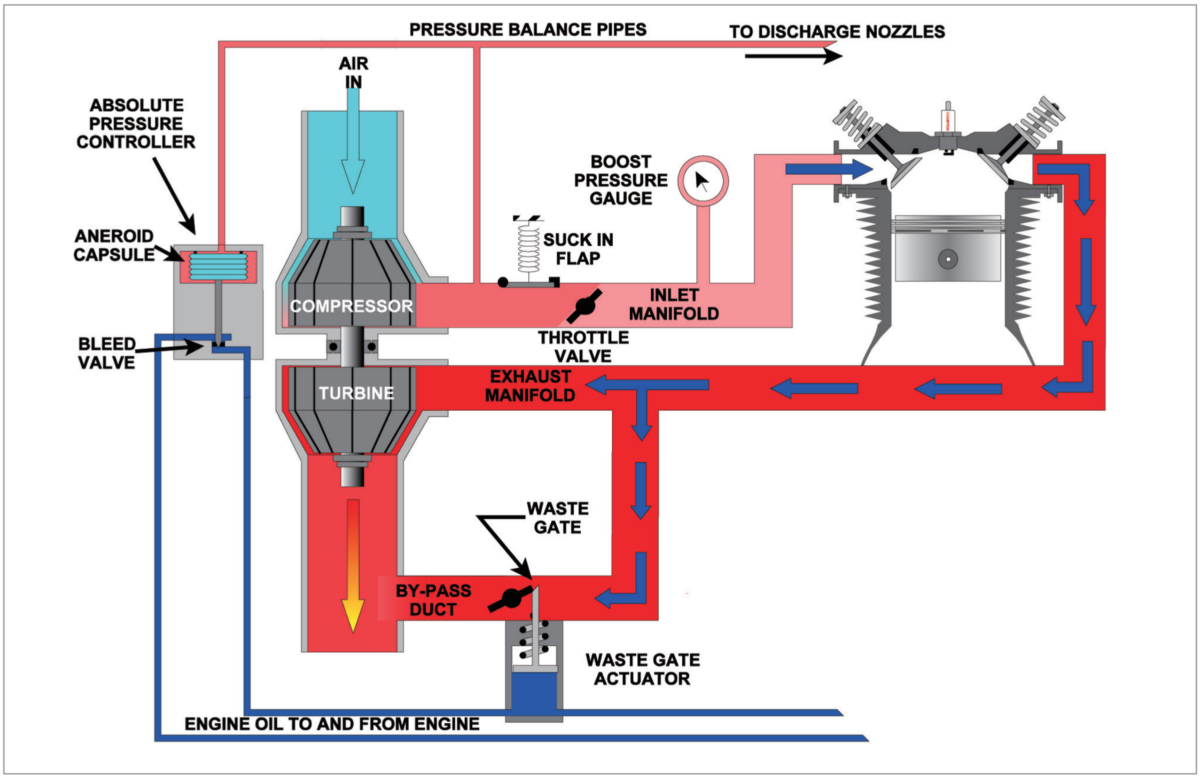


Figure 11.4 Operation of the APC.

The APC uses an aneroid capsule sensitive to compressor outlet pressure to control the oil bleed from the wastegate actuator, thereby controlling wastegate position to maintain the required compressor outlet pressure. The throttle then controls manifold pressure. At low power settings full oil pressure is applied to the wastegate actuator, which closes the wastegate and diverts all exhaust gases through the turbine to maintain the compressor outlet pressure at the designed value. The oil which is used to move the piston in the wastegate is taken directly from the engine lubrication system, this oil is also used to cool and lubricate the turbocharger bearings. Additional safety features may be built into some systems typically an Overboost Warning Light, and if this boost is exceeded then an Overboost Relief Valve (Dump Valve) will open and relieve deck pressure to ambient. As was stated earlier so many variables occur when any of the related conditions are altered that it may be useful to review what could occur as a result of a change of throttle position:

a) The pilot moves the throttle and so establishes a different pressure drop across the throttle, and also varies the **MAP**.

b) The APC senses the change and repositions its oil bleed valve.

c) The new bleed valve setting will change the oil flow and establish a new pressure on the wastegate actuator piston, which in turn will change the position of the wastegate butterfly valve.

d) The new wastegate position will change the amount of exhaust gas flowing to the turbine.

e) This changes the amount of supercharging provided (Deck Pressure).

f) This new pressure then changes the pressure drop across the throttle valve, and the sequence returns to the second step above and repeats until an equilibrium is established.

The net result of these events is an effect called throttle sensitivity, when this operation is compared with the operation of a normally aspirated engine, the turbocharged engine's **MAP** setting will require frequent resetting particularly if the pilot does not move the throttle valve slowly and wait for the system to seek its stabilization point before making further adjustments to the throttle. The differential pressure controller helps to reduce unstable conditions which can be called **Bootstrapping** during part throttle operation. Bootstrapping is an indication of unregulated power change that results in a continual drift of **MAP**. It is an undesirable cycle of turbocharging events causing the **MAP** to drift in an attempt to reach a state of equilibrium.

Bootstrapping is sometimes confused with **Overboost**, but it is not detrimental to engine life to the same degree that **Overboost** is, and this latter condition can cause serious engine damage. Careful handling of the throttle and selecting a higher rpm prior to increasing the boost when increasing power, and a lower boost prior to reducing the rpm when reducing power will prevent **Overboosting** with the possible consequences of high engine loading, detonation and a reduction in engine life.

Wastegate Position

Maintaining a constant pressure at the outlet of the turbocharger up to critical altitude depends on being able to keep increasing the speed of the turbine as the aircraft climbs. This is done by progressively closing the wastegate and diverting an increasing amount of exhaust gas through the turbine. The position of the wastegate is therefore an important factor governing the performance of the engine.

The position of the wastegate throughout the running of an engine from start to critical altitude, including engine power output, turbine speed, and the manifold pressure are all shown in *Figure 11.5.*

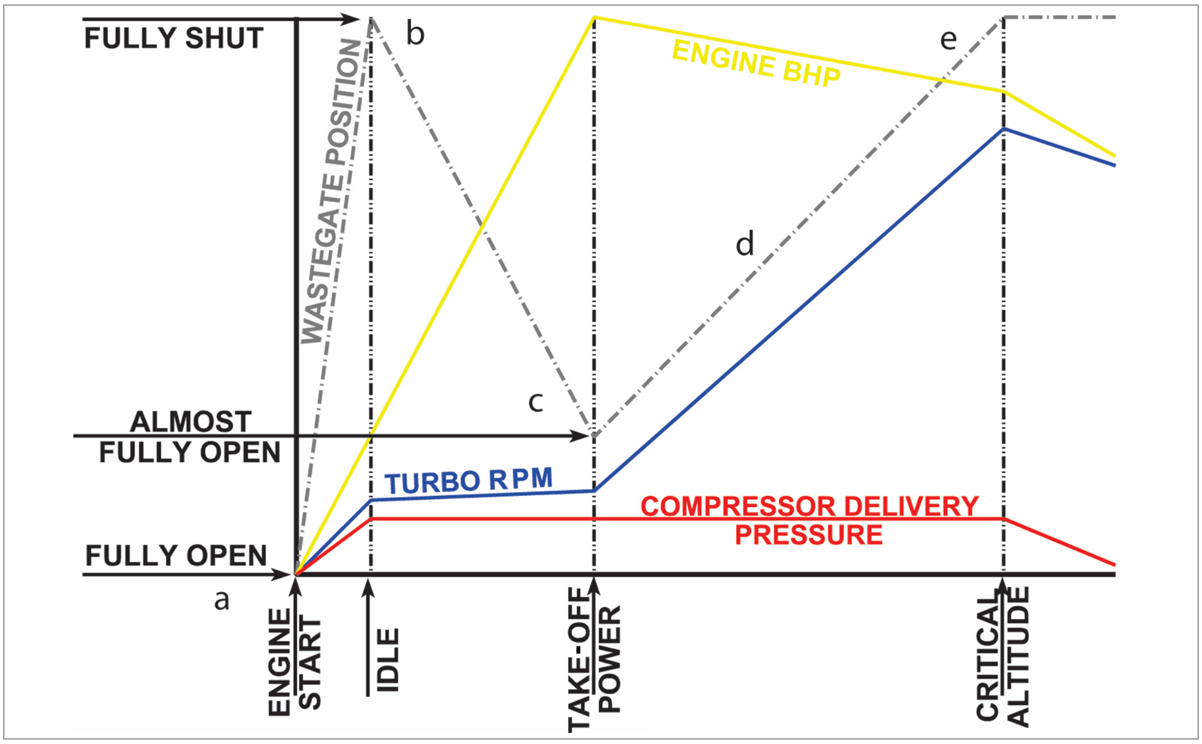


Figure 11.5 The relationship of wastegate position, engine power, manifold pressure & turbocharger rpm to each other.

a) **Prior to start**, the wastegate must be open to allow the free flow of exhaust gases to atmosphere, otherwise the engine would be very difficult, if not impossible, to start. This opening is achieved by the spring in the Wastegate Actuator which forces it fully open.

b) **Immediately after start**, there is probably not enough exhaust gas to spin the turbine fast enough to create the required pressure at the outlet of the compressor. The **Aneroid Capsule** will therefore be expanded, closing the **Bleed Valve** in the **Absolute Pressure Controller (APC)**, trapping oil within the wastegate actuator causing its piston to close the wastegate fully.

c) **Upon opening the throttle**, sufficient exhaust gas will be produced to turn the turbine at a speed that will enable the compressor to achieve more than the required pressure at its outlet. This increased pressure is sensed at the absolute pressure controller and oil is released through the bleed valve from within the wastegate actuator, thus allowing its internal spring to start opening the wastegate. The wastegate will continue to open as the throttle is opened, **until at full throttle at Sea Level ISA pressure it is almost fully open.** The extra wastegate opening is required to cater for those days when the ambient pressure is greater than ISA, without the opening there would be no way to reduce the turbine speed to maintain the compressor outlet pressure within limits.

d) **From the moment of take-off**, and throughout the climb, the pressure at the compressor inlet falls, causing its outlet pressure to fall also. This drop in outlet pressure is signalled to the APC, which closes the bleed valve trapping oil in the wastegate actuator causing it to progressively close the wastegate.

e) **Eventually the wastegate will be fully shut** and no more increase in turbine speed is possible, this is termed the **Critical Altitude.**

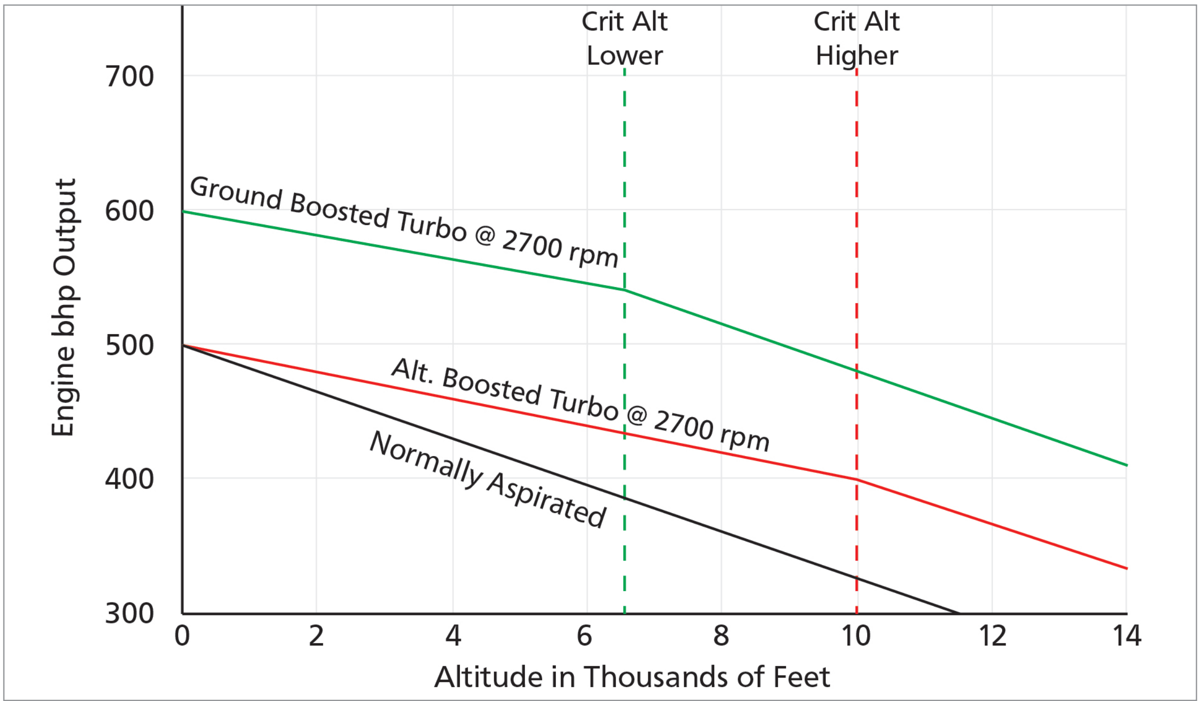


Figure 11.6 A comparison of the power curves of a normally aspirated engine & a turbocharged engine.

Now the outlet pressure of the compressor will fall and the inlet manifold pressure and engine power output will fall in sympathy. Of course, the engine power output will decrease with every foot of the climb from the moment of take-off, this is typical of a turbocharged engine, but now, after Critical Altitude, the decrease gets greater, approximating that of a normally aspirated engine.

Alternative Turbocharger Control

Other types of turbocharger control are described below:

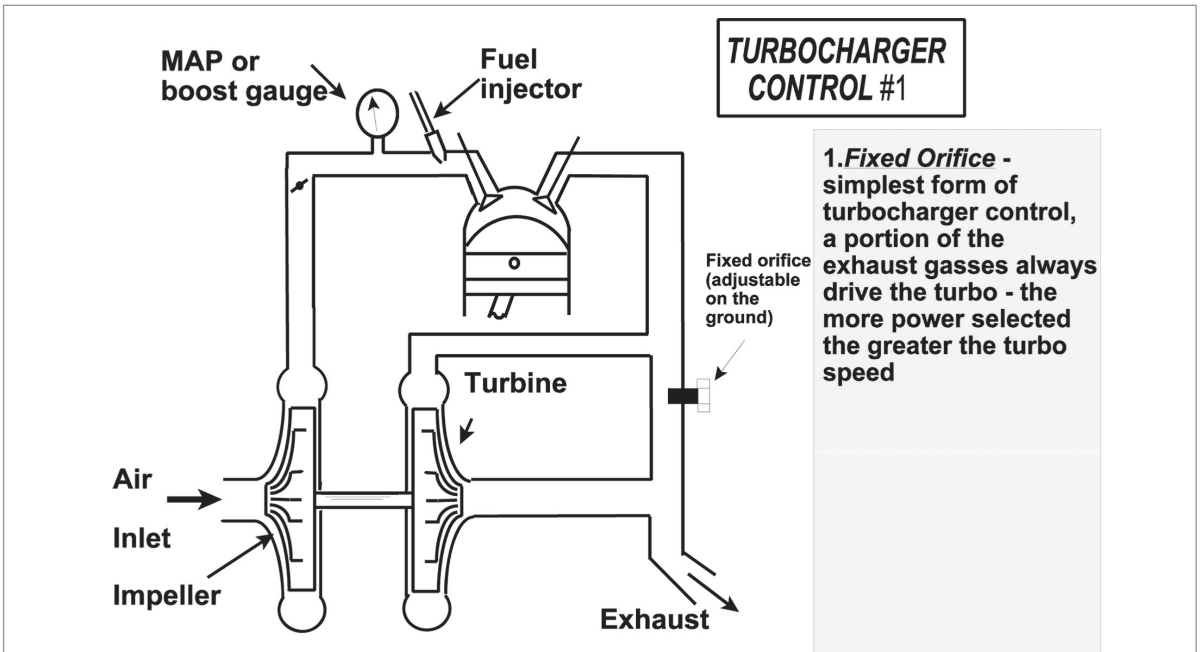


Figure 11.7

a) The simplest form of control is to have a **fixed orifice** exhaust bypass *(Figure 11.7)* so that a proportion of the exhaust gases will always drive the turbo, and the manifold pressure is controlled strictly by the throttle valve, remembering that as the throttle is opened to gain more **MAP** or **Boost** the turbine speed will increase and the throttle input pressure and **MAP** will also respond to the chain reaction, rapid movement of the throttle **will** probably cause overboosting with this type of system.

b) There are two further controllers which may be encountered as a pair (dual)! A **Density Controller** and a **Differential Pressure Controller**. Only fitted to a more sophisticated system the density controller will limit the Maximum **MAP** or **Boost** below the critical altitude when the throttle is opened fully. The density controller is fitted with two bellows sensing compressor outlet pressure and temperature. The bellows are filled with dry nitrogen and allow the pressure to increase as the temperature increases, remember that as the wastegate closes the turbo runs faster and compressor rpm can be up to 110 000. The effect of having a density controller will be that maximum available pressure will increase up to critical altitude and in so doing will reduce the normal loss associated with the increased charge temperature at a constant pressure.

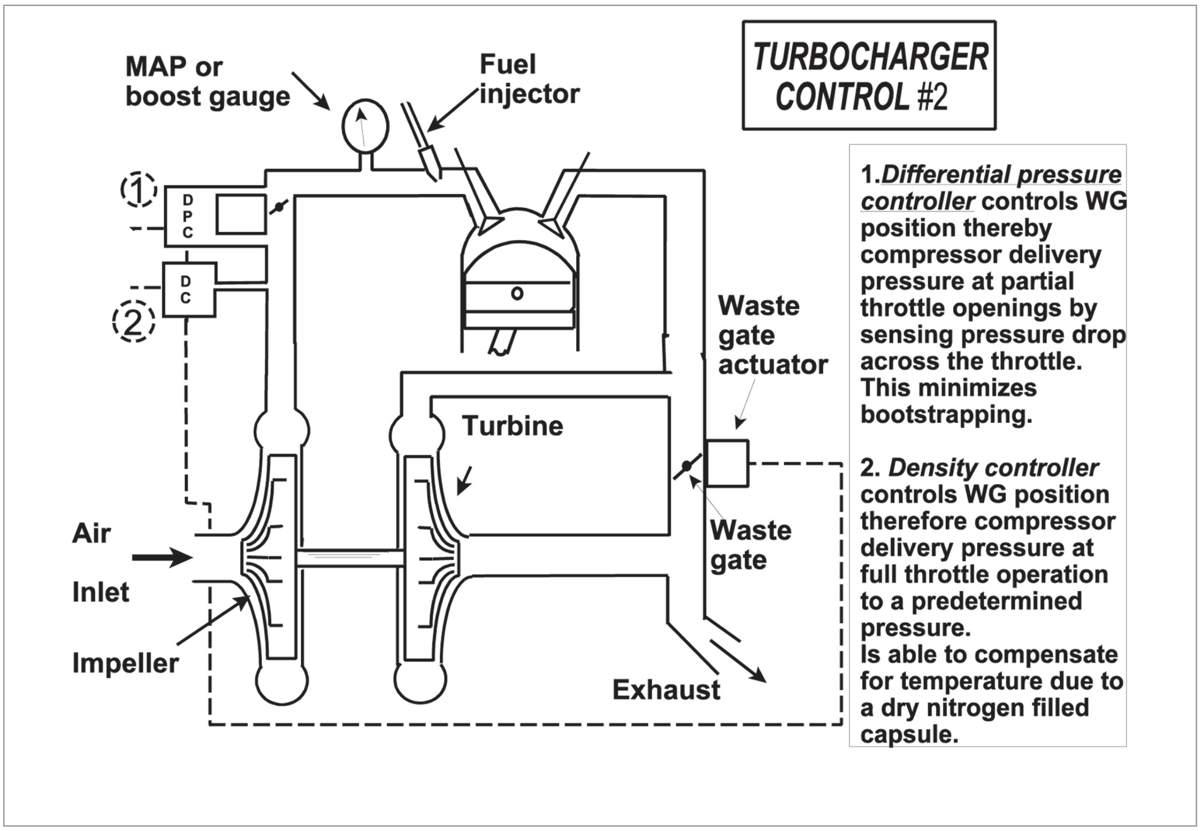


Figure 11.8

c) The Differential Pressure Controller operates at all positions of the throttle **other** than the fully open position. To reduce the compressor outlet pressure if a lower manifold pressure is required. It must be remembered that only one of these two controls will be in use and controlling the wastegate position at any moment in time.

Internally Driven Superchargers

Internally driven superchargers are generally used on medium and high powered piston engines (approximately 250 BHP and above), and are fitted downstream of the throttle valve. In the past, the superchargers of high powered engines have often been driven at two speeds in order to save power at low altitudes, the low speed gearing being used at low altitudes, and the high speed gearing at high altitudes. Some high powered superchargers have also been fitted with two impellers working in series in order to raise the overall compression ratio, but current engines generally employ a single impeller driven at a fixed speed ratio to the crankshaft (usually between 6:1 and 12:1).

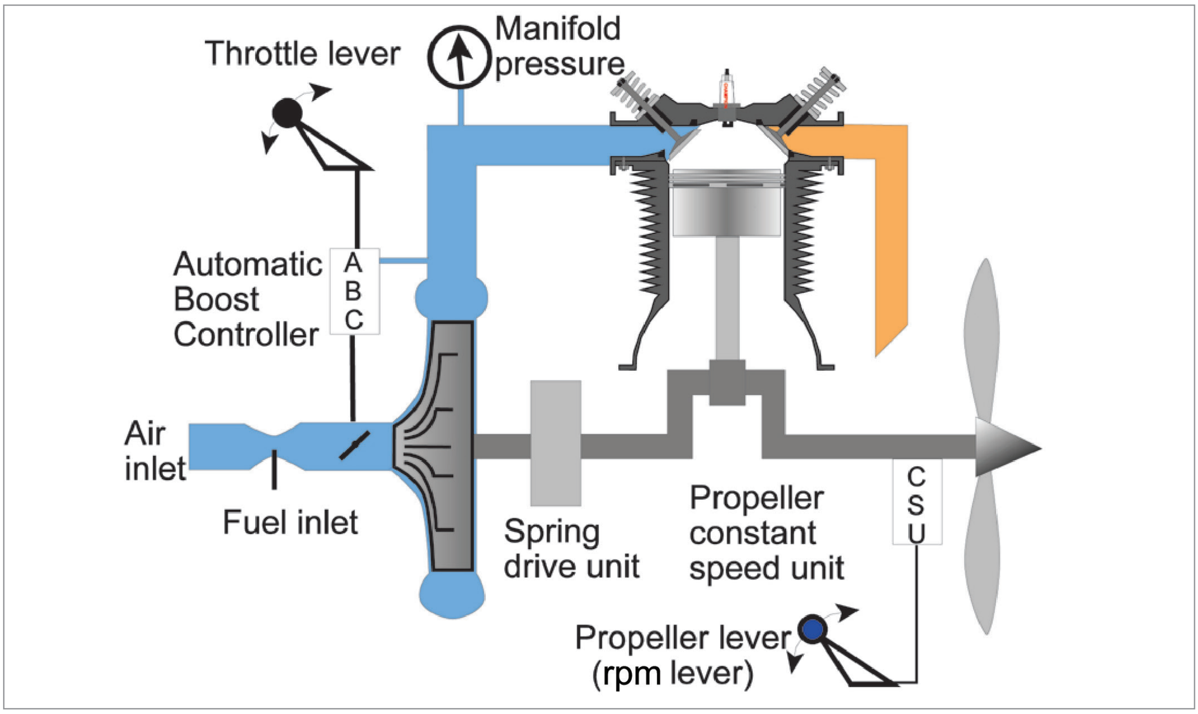


Figure 11.9 Internally driven supercharger - general arrangement.

This type of supercharger is usually capable of maintaining sea level manifold pressure up to an altitude of 5000 to 10 000 ft, at Rated Power 1 settings, depending on the gear ratio.

Supercharger Drives

A shaft, splined into the rear of the crankshaft, provides the initial drive to the supercharger impeller. Such a shaft may incorporate a **Spring Drive Unit**, which transmits the drive through intermediate gears to the impeller pinion and is used to limit the torque transmitted to the supercharger impeller during high rates of propeller/engine acceleration or deceleration, it may also include a centrifugal clutch.

Supercharger Controls

Since a supercharger is designed to compress air and provide sea level pressure, or greater, in the induction manifold when atmospheric pressure is low, excessive manifold pressures could be produced when atmospheric pressure is high. It is necessary, therefore, to restrict throttle opening below full throttle height, and, to relieve the work load on the pilot, this is often done automatically. There are two controls that affect the pressure developed by the supercharger.

The Throttle Lever (The Power Lever)

The throttle lever position, within the limits imposed by full throttle height, determines the boost pressure that is delivered by the supercharger. The throttle is, in effect, a boost selection lever and, together with the propeller control lever, determines the power output of the engine.

The Propeller Pitch Control Lever (The rpm Lever)

Current practice is to install a variable pitch propeller to aircraft engines, where the blade angles can be adjusted in flight between fine and coarse limits, resulting in the rotational speed of the engine increasing or decreasing.

The Action of the Throttle in the Internally Supercharged Engine

At sea level the throttle valve in the supercharged engine must be partially open (choked), so as to restrict manifold pressure and prevent excessive cylinder pressure, but as the aircraft climbs the throttle valve must be progressively opened (either manually or automatically) to maintain this manifold pressure. Eventually a height is reached where the throttle is fully open, and this is known as **Full Throttle Height (FTH)**, above this height power will fall off as with the normally aspirated engine.

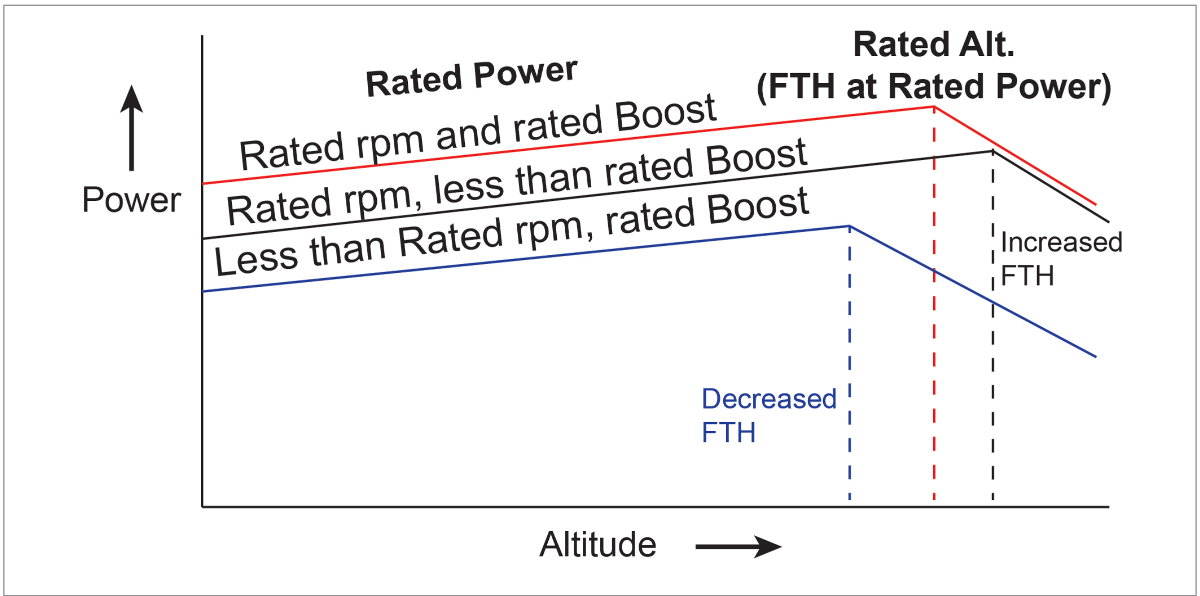


Figure 11.10

Since the effect of the supercharger depends on the speed of rotation of the impeller, each power setting will have a different Full Throttle Height according to the engine speed and manifold pressure used, the Full Throttle Height at Rated Power settings is known as **Rated Altitude,** shown in *Figure 11.10.*

***Note: Rated Power** or Maximum Continuous Power (MCP) is the maximum power at which continuous operation is permitted. Take-off Power, and sometimes Climb Power, may have a time limitation imposed upon their use. At **Rated rpm** and at **Rated Boost** (manifold pressure), the height achieved is known as **'Rated Altitude'** which is a full throttle height but only when Rated rpm and Rated Boost are set (rated power).*

Summary

The effect of climbing at less than Rated Power by maintaining Rated rpm with less than Rated Boost selected is to increase the Full Throttle Height.

The effect of climbing at less than Rated Power by maintaining Rated Boost with less than Rated rpm selected is to decrease the Full Throttle Height.

This is because it is necessary to increase the throttle opening to make up for reduced compressor output (remember it is the size and rotational speed of a Centrifugal/Radial Compressor that determines its output). The throttle-valve will open more quickly in the climb to compensate for the slower rpm, or more slowly when the rpm is maintained and the boost selection is low.

The propeller control lever can be said to be an engine speed control and, as the impeller is geared to the crankshaft, any change in engine speed will result in a corresponding change in the speed of rotation of the impeller.

Automatic Boost Control

The supercharger is designed to maintain a given pressure at altitude, to do this the impeller must be driven at a high speed because of the considerable reduction in atmospheric pressure at altitude. Therefore, at low altitudes where the air is more dense, the supercharger produces too much pressure, consequently, to avoid severe detonation and mechanical stresses due to excessively high combustion pressure, the delivery pressure must be restricted by only partially opening the throttle valve.

As the aircraft climbs, the throttle valve must be progressively opened further to maintain a constant boost pressure. To relieve the pilot of the responsibility of constantly varying the position of the throttle lever during climb or descent, the boost pressure is kept constant automatically by the Automatic Boost Control unit (**ABC**) which is generally attached to the carburettor. *Figure 11.11* shows a diagram of an Automatic Boost Control unit.

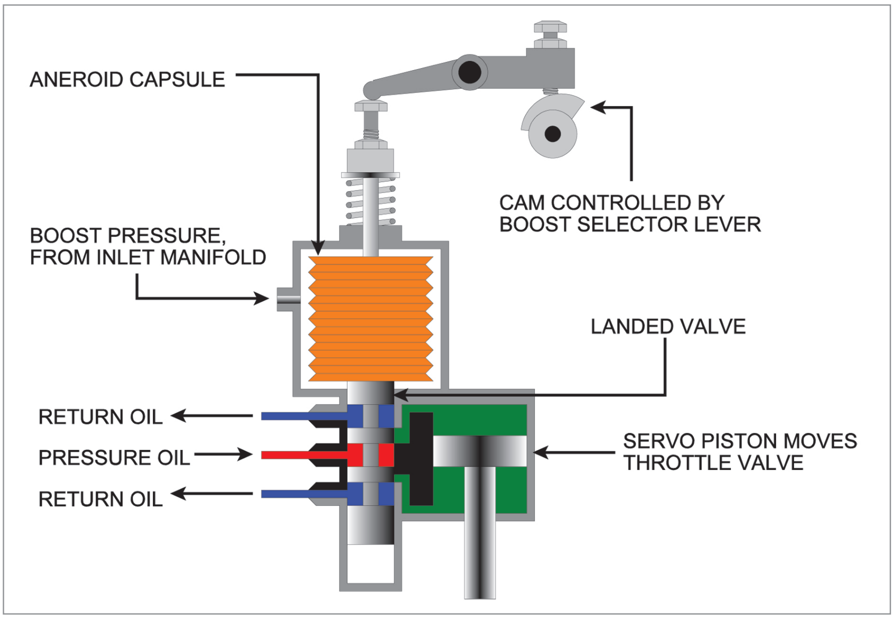


Figure 11.11 An automatic boost control unit.

Normally Aspirated vs. Internally Supercharged

The power developed by the normally aspirated engine is at a maximum at sea level, and progressively decreases as altitude is increased.

The power developed by the supercharged but otherwise identical engine, at the same speed and manifold pressure, is less than that of the normally aspirated engine at sea level, and this power loss represents the power required to drive the supercharger. However, as height is increased, the power developed by the supercharged engine at constant throttle settings increases as a result of the decreased temperature of the atmosphere.

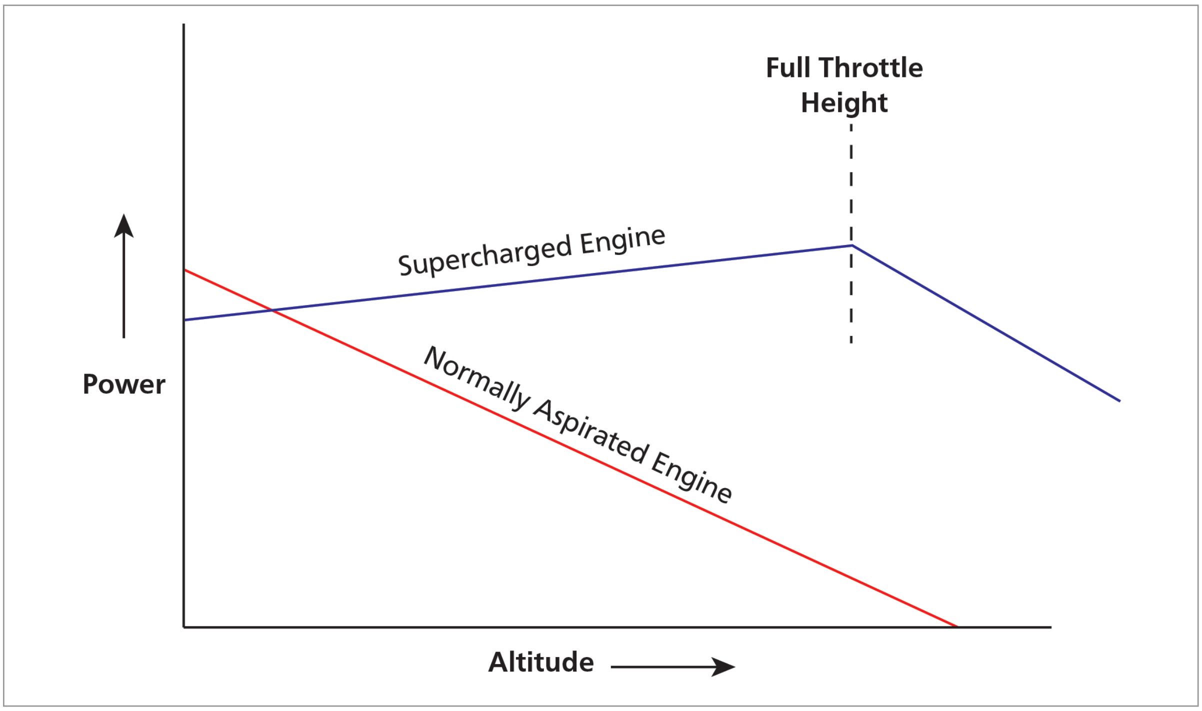


Figure 11.12

The decreased temperature increases the density of the air, and thus a greater weight of air is pumped into the cylinders for the same manifold pressure. Decreased air pressure also causes less back pressure on the exhaust, thus improving scavenging of the cylinders.

Engine Power Output

The effect of altitude change on turbocharged and supercharged engines is vastly different. A perusal of *Figure 11.5 and Figure 11.12* will show how the power output of a turbocharged engine **decreases** with increase of altitude, while the output of the engine fitted with an internal supercharger **increases** with increase of altitude. This is due to the variation of exhaust back pressure with each type.

Engine Power Checks. Reference rpm

When an engine is first installed in an aircraft, a check of its performance is made and a **Reference rpm** is established. This rpm is an indication of the engine's power output with the propeller on the fine pitch stop, and it is almost constant, regardless of the airfield altitude or temperature.

A note of the Reference rpm would be made and it would be placarded somewhere convenient in the cockpit, e.g. on the relevant rpm gauge.

Once the Reference rpm has been established it should not change appreciably, any change would indicate some form of malfunction.

A new Reference rpm will have to be established every time a major engine component, such as a carburettor or a magneto, is changed.

Engine Power Checks. Static Boost

Before the engine is started, the Boost Pressure Gauge or the Manifold Absolute Pressure Gauge (depending on whether the system is British or American), will show approximately ambient atmospheric pressure.

At exactly sea level pressure on an ISA day, this will mean that a reading of 29.92 inches of mercury (MAP gauge), or Zero Boost (Boost Pressure Gauge). With an increase of airfield altitude the gauge reading will of course fall, and conversely, if the airfield ambient pressure is above ISA sea level pressure then the gauge reading will rise.

The gauge reading at this point, i.e. before engine start, is known as **Static Boost**, and note should be taken of it in order that a check of engine power output can be made.

Checking the Engine Power Output

When the engine is first started, the pressure in the inlet manifold will **decrease** below the Static Boost figure and will probably not begin to rise until about 1600 or 1700 rpm is established. With maximum rpm selected, i.e. the propeller on the Fine Pitch Stop, as the throttle is progressively opened, the inlet manifold pressure should regain the Static Boost figure at the Reference rpm, plus or minus a small tolerance of, say 50 rpm.

The Reference rpm will vary with different models of engine, but would on average be approximately 2000 rpm.

Any result which is outside tolerance may be the result of a cylinder down on power, the ignition system malfunctioning, a carburettor maladjustment, or even an improperly set propeller low pitch stop.

Comparing the Turbocharger and the Supercharger

When making comparisons between turbochargers and internal superchargers it is inevitable that the question of "which is best?" is asked. If it was just a matter of added performance at ground level for a given cost, then the turbocharger would probably win.

There are other considerations to be taken into account however, first of all, do we only want the added performance at ground level? Unavoidably with an aircraft the answer must be no, in which case the internal supercharger, with its ability to increase engine power with aircraft altitude, must be favourite.

Secondly, do we require that the response to throttle opening be instant? If the answer to this is yes, then once again the internal supercharger wins hands down. The turbocharger, for all that it is the cheaper option, cannot with present day technology respond to rapid throttle opening without suffering from the phenomenon known as **turbo-lag**.

Turbo-lag is the result of the time it takes to speed up the turbine/compressor after the signal of low compressor output has been sent to the Absolute Pressure Controller (APC) and the wastegate actuator has reacted by closing the wastegate.

Summary

	SUPERCHARGER	TURBOCHARGER
1	Internally driven	Externally driven
2	Rotational speed controlled by rpm	Rotational speed controlled by Wastegate position.
3	Compresses mixture	Compresses air
4	ABC senses manifold pressure and controls the throttle	APC senses compressor discharge pressure and controls the wastegate
5	Compressor discharge pressure same as manifold pressure	Compressor discharge pressure greater than manifold pressure
6	Throttle controls manifold pressure	Throttle controls manifold pressure
7	Decreased exhaust back pressure in the climb	Increased exhaust back pressure in the climb

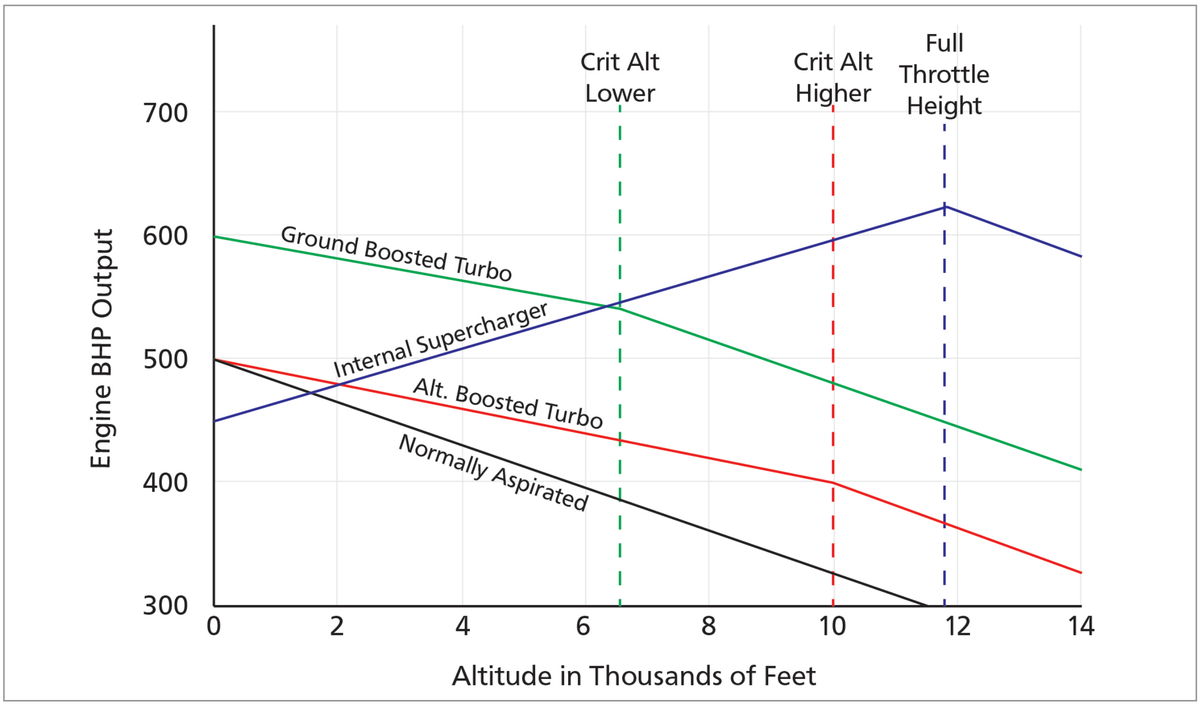


Figure 11.13

Diesel Engines

Diesel engines also suffer from a loss of volumetric efficiency with altitude, high elevation take-offs and on hotter than standard days.

For this reason turbochargers (external superchargers) may be fitted to diesel engines so as to improve performance in a similar way to the conventional piston engine. Intercoolers are also employed to restore density after compression.

Questions

1. **The Manifold Pressure Gauge fitted to a supercharged engine measures:**

a. the absolute pressure in the induction manifold
b. the differential pressure across the supercharger compressor
c. the ratio between the atmospheric pressure and the cam rise at the supercharger inlet
d. the pressure upstream of the throttle valve

2. **An Automatic Boost Control Unit:**

a. prevents detonation and dissociation in the cylinder
b. maintains an automatic preset boost pressure
c. maintains the correct mixture strength for the boost pressure set
d. sets the position of the wastegate to ensure the preset boost is maintained

3. **The use of a turbocharger on an engine will:**

a. improve the exhaust scavenging efficiency
b. raise the volumetric efficiency of the engine
c. cause an automatic rise in the engine rpm as altitude is gained
d. cause an automatic rise in engine power as altitude is gained

4. **The motive force used to drive the turbocharger is:**

a. torque from the crankshaft via a spring drive unit
b. torque from the accessory gearbox
c. energy from the exhaust that would otherwise have been wasted
d. energy from the reduction gearbox

5. **The power increase that occurs with initial increase in altitude when an engine has an internal supercharger fitted, is due to:**

a. the reduced weight of mixture being passed to the engine
b. the decreasing density of the atmosphere
c. the reducing exhausts back pressure
d. the increasing charge temperature

6. **Rated Altitude is:**

a. the height at which the boost pressure ceases to be effective with a specific rpm set
b. a comparison between the boost pressure at sea level and that at a given altitude
c. the maximum altitude at which Rated Boost can be maintained with Rated rpm set
d. the altitude at which the wastegate becomes fully shut

7. **The speed of the turbine of a turbocharger is controlled by:**

a. the diversion of exhaust gases
b. controlling the exit of the exhaust gas passing out of the eye of the impeller
c. the use of a variable controller
d. an automatic gearbox positioned between the turbine and the impeller

8. **The turbocharger wastegate is spring loaded towards:**

a. the open position
b. the closed position
c. a neutrally balanced partly open position
d. the maximum boost position

9. **The turbocharger bearing is lubricated and cooled by:**

a. its own internal self-contained oil system
b. the engine oil
c. a total loss system
d. a tapping in the scavenge oil system

10. **Static Boost is:**

a. always the ISA atmospheric pressure for the airfield altitude
b. obtained by opening the throttle to give a boost gauge reading of 30 in Hg or 0 psi.
c. the boost pressure gauge reading when the engine is not running. Selecting a suitable throttle position will give the same boost gauge reading when the engine is running
d. the difference between the induction manifold pressure and the exhaust manifold pressure

11. **The automatic boost pressure control capsules are made sensitive to:**

a. atmospheric pressure
b. carburettor inlet pressure
c. boost pressure
d. cabin pressure differential

12. **In order to maintain a constant boost pressure with increasing altitude, the ABC:**

a. holds the throttle valve at a constant position
b. progressively opens the throttle valve
c. progressively closes the wastegate
d. progressively closes the throttle valve

13. **"Boost pressure" is the:**

a. inlet manifold pressure in pounds per square inch above or below standard mean sea level pressure
b. absolute pressure in the inlet manifold measured in inches of mercury
c. absolute pressure in the inlet manifold measured in millibars
d. inlet manifold pressure in pounds per square inch above or below atmospheric pressure

14. **"Full Throttle Height" is:**

a. the height at which the engine is at Rated Boost
b. the maximum height at which a specified boost can be maintained at a specified rpm
c. the height at which the wastegate is fully closed
d. the cruising height for any specific boost

15. The purpose of an intercooler is:

a. to minimize the risk of detonation
b. to increase the volume of the charge
c. to decrease the density of the charge
d. to prevent overheating of the exhaust manifold

16. The function of a diffuser in a supercharger is:

a. to decrease the temperature and increase the velocity of the charge
b. to increase the velocity and decrease the pressure of the charge
c. to decrease the velocity and decrease the pressure of the charge
d. to decrease the velocity and increase the pressure of the charge

17. Air enters the compressor of a turbosupercharger:

a. at the tip and passes across the impeller blades to exit at the eye
b. at the diffuser and exits at the impeller
c. at the eye and passes across the diffuser blades before exiting at the impeller tip
d. at the eye and passes across the impeller blades to exit at the tip

18. The wastegate of a turbosupercharger is fitted:

a. in the turbine bypass
b. in the inlet manifold
c. to maximize exhaust back pressure
d. in series with the turbine

19. The wastegate is operated by:

a. the automatic boost control unit
b. the wastegate actuator
c. inlet manifold pressure
d. exhaust gas temperature

20. With a turbocharger installed on the engine, its exhaust back pressure:

a. remains the same
b. is decreased
c. is increased
d. decreases in the climb

21. A high performance supercharger may require an intercooler to be placed:

a. between the supercharger and the inlet valve
b. at the carburettor intake
c. between each cylinder
d. between the engine block and the exhaust manifold

22. With an increase of compressor discharge pressure the fuel flow will:

a. increase
b. remain constant
c. decrease
d. increase, but only in proportion to altitude increase

23. A turbocharger's rotational speed is determined by:

a. the diversion of exhaust gas
b. the position of the throttle valve
c. the density of the air at the compressor intake
d. bleeding off excess exhaust pressure

24. During take-off from a sea level airfield with ISA conditions, the position of the wastegate of a turbocharged engine is:

a. fully open
b. almost fully open
c. controlled by the throttle position
d. fully closed

25. Maximum Continuous Power (MCP) is:

a. unrestricted, but only if economical cruising power is set
b. the maximum power the engine will give at any time
c. given a 5 minute limitation
d. unrestricted

26. The primary purpose of a supercharger is to:

a. raise the temperature of the charge entering the cylinder
b. increase the mass of the charge entering the cylinder
c. improve the engine's exhaust scavenging capability, and hence increase its power output
d. allow the use of high octane fuel

27. The type of fuel used in a turbocharged engine would be:

a. AVTUR
b. AVGAS
c. AVTAG
d. AVPIN

28. At an idle or low power condition, the turbocharger wastegate is normally:

a. partially open
b. fully open
c. closed
d. half open

29. When the air or the mixture passes through the diffuser shroud, the energy conversion is from:

a. kinetic to pressure
b. heat to potential
c. mechanical to heat
d. potential to kinetic

30. **The construction of a turbocharger ensures that the turbine and the compressor:**

a. are on the same shaft
b. are on different shafts
c. are connected by mechanical gearing
d. are controlled by the ABC

31. **The wastegate fitted to a turbocharger regulates the quantity of:**

a. the mixture that enters the induction manifold
b. the atmosphere that can enter the compressor
c. the exhaust gas that will bypass the turbine
d. the exhaust gas that leaves the compressor

32. **The main function of a supercharger is to:**

a. increase the thermal efficiency of the engine
b. increase the compression ratio of the engine
c. maintain sea level pressure in the engine to above rated altitude
d. increase the volumetric efficiency of the engine

33. **The response of a turbocharged engine to rapid throttle opening, when compared to a normally aspirated engine:**

a. is initially better, but exhaust back pressure will cause a flat spot
b. is always better
c. is worse
d. is identical

34. **With a constant manifold pressure set during the climb, the power output from an internally supercharged engine:**

a. decreases
b. increases
c. remains constant
d. is unaffected by altitude change

35. **An internal supercharger is one which:**

a. is driven by exhaust gases
b. compresses the air
c. compresses the exhaust gases
d. compresses the mixture

36. **If the wastegate of a turbocharged engine seizes in the climb before critical altitude has been reached:**

a. engine power will be automatically adjusted by the ABC
b. engine power will rise by approximately 10%
c. reducing back pressure will compensate for any loss in power
d. engine power will fall as the climb continues

37. **To prevent large acceleration loads on the compressor and the drive shaft of an internal supercharger, it is usual to:**

a. prohibit “slam” acceleration
b. incorporate a spring drive mechanism in the driving gears
c. rely on the inertia absorbing qualities of the exhaust gases
d. use a Vernier drive coupling

38. **The rotational speed of the turbocharger of an engine which is at full throttle at low altitude is:**

a. between minimum and maximum
b. maximum
c. controlled by the ABC
d. minimum

39. **Maintaining a constant manifold pressure in a turbocharged engine during the climb will cause:**

a. the exhaust gas temperature to decrease due to a decrease in exhaust back pressure
b. the wastegate to open
c. the wastegate to progressively close
d. the diffuser rotational speed to increase

40. **Overboosting an engine fitted with a turbocharger is prevented by the installation of:**

a. an automatic boost control unit
b. a manifold pressure gauge
c. a wastegate pressure controller
d. a suck in flap

41. **A turbocharger which is designed to maintain sea level pressure at altitude is termed:**

a. an altitude-boosted turbocharger
b. a turbosupercharger
c. an internal supercharger
d. a ground boosted turbocharger

42. **With the power lever opened for take-off power at sea level, the throttle butterfly of an engine fitted with an internal supercharger would be:**

a. fully open
b. in a choked position
c. partially open
d. fully closed

43. **“Static Boost” is the manifold pressure indicated on the boost pressure gauge when:**

a. the engine is stopped
b. the engine is running at the manufacturer’s recommended idle speed
c. the engine is running at its rated power
d. the manifold gauge needle is opposite the lubber line

44. **The limit of the amount of supercharging that an engine can tolerate is reached when:**

a. maximum rpm is reached
b. the engine is at its rated altitude
c. maximum boost pressure is obtained
d. the engine starts to suffer from detonation

45. **The rotational speed of a turbocharger is dependent upon:**

a. engine rpm and wastegate position
b. engine rpm only
c. throttle position only
d. propeller pitch and altitude

46. **The inlet manifold pressure of a turbocharged engine in an aircraft which is climbing will:**

a. increase to full throttle height and then fall
b. increase to critical height and then remain constant
c. remain constant to critical altitude and then fall
d. decrease to critical altitude and then remain constant

47. **The type of compressor normally used in a supercharger is:**

a. an axial compressor
b. a Rootes compressor
c. a centrifugal compressor
d. a reciprocating thrunge compressor

48. **The compressor output pressure of an internal supercharger is:**

a. the same as manifold pressure
b. greater than the manifold pressure
c. sometimes greater, sometimes less than the manifold pressure
d. less than the manifold pressure

49. **The position of the wastegate in a turbocharged engine is:**

a. in the inlet manifold
b. downstream of the turbine
c. in parallel with the turbine
d. in parallel with the compressor

50. **The maximum engine brake horsepower with a specified rpm and manifold pressure set which permits continuous safe operation is termed:**

a. maximum power
b. take-off power
c. critical power
d. rated power

51. **The compressor output of a turbocharger unit is:**

a. the same as the manifold pressure
b. greater than the manifold pressure
c. sometimes greater, sometimes less than the manifold pressure
d. less than manifold pressure

52. **Within the compressor of a turbocharger:**

a. the pressure increases and the temperature decreases
b. both the pressure and the temperature increase
c. both the pressure and the temperature decrease
d. the pressure increases and the temperature remains constant

53. **The type of compressor normally fitted to turbochargers and superchargers would compress the air:**

a. axially
b. co-axially
c. in the diffuser only
d. centrifugally

54. **If the wastegate of a turbocharged engine seizes during the climb, the manifold pressure will:**

a. remain constant
b. decrease
c. increase
d. initially increase and then decrease

55. **To maintain the Rated Boost of a supercharged engine while reducing the rpm:**

a. the throttle valve must be opened
b. the wastegate must be closed
c. the wastegate must be opened
d. the throttle valve must be closed

56. **The effect of selecting Rated Boost, but less than Rated rpm on the climb, would be that:**

a. the Rated Altitude would be lower
b. the Full Throttle Height would be less
c. the Rated Altitude would be higher
d. the Full Throttle Height would be higher

57. **The Automatic Boost Control Unit operates:**

a. the Boost Control Lever
b. the wastegate
c. the throttle butterfly
d. the rpm gauge and the manifold pressure gauge

58. **Boost pressure is indicated on:**

a. the cylinder head temperature gauge
b. the manifold pressure gauge
c. the fuel pressure gauge
d. the rpm gauge and the manifold pressure gauge

59. **With an increase of compressor discharge pressure, the fuel flow will:**

a. decrease
b. remain constant
c. initially increase, but subsequently decrease
d. increase

60. **Superchargers are used to overcome:**

a. the decrease in density due to the increase in altitude
b. the increase in temperature due to the increase in altitude
c. the fuel density variation that occurs with an increase in altitude
d. the exhaust back pressure

61. **The boost pressure of a turbocharged engine is controlled by:**

a. adjusting the throttle position
b. varying the speed of the turbocharger
c. the ABC
d. changing engine rpm.

62. **In a supercharger, the mixture:**

a. enters through the eye of the impeller and leaves at the periphery
b. enters at the periphery and leaves through the eye
c. enters through the turbine and leaves through the compressor
d. enters through the compressor and leaves through the turbine

Answers

1	2	3	4	5	6	7	8	9	10	11	12
a	b	b	c	c	c	a	a	b	c	c	b

13	14	15	16	17	18	19	20	21	22	23	24
a	b	a	d	d	a	b	c	a	a	a	b

25	26	27	28	29	30	31	32	33	34	35	36
d	b	b	c	a	a	c	d	c	b	d	d

37	38	39	40	41	42	43	44	45	46	47	48
b	a	c	b	a	b	a	c	a	c	c	a

49	50	51	52	53	54	55	56	57	58	59	60
c	d	b	b	d	b	a	b	c	b	d	a

61	62
a	a

Chapter

12

Piston Engines - Propellers

Introduction

Purpose of a Propeller

The purpose of a propeller is to convert the power delivered by an engine into propulsive thrust in order to propel an aircraft. This is achieved by the acceleration of a comparatively large mass of air rearwards, thereby producing forward thrust (remember Newton's third law). The acceleration applied is not large when compared with other reaction systems. The aerodynamic considerations of the propeller are fully discussed in the Principles of Flight book. It is recommended that the relevant chapters are read together with this chapter.

Blade Geometry

A propeller consists of two or more aerodynamically shaped blades attached to a central hub. This hub is mounted onto a propeller shaft driven by the engine. The whole assembly is rotated by the propeller shaft, rather like rotating wings.

Like a wing, a propeller blade has a root and a tip, a leading and trailing edge and a cambered cross-section whose chord line passes from the centre of the leading edge radius to the trailing edge. The forward, cambered side is called the 'back' of the blade, while the flat, rearward facing side is termed the pressure or thrust 'face'. At the root area, where the section of the blade becomes round, this is termed the blade 'shank', while the base of the blade, where any pitch-change mechanism would have to be attached, is called the blade 'butt'.

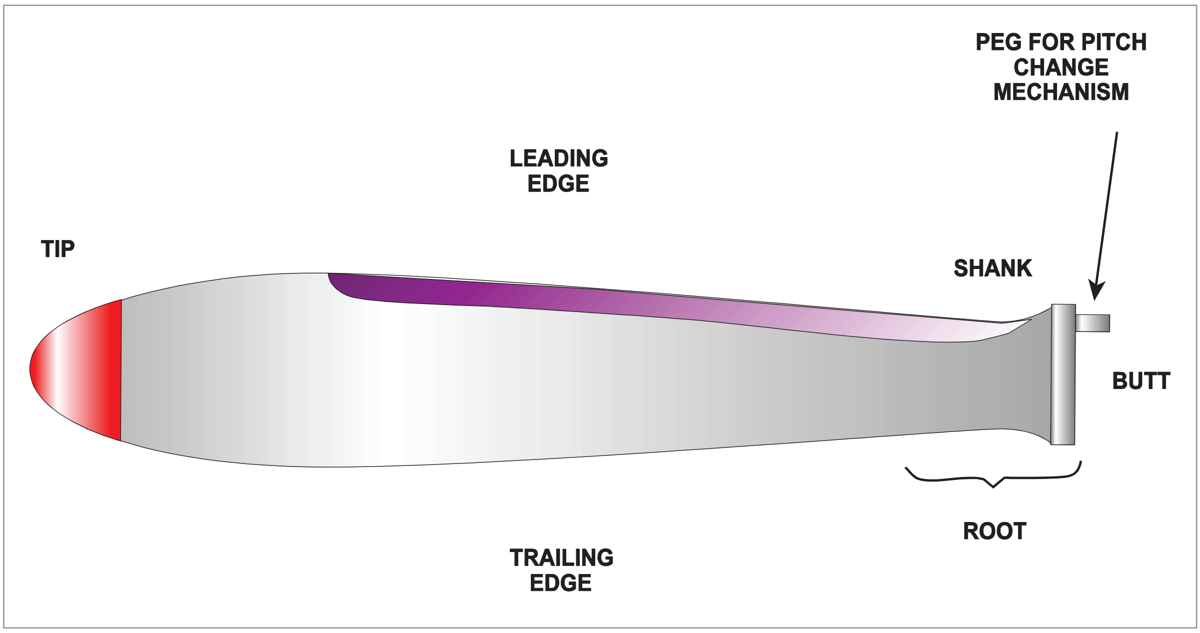


Figure 12.1 Blade nomenclature

Blade Terminology

Most of the terms in the diagram below are explained fully in the Principles of Flight book and are repeated here as a reminder. Those that are important from the mechanical point of view we will discuss further.

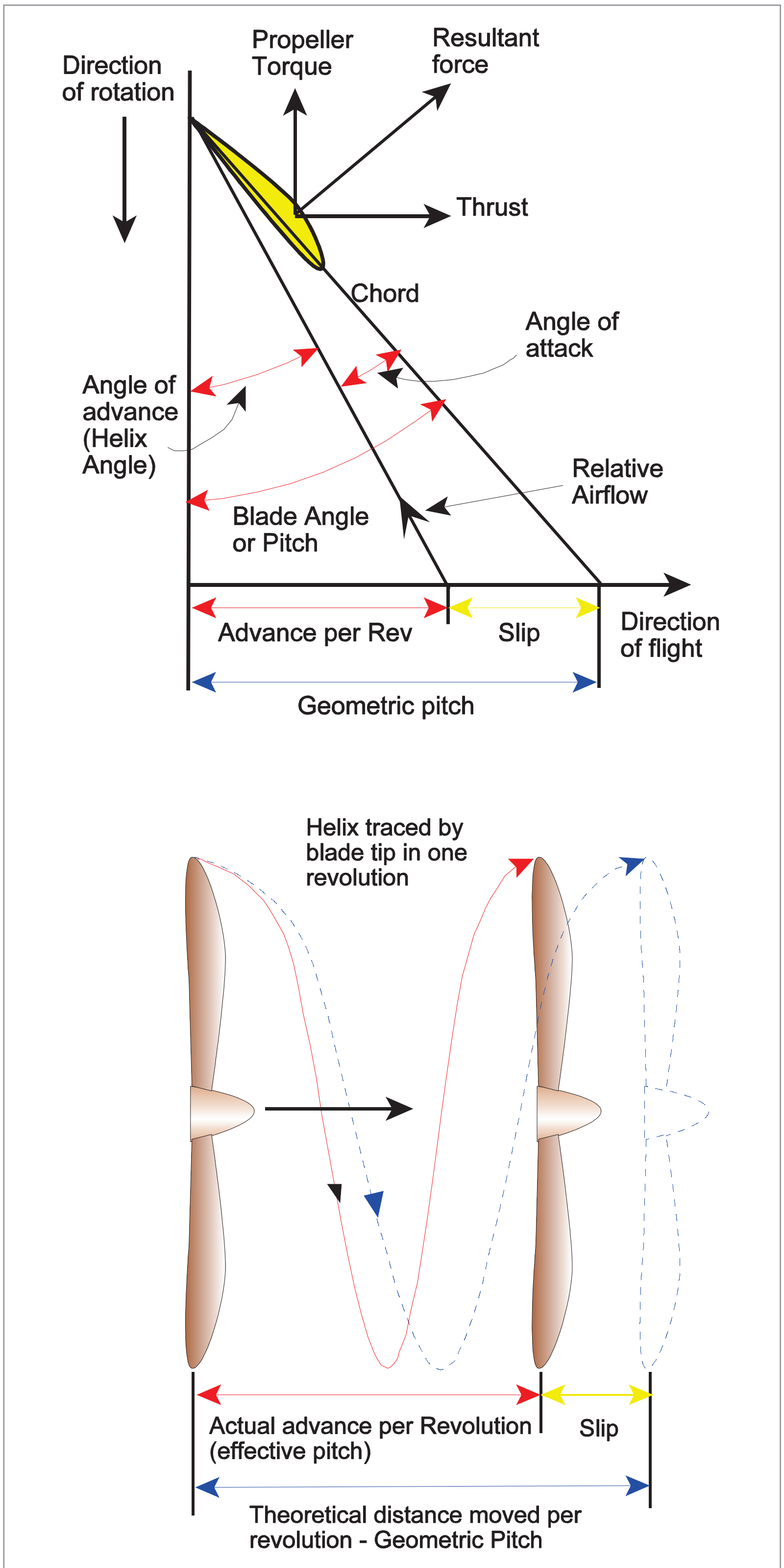


Figure 12.2 Terminology.

Pitch, or Blade Angle

The propeller blade is set into its hub so that its chord line forms an angle with the plane of rotation of the whole propeller. This is called pitch, or blade angle.

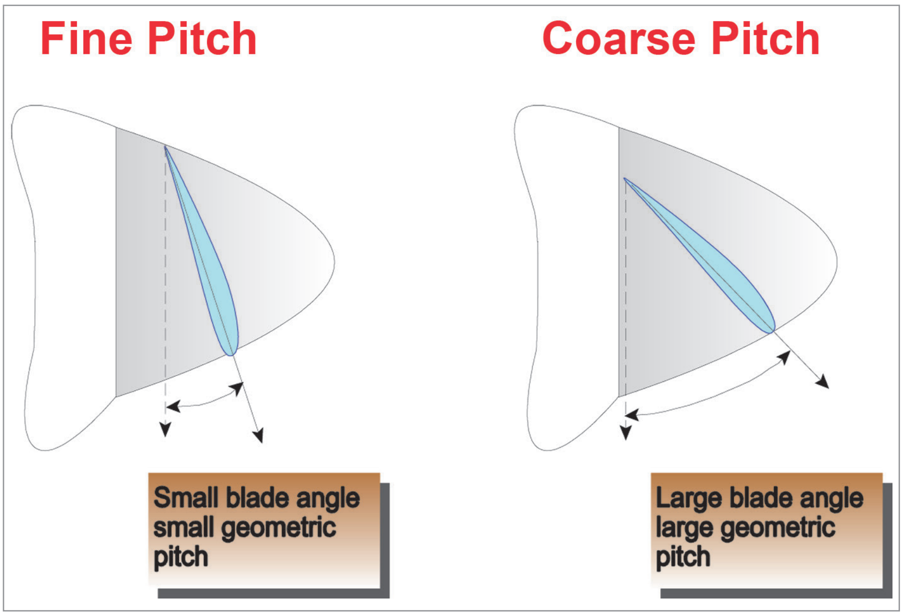


Figure 12.3 Blade angle

Angle of Attack

The path of the propeller blade through the air, a helix, determines the direction from which it will receive its relative airflow. This path is the resultant of blade rotational velocity and aircraft forward velocity. The blade angle is chosen so that the leading edge is pointing into the relative airflow at a small angle of attack. (Ideally 2-4 degrees).

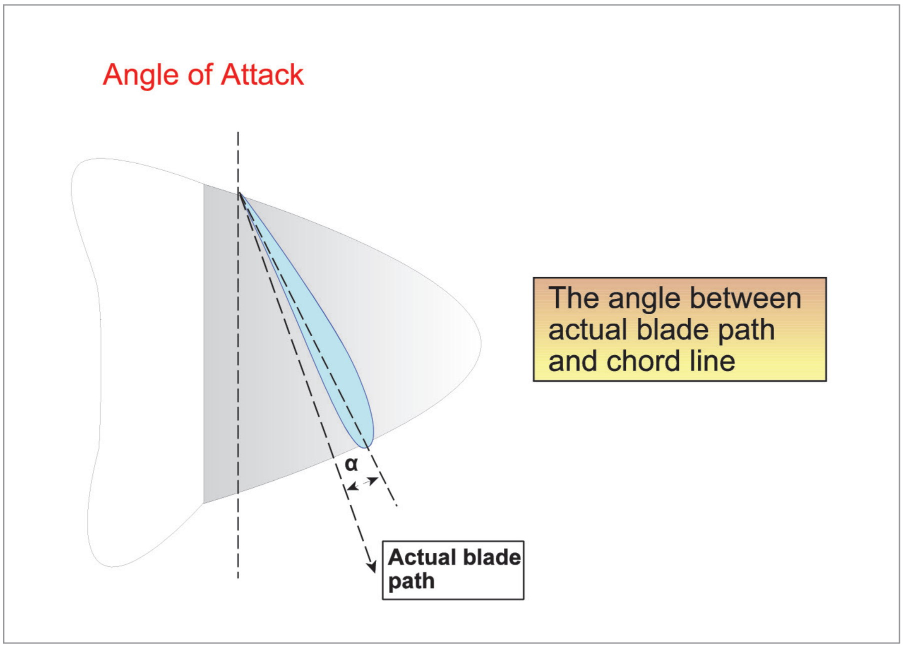


Figure 12.4 Angle of attack

Blade Twist or Wash-out

As the rotational speed of any point on a propeller blade increases with its radius from the centre of the hub, then the magnitude of the total reaction generated along the blade will also increase with increase of radius.

This would lead to a marked increase in thrust developed at the outer part of the blade when compared with the root area, which would exaggerate the bending forces along the blade.

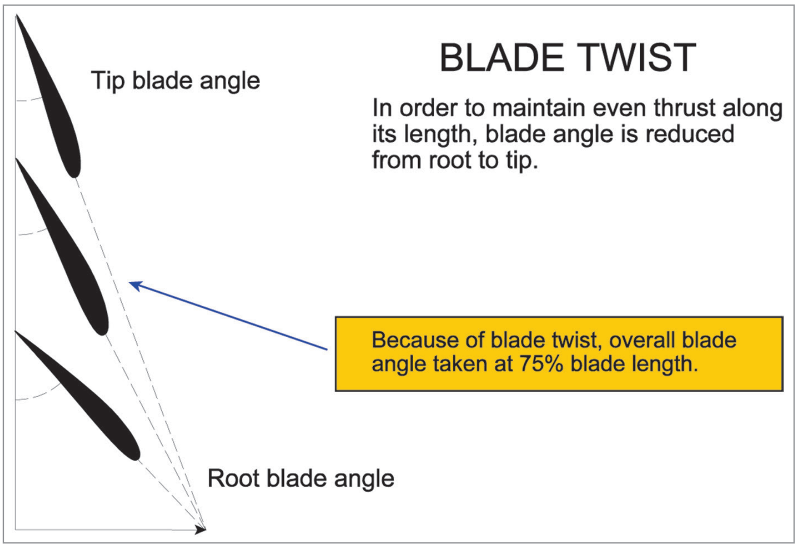


Figure 12.5

To even out the thrust developed along the blade, the angle of attack is maintained by reducing the blade angle from root to tip.

Fixed Pitch Propellers

Disadvantages

A fixed pitch propeller receives its relative airflow from a direction governed by the aircraft's true airspeed (TAS) in the direction of flight and its own rpm in the plane of rotation. The operating angle of attack will be the angle between the relative airflow and the chord line of the propeller blade. This chord line will be set at an angle to the plane of rotation; the "blade angle" or propeller "pitch angle".

Referring to *Figure 12.6*, it can be seen that an increase in TAS will reduce the angle of attack, whereas an increase in rpm will increase it.

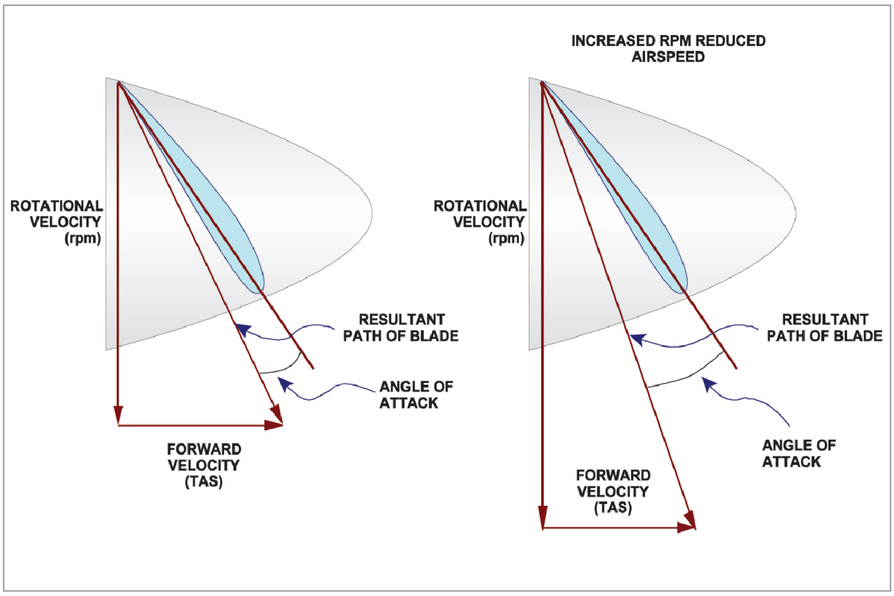


Figure 12.6 Reduced TAS and increased rpm

Propeller Efficiency

At high forward speed/low rpm (power off dive) it is possible to reduce the angle of attack to zero, while at low TAS/high rpm (climb) it is possible to stall the propeller blade. Both extremes are obviously inefficient and therefore undesirable. The conclusion that must be drawn is that for a given fixed pitch, a propeller will only work efficiently at one combination of TAS and rpm. The efficiency achieved will usually be in the range 80-90% and is properly rendered as:

$$\text{Propeller efficiency \%} = \frac{\text{Thrust Power} \times 100}{\text{Engine Power}}$$

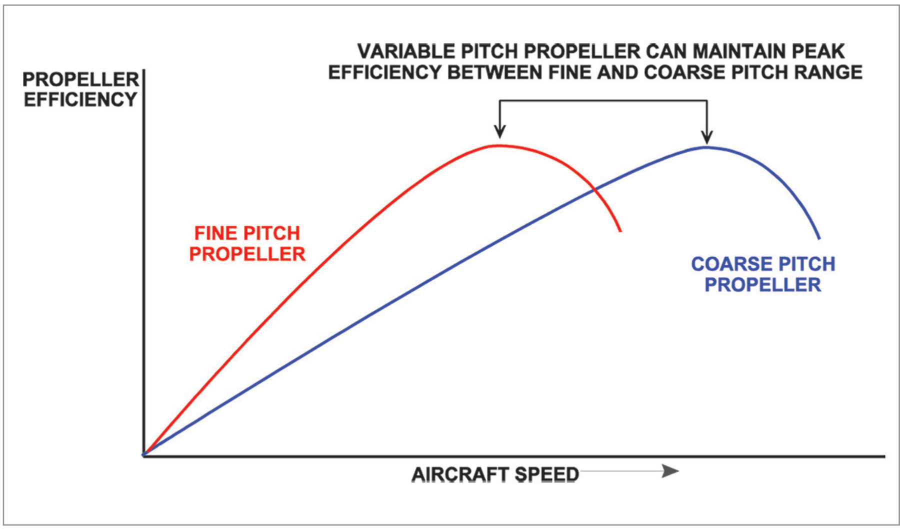


Figure 12.7 Propeller efficiency curves

With a fixed pitch propeller being driven by a piston engine, the rpm is dependent on the power setting (throttle position) selected by the pilot and the TAS of the aircraft. It would be possible to overspeed the engine in a dive if the throttle were not backed off (closed). Conversely, with the aircraft stationary on the ground it may not be possible to achieve rated rpm with the throttle fully open.

Variable Pitch (Constant Speed) Propellers

Advantages over Fixed Pitch Propellers

The power setting of a piston engine is defined by a combination of manifold pressure (boost) and rpm. Where separate Power Lever and rpm Lever control is provided, it is possible to vary one while leaving the other constant, so optimizing the operation of the engine/propeller combination to give best efficiency/fuel economy and least engine wear and tear.

In order to achieve this a "Variable Pitch" propeller must be used; enabling the pilot to select a propeller pitch and thus to vary rpm independently of manifold pressure, provided that the propeller is operating between its internal fine and coarse pitch stops.

Once an rpm has been selected, a control unit (CSU - Constant Speed Unit or PCU - Propeller Control Unit) will automatically vary the propeller pitch angle and therefore its angle of attack to the prevailing relative airflow in order to maintain the selected rpm despite airspeed and manifold pressure variations.

Variable pitch propellers can also incorporate a "Feathering" feature, the advantages of which will be discussed later in this chapter.

Alpha and Beta Range

Definitions

Referring to *Figure 12.8*, it can be seen that it is possible to provide a range of propeller blade angles ranging from "feathered", as coarse as it is possible to go, all the way to "reverse pitch", as fine as it is possible to go in normal propeller control.

The "Alpha" (flight) range of pitch angles ranges from "feathered" to "flight-fine" pitch, while the "Beta"(ground) range of angles is from "flight fine" pitch to "reverse" pitch.

The method of control within alpha and beta ranges will be described later in this chapter.

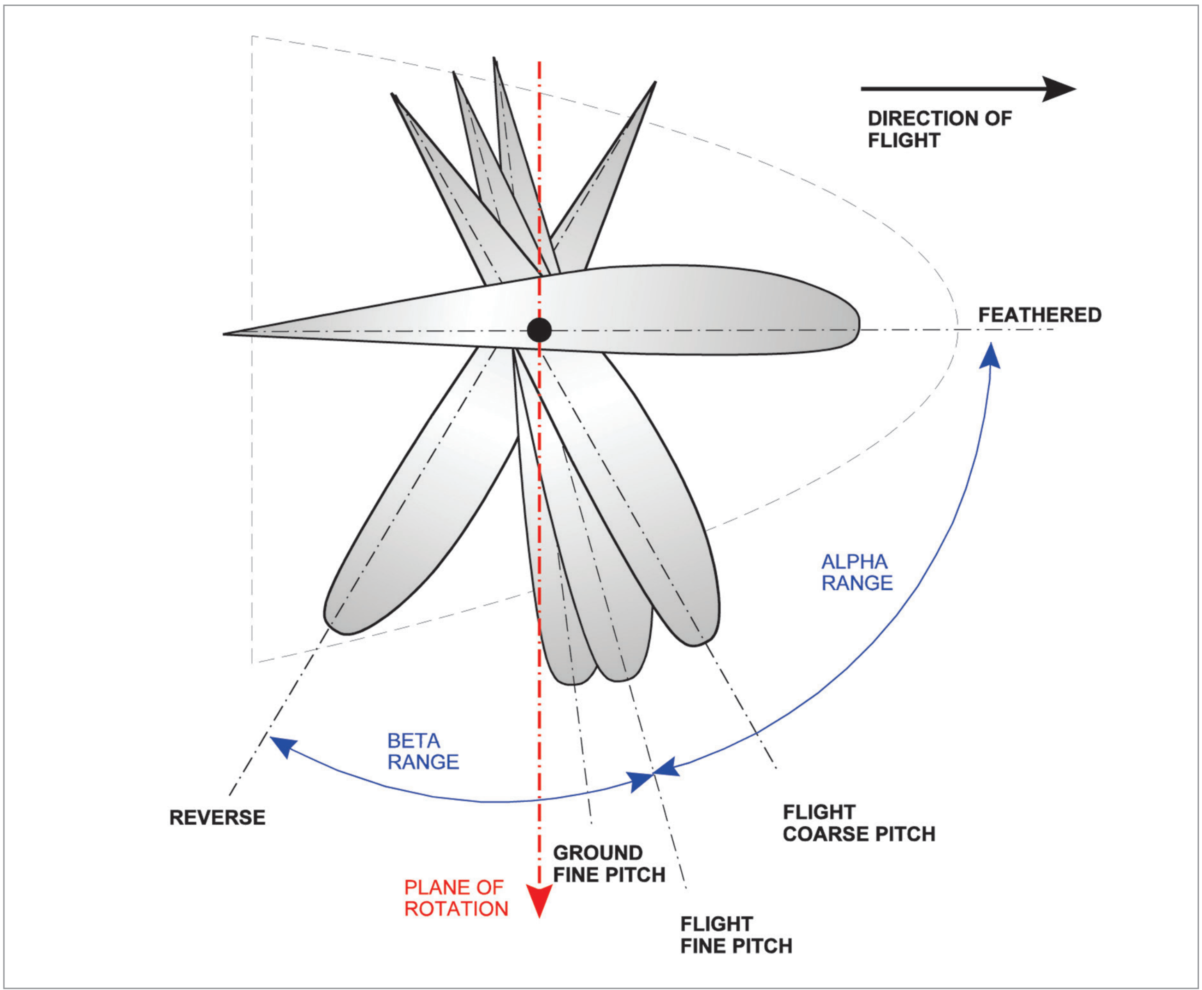


Figure 12.8 Alpha and Beta range.

Variable Pitch Propellers

The basic problem with varying pitch is twofold; one of actuation and one of control. The problem(s) and normal methods of solution will be examined in turn.

Actuation

Theoretically it should be perfectly possible to design either pneumatic or electrical actuation of a propeller's pitch change mechanism, the former is unknown and the latter quite rare.

The preferred method of pitch change actuation has turned out to be hydraulic, utilizing the engine's lubrication system as the source of hydraulic power. The pressure boosted where necessary by a small, additional oil pump mounted in the CSU or PCU.

Single Acting Propeller - Principle of Operation

A single acting propeller is constructed basically like any other, in that the blades are arranged around a central, engine-driven hub with the cylindrical hydraulic pitch-change mechanism mounted to the front.

The pitch change cylinder contains a moveable piston which is pushed rearwards by boosted engine oil pressure. Although it is possible to arrange things otherwise, usually this rearward movement of the piston will turn the propeller blades towards fine pitch. This is accomplished by a mechanical linkage behind the piston operating an actuating pin on the butt of each blade; off-set so as to impart the correct range of angular motion.

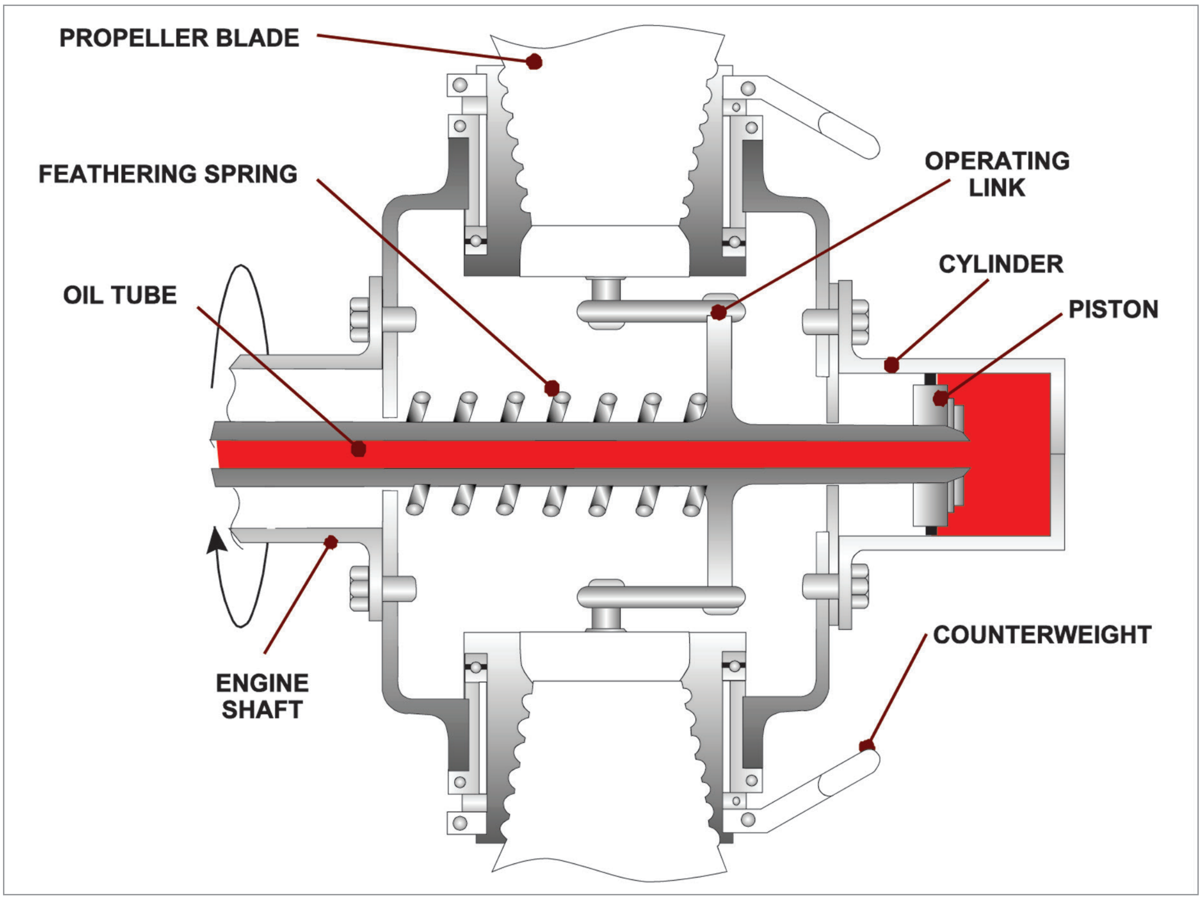


Figure 12.9 The single acting propeller

Blade rotation towards coarse pitch is provided by either a spring, or centrifugally actuated counter weights. Most propellers of this type, however, will contain both. Some propellers replace the spring with compressed gas, requiring a reversal of the hydraulic direction.

The springs have a dual function, they assist the centrifugal counterweights in operating the propeller blades to coarse pitch and, where this facility is provided, actuate the blades into the feathered position when rpm is low with consequent loss of centrifugal action.

CSU/PCU Functions (Figure 12.12 & Figure 12.15)

The function of the control unit in controlling rpm at the pilot's command is to control the oil flow in three modes:

- Oil supply to fine pitch. (rpm increases)
- Oil shut off/hydraulic lock. (rpm steady)
- Drain of fine-pitch oil back to scavenge. (rpm decreases)

Double Acting Propeller - Principle of Operation

The double acting propeller may be similar in mechanical operation to the single acting unit, or may achieve pitch angle change via a cam-slot operated, rotating bevel gear actuating bevel gear segments at the base of each blade.

The link operated mechanism will be used as the generic type for study purposes.

This type of propeller has a similar, if rather larger pitch change cylinder mounted to the front of the hub. It also contains a hydraulic piston, but this is now isolated from the centre of the hub and the fore-and-aft links provided with pressure seals. This allows hydraulic pressure to be directed to either side of the piston. Fine-pitch oil to one side and coarse-pitch oil to the other. Assistance from springs or centrifugal counter-weights is therefore not required.

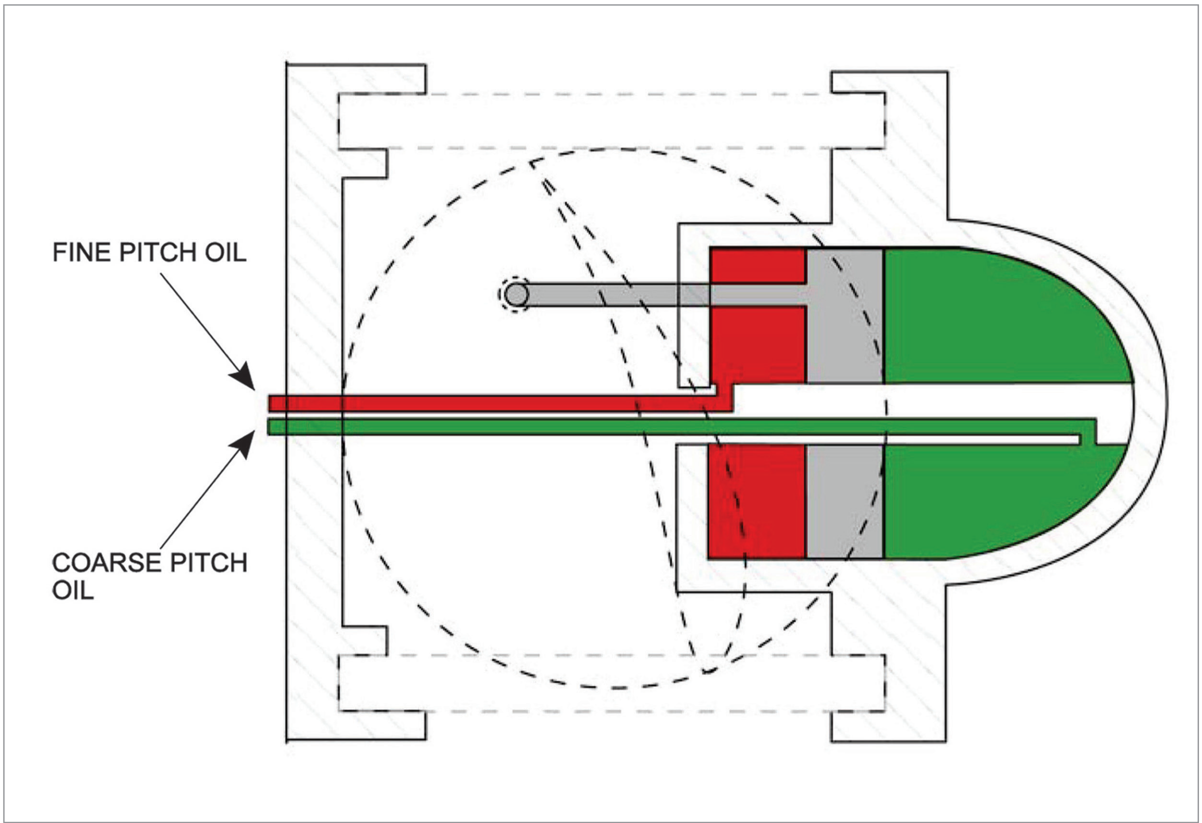


Figure 12.10 The double acting propeller.

CSU/PCU Functions (Figure 12.12 & Figure 12.15)

As with the single acting propeller's controller, there are three control modes for the CSU/PCU:

- Deliver fine-pitch oil. (Increase rpm). Allow drain of coarse-pitch oil.
- Oil shut off/hydraulic lock. (Constant rpm).
- Deliver coarse-pitch oil. (Decrease rpm). Allow drain of fine-pitch oil.

The Constant Speed Propeller - Operation

A constant speed propeller must be capable of all the pitch change operations mentioned above, as selected by operation of the rpm lever in the aircraft cockpit. It must also be capable of maintaining a selected rpm, within its own operational limits, through changes in airspeed, altitude and power setting.

When the CSU senses that rpm is as selected, no action ensues. However, changes in any of the above mentioned external conditions will result in a tendency to either increase rpm above, or decrease rpm below that selected.

A tendency for rpm to increase, an overspeed condition, must be met with a supply of oil to the coarse pitch side of the pitch change unit's piston. The pitch will then coarsen and propeller torque will rise as a result of the increase in the blade angle of attack. Propeller torque now exceeds engine torque and will cause rpm to decrease back to the selected setting. As rpm drops back to where it should be, the valve selection in the CSU which caused the oil flow in the first place must be removed progressively.

A tendency for the propeller to underspeed must be met with the opposite reaction. A supply of oil must be sent to the fine pitch side of the operating piston to decrease the propeller's pitch angle. This will decrease the propeller's torque. Engine torque now exceeds propeller torque, so rpm will tend to rise to regain the pilot's selection. When propeller torque equals engine torque, rpm remains constant.

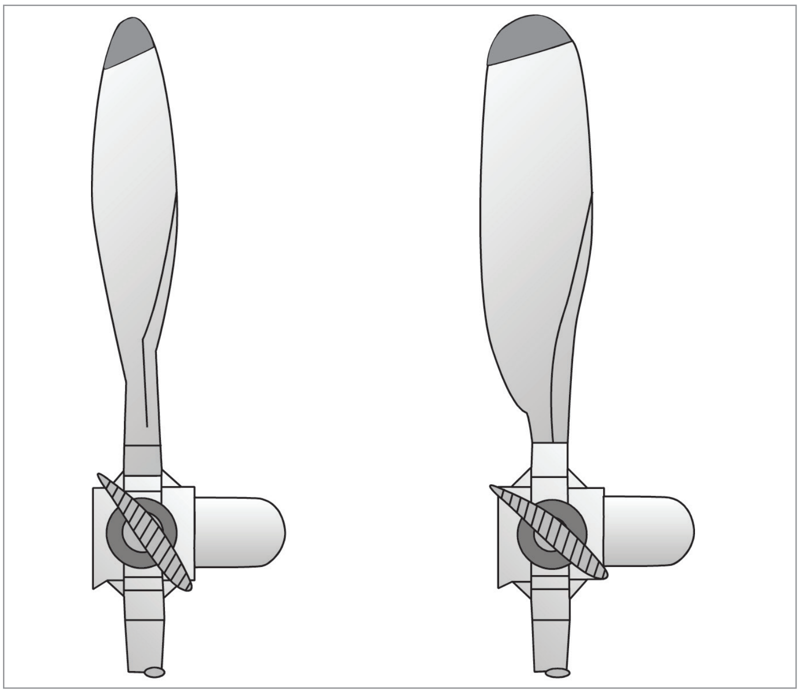


Figure 12.11 Propeller with various pitch angles.

The Simple Constant Speed Unit

Propeller pitch change and thus rpm are controlled by the Constant Speed Unit (CSU). This is engine driven and thus detects any changes to engine rpm so as to correct it via propeller pitch changes. Coarse pitch to correct an overspeed and fine pitch to correct an underspeed.

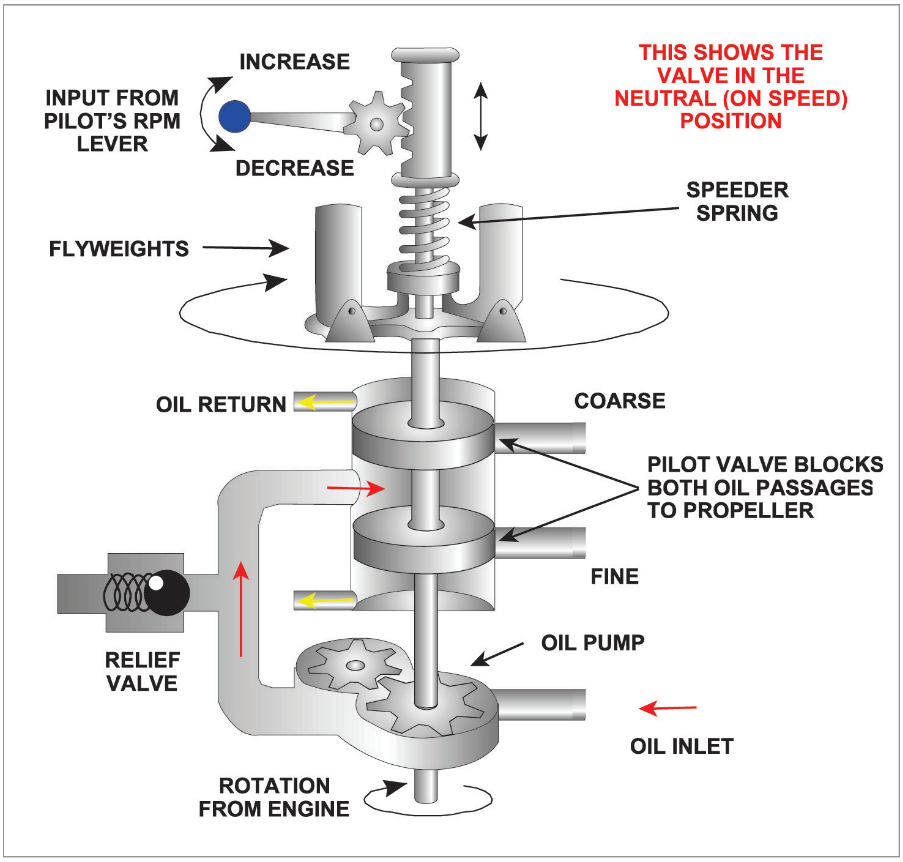


Figure 12.12 A simple constant speed unit.

A CSU is engine driven from a convenient gear, usually at the front of the engine, just behind the propeller itself. The drive shaft usually also drives a small oil pressure boosting pump to raise the pressure of the engine's own lubrication supply to a more useful figure. (120-200 psi would be satisfactory.)

The drive also rotates a centrifugal flyweight assembly in which the weights are "L" shaped and arranged to provide the upward movement of a double-landed hydraulic control valve. This upward force is opposed by a coil spring (speeder spring) acting downward on the control valve. This spring is arranged such that its compressive downward force may be adjusted through the up and down movement of a rack and pinion. The pinion is rotated by pilot operation of the rpm lever. Pushing the rpm lever forward will rotate the pinion so that the rack is pushed down, compressing the spring and tending to push down the control valve. Pulling the rpm lever to the rear will result in spring compressive force being reduced.

The "On Speed" Condition

The control valve receives pressure oil from the engine and the CSU booster pump and is arranged so that the oil is trapped and prevented from passing to the pitch change cylinder while the engine is "on speed" with no change of rpm selected. This is because the selected spring pressure downwards is exactly balanced by the flyweight force upwards as in *Figure 12.12*

The "Overspeed" Condition

Should the engine's torque exceed the torque generated by the propeller during flight, rpm would tend to rise. This will lead to a rise in centrifugally generated flyweight force and lift up the control valve against the spring force.

The rise of the control valve will expose the coarse pitch line to the pitch change cylinder so that pressure oil may flow to the coarse pitch side of the piston. At the same time, the fine pitch line is exposed and connected to drain.

The propeller blades will move towards coarse pitch, increasing their angle of attack to the relative airflow, generating more total reaction and thrust and raising the propeller's torque.

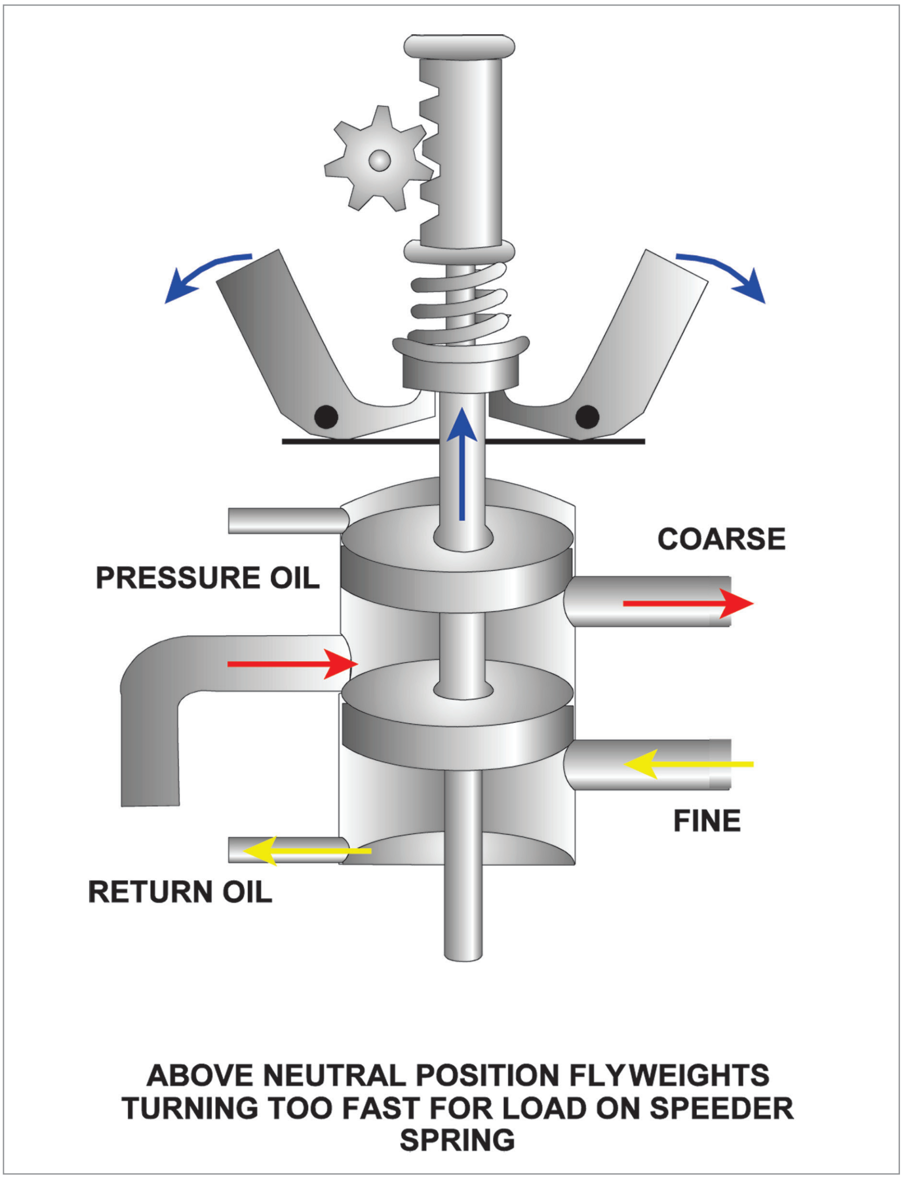


Figure 12.13 Overspeed condition.

When the propeller's higher torque matches the engine's torque, the rise in rpm will be arrested, the rpm returning to the selected setting. When this is achieved, the flyweights will fall back to their previous, balanced position with regard to spring force, the coarse and fine oil ports will close and the CSU resumes the "on speed" condition.

The "Underspeed" Condition

In this condition the propeller's torque exceeds the engine's torque, causing rpm to decrease. Centrifugal flyweight force will decline and the CSU's spring force will now exceed that produced by the flyweight assembly. The flyweights will collapse inwards. This will cause the control valve to be pushed down by the spring force, exposing the fine pitch oil port to pressure, while connecting the coarse pitch oil port to drain.

Pressure oil will now flow to the fine pitch side of the pitch change piston, moving the propeller blades to a smaller angle of attack to the relative airflow. This will, in turn, cause a decrease in total reaction, thrust and propeller torque.

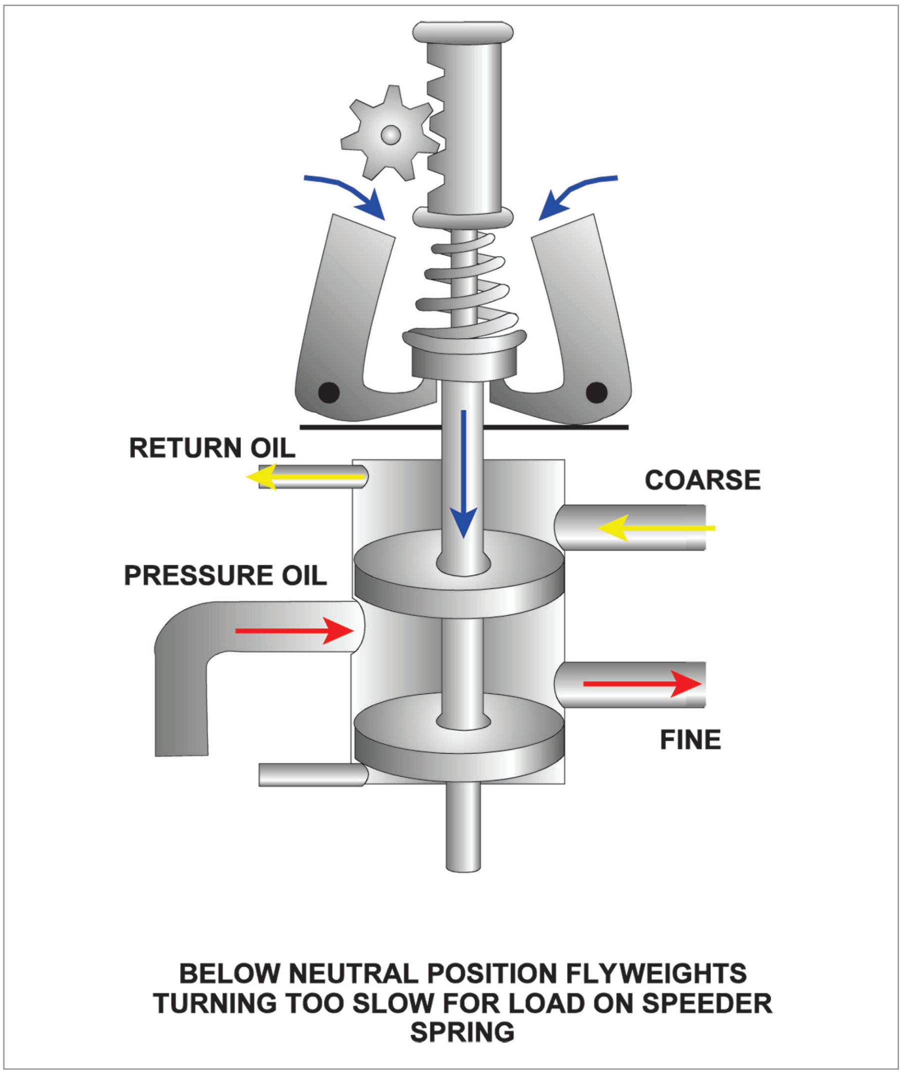


Figure 12.14 Underspeed condition.

The engine's torque will now exceed that produced by the propeller and rpm will tend to rise. This will produce a rise in propeller torque until it once again matches that of the engine. Flyweight force will also increase with the rise in rpm until it once again exactly balances the selected spring force. The control valve will be returned to the neutral position with both fine and coarse pitch ports closed off. The CSU and propeller are now back "on speed". The movement of the control valve during normal operation is very small and the change in propeller rpm is smooth and progressive.

Propeller Control Unit - PCU

This unit is generally similar to the basic CSU and controls a propeller in the same way. It is used with turboprop engines, particularly those controlled by a single flight deck lever instead of the more usual double presentation of separate power and rpm levers. As this single lever is connected to both the PCU and engine Fuel Control Unit (FCU), rpm and fuel flow are altered together. This enables the engine to overcome the combined inertia of propeller and compressor/turbine assembly together in a co-ordinated fashion, allowing rapid acceleration without the danger of over-stressing the turbine and other "hot end" components.

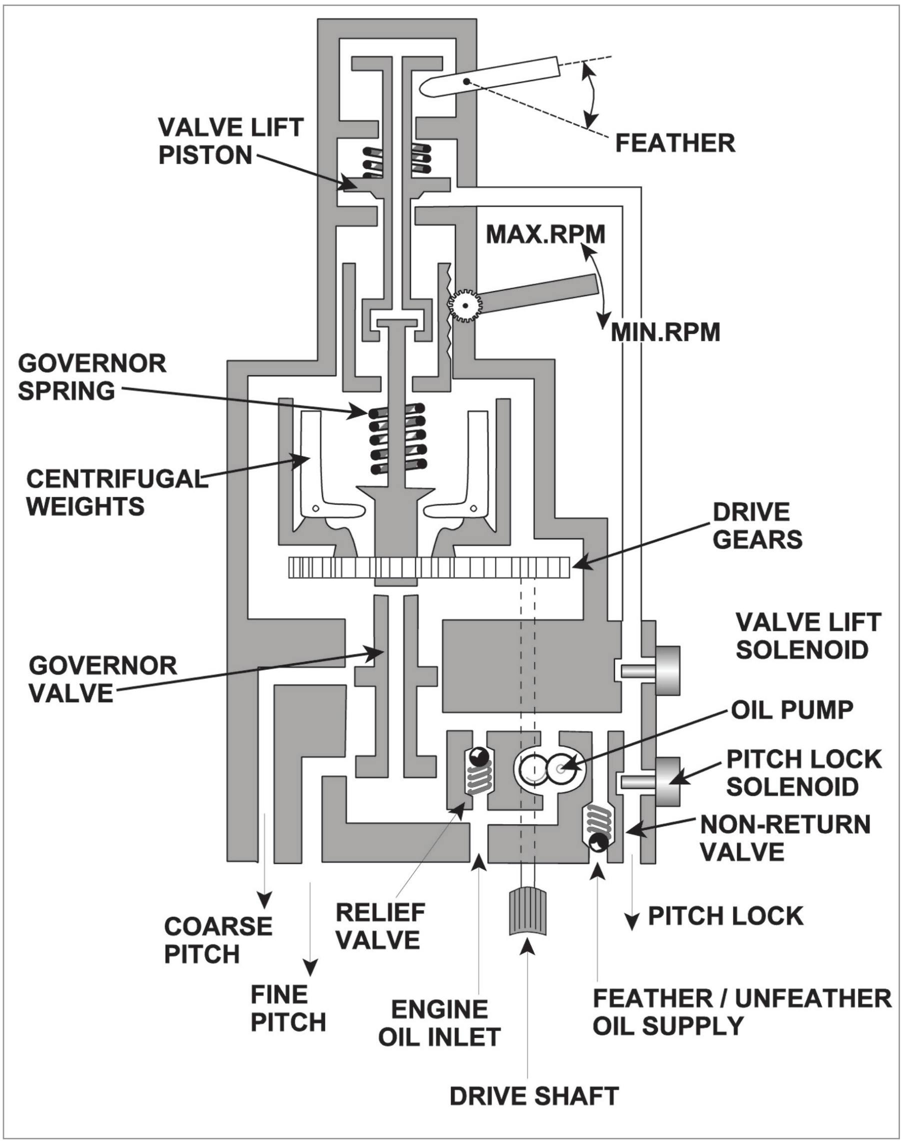


Figure 12.15 A PCU.

It can be observed from *Figure 12.15* above that the PCU contains a number of additional components when compared with a basic CSU.

Mechanical Feathering Lever

This lever is located in a PCU, above the standard components and is a means of mechanically lifting the control valve upward into the feather position when the engine high pressure (HP) cock is closed in flight.

Valve Lift Solenoid and Piston - Autofeathering

In the event of a low torque signal in the engine's torque meter system, coupled with a high power selection, a turboprop's propeller is usually furnished with the means to feather itself. "Autofeather". This leaves the pilot free to concentrate on controlling the aircraft, which may be close to the ground during take-off or go-around.

The PCU has a "Valve Lift Solenoid" which is energized at the same time as a separate feathering pump's electric motor is energized. The separate feathering oil supply is now able to go to the valve lift piston, raising the control valve into an exaggerated coarse pitch (feather) position. The feathering oil supply can now go to the coarse pitch side of the pitch change piston, pushing it onto the feathering stop as the fine pitch oil drains away. The feathering stop is an internal stop, within the pitch change mechanism, which coincides with that blade position, edge-on to the aircraft's airflow, which will generate zero aerodynamic force in either direction. The propeller will stop, unless some drive force is applied.

Pitch Lock Solenoid - Ground Fine and Reverse Pitch

Many turboprop and a few high-powered piston engined aircraft are provided with a means to aerodynamically reverse the pitch of their propellers or to select a super-fine pitch, (ground fine), several degrees finer than the finest pitch available in flight (flight fine). This latter being confined to those turboprops whose gas generator spool and propeller drive are physically connected.

The mechanical details within the pitch change mechanism will be discussed later, but the PCU contains a "Pitch Lock Solenoid" which, when energized will allow pressure oil to flow directly to the pitch lock mechanism within the pitch change cylinder. So effecting the change from flight fine to ground fine pitch or, where so provided, opening the way to the reverse pitch range.

Feathering and Unfeathering

Should one of the engines on a multi-engine aircraft fail, its CSU would sense a drop in engine torque and rpm and, operating normally, would drive the propeller on that engine towards fine pitch in an effort to keep the rpm up to the selected level.

This would result in the propeller being put into a "windmilling" situation; with its pitch change piston sitting on the flight fine pitch stop. The first result would be a very large asymmetric drag, leading to a violent yaw towards the failed engine. Secondly, if the engine was to continue to turn, driven by the propeller, it would be in serious danger of complete mechanical breakdown and possibly fire.

So, to minimize drag and prevent further damage the propeller is provided with a means to turn the blades into an edge-on, null position where no aerodynamic force is generated either forwards or backwards. This is called "Feathering" the propeller.

In normal circumstances there would, of course, be no requirement to unfeather a failed engine. What would be the point? However, aircraft manufacturers, mindful of the large market for training aircraft worldwide, will usually provide an unfeathering facility in order that asymmetric flight may be practised during training.

Feathering and Unfeathering a Single Acting Propeller

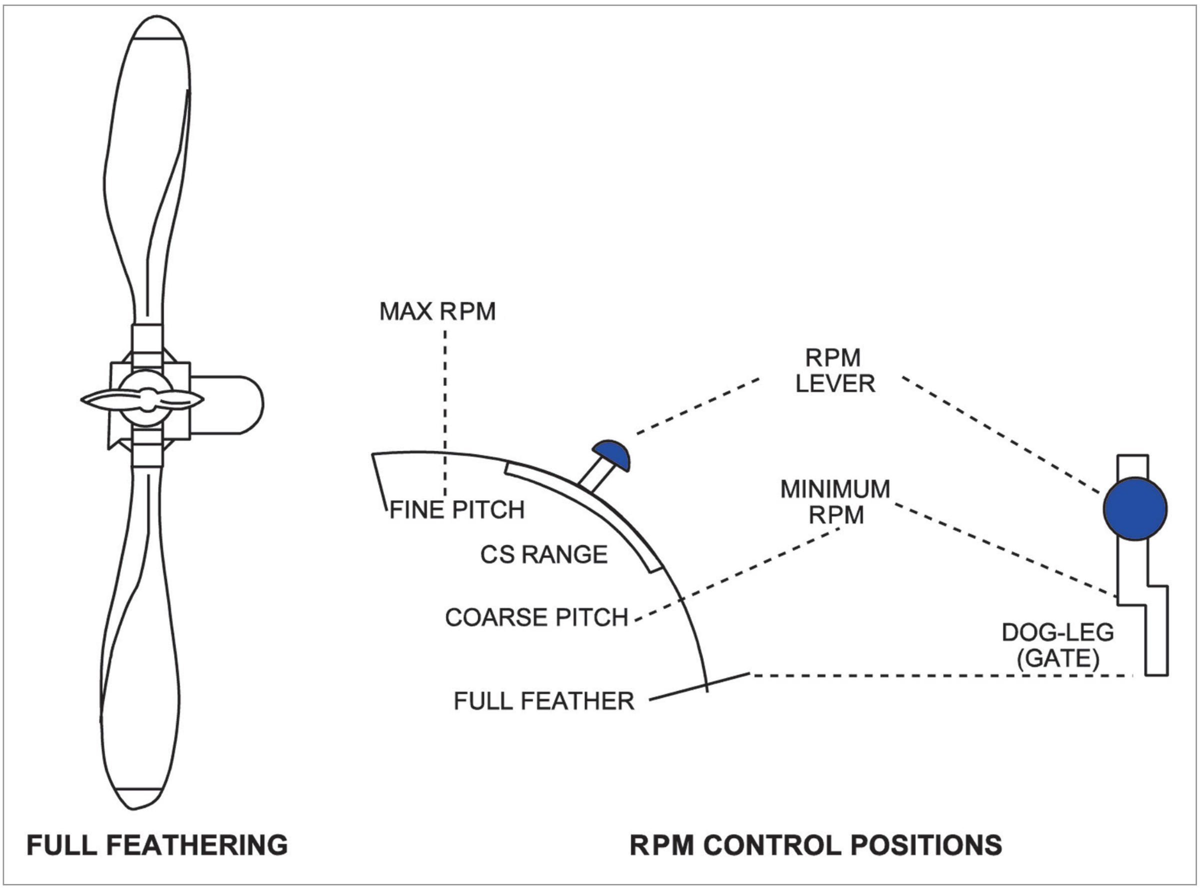


Figure 12.16 Feathered propeller & prop control gate showing feather.

Feathering - Single Acting Propeller

To feather a single acting propeller, the propeller (rpm) control lever is moved fully to the rear and then dog-legged to one side or pushed inward (according to the particular linkage) to allow a further rearward movement into the "feathered" position.

This raises the rack in the CSU as far as it will go, simulating an exaggerated "overspeed" condition by removing all loading from the speeder spring and allowing the flyweights to fly right out if the engine is running and lifting the control valve right up. Most CSUs cater for the engine stopped situation (zero flyweight force) by arranging that a full feather selection will bypass the speeder spring to physically lift the control valve upwards.

Any oil in the pitch change cylinder can now drain away allowing the counter weights, if the engine is turning, or, the spring if not, to push the piston onto the feathering stop.

Unfeathering - Single Acting Propeller

The speeder spring is given some pressure by moving the propeller lever to a position parallel with the lever of the operating engine. This moves the control valve down, ensuring that any pressure oil will be directed to fine pitch. It is common practice, where single acting propellers are used to provide a reserve of pressurized oil in an accumulator; trapped by a non-return valve and released by a solenoid operated valve.

The oil is released into the CSU by energizing the solenoid via a cockpit mounted button. The oil will force the piston off the feather stop towards fine pitch. As soon as there exists an angle of attack to the aircraft's relative airflow, aerodynamic reaction will cause the propeller and engine to turn. Ignition and fuel, in accordance with the operating manual, are all that are required to achieve restart.

By not placing the propeller control lever to its maximum rpm setting, a violent over-swing in yaw is prevented as the engine power is restored.

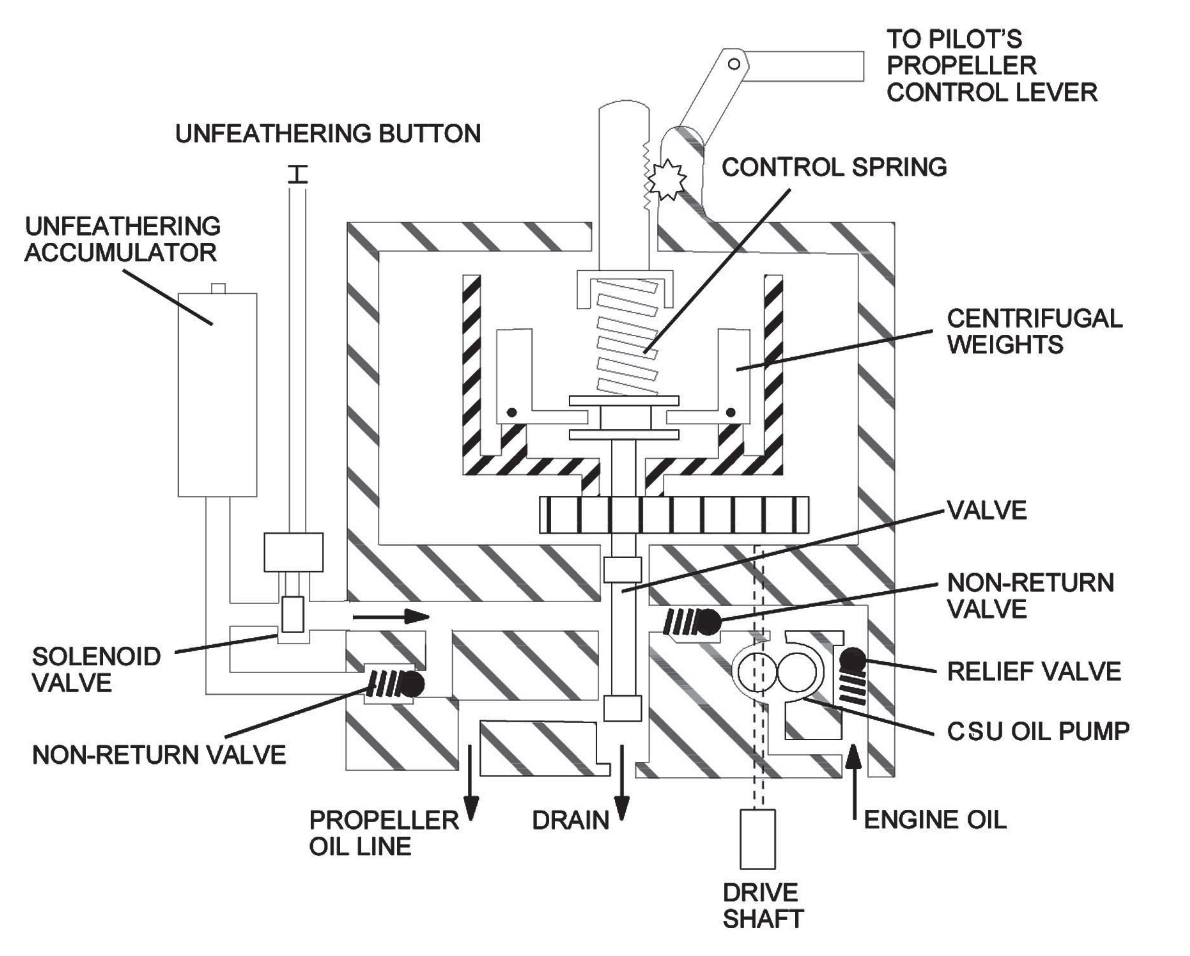


Figure 12.17 CSU with unfeathering accumulator

Centrifugal Latch (Feathering Stop)

When an aircraft with a single acting propeller is stopped on the ground after flight, the propeller will be in fully fine pitch. There is a considerable quantity of pressure oil trapped in the fine-pitch side of the pitch change cylinder, holding the propeller in the fully fine position, but opposed by the force of the feathering spring. After shutdown, the trapped pressure will gradually leak away through the fine clearances of the CSU control valve. The feathering springs will gradually push the propeller blades towards the fully feathered position overnight.

While this condition would be acceptable on a free turbine turboprop, this would result in an unacceptably high loading on the engine starter motor for a piston engine. To prevent this, centrifugal latches, disengaged with the engine running, will be engaged at an rpm below the manufacturer's chosen setting, typically 700 rpm. This latch assembly engages latch pins attached to the rear of the pitch change piston after forward movement equivalent to about

5° of blade angle, preventing it from being pushed further forward and into the feathered position by the feathering spring.

When the engine is started, oil pressure will quickly build up and re-position the propeller pitch-change piston onto the fine pitch stop, moving the blades to fully fine pitch. Centrifugal force will disengage the latch system as rpm is raised through 700, up to warm-up setting - 1100 - 1200 rpm.

When centrifugal latches are fitted, it is not possible to feather a failing engine once rpm has fallen below the latch setting. It is thus important to complete the feathering drill before this occurs.

Feathering - Double Acting Propeller

As a double acting propeller has no mechanical assistance from counterweights, springs etc., all actuation must be hydraulic. Reference to *Figure 12.18* below shows that a protected source of feathering oil is provided. Usually as an isolated part of the main oil tank in a dry-sump lubrication system. This oil is sent to the propeller by an electrically driven "Feathering Pump".

The pilot's basic control selection for feathering the propeller remains the same. The rpm lever is brought back to full coarse, then the feathering stop/gate is negotiated and the lever taken further back into the "feather" position. This lifts the CSU/PCU control valve fully upwards, ensuring oil feed to the coarse pitch side of the pitch change piston and drain from the fine pitch side. The "Feather" button in the cockpit is pushed in, energizing a button hold-on relay and, in turn, the feathering pump relay to drive the pump.

Feathering oil now passes through the CSU/PCU, pushing the pitch change piston onto the feathering stop. Oil pressure will now build up, operating a pressure operated cut-off switch (often called the POCOS) which will interrupt supply to the button hold-on coil. The feathering button releases, de-energizing the feathering pump relay and the pump stops.

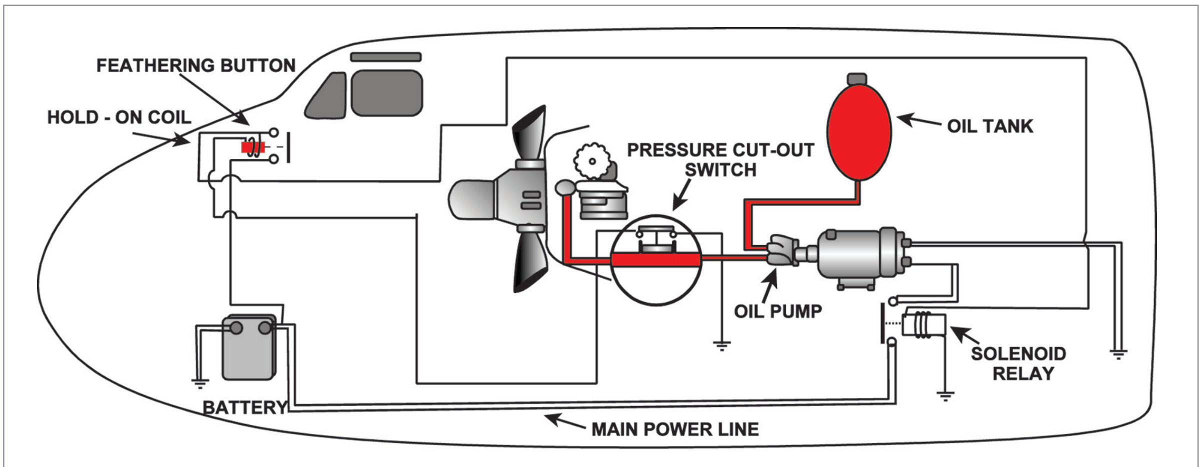


Figure 12.18 Typical feathering installation.

Unfeathering - Double Acting Propeller

As any aero-engine if free to rotate, will unfeather itself by windmilling action, all that is required is that the blades are moved a few degrees away from the feathered position. The rpm lever is taken out of the feathering gate and placed alongside the lever of the other, live engine(s). This pressurizes the speeder spring and pushes the control valve down to arrange fine pitch supply and coarse pitch drain. The feathering button is now pressed to run the feathering pump. Once windmilling has started, the button needs to be physically pulled out, overcoming the hold-on coil and thus stopping the pump. The rest of the restart drill is accomplished in accordance with the aircraft operating manual.

Beta Range Operation

Some turboprop engines are provided with a system of control defined by “Alpha” and “Beta” ranges of propeller operation. The Alpha range is used at high speed during the take-off run, in flight and during the initial, high speed part of the landing roll-out. The Beta range, however, is used only on the ground. It is selected during the landing roll-out by removal of the flight fine pitch stop inside the propeller’s pitch change cylinder.

Most propellers make this selection via a lever on the central control console, sometimes the throttle lever. Warning lights then illuminate to indicate that all propellers have carried out the selection, which is merely to move to a much finer pitch setting termed “Ground Fine Pitch”. There will be a significant aerodynamic braking effect as the propeller goes into ground fine pitch. Power control is normal while taxiing and during the initial part of the take-off run. Later in the take-off run, however, the normal process of pitch coarsening with increasing TAS will cause the “Flight Fine Pitch” stop (inside the pitch control unit) to re-engage automatically.

Later propellers may be equipped with a much greater range of blade movement in the Beta range. Extending from around +8° to -3° pitch (full reverse), it is similarly selected at the same time as the older system, i.e. during the high-speed, initial part of the landing roll-out. In this case however, the braking effect from reverse pitch is much better than would result from merely ground fine.

When the flight fine pitch stop is withdrawn, the power lever can be moved rearward, through the gate into the Beta range. Weight-on-wheels switches ensure that this can only happen on the ground. With the propeller (rpm) lever left at fully fine (max. rpm), the Beta range is controlled by rearward movement of the power lever. Pitch is increasingly made more negative as power is increased. Rpm varies with PCU governor control being over-ridden as the power levers are so arranged as to raise and lower the PCU control valve to obtain the pitch changes required. A mechanical feed-back system resets the control valve to neutral once the required pitch angle has been obtained.

While the propeller blades are transiting into the reverse position, the PCU speeder spring is pushed downwards to give a downward selection of the control valve. This simulates an underspeed, ensuring that any pressure oil will be sent to the fine pitch side of the pitch change piston. The follow-up cam on the blade root via a yoke, cam and beam linkage will remove the control valve selection when the desired blade angle has been achieved.

Synchronizing

In order to reduce tiring noise and vibration on propeller driven aircraft, the engine/propeller assemblies are often provide with a means to equalize the rpm. A Synchronization system will reduce the annoying “beat frequency” and lower noise levels significantly.

The aircraft will have a designated “Master Engine” whose PCU can generate an rpm signal to a control unit also receiving rpm signals from the other “slave” engines. When the synchronizing system is engaged, any rpm differences between the master and slave engines will be sensed by the control unit. This generates proportional, positive or negative current output to torque motors mounted on the slave PCUs; such that lower rpm will cause the torque motor to turn one way, while higher rpm will cause a rotation of the torque motor in the opposite direction.

The torque motor rotation will reset the speeder spring to ensure a correction to slave rpm. When no difference in rpm exists between "master" and "slave", no output is sent to the slave torque motors. Many aircraft are provided with a visual indication (synchroscope) of slave engine rpm differences in the form of miniature propellers which only rotate when an rpm difference exists.

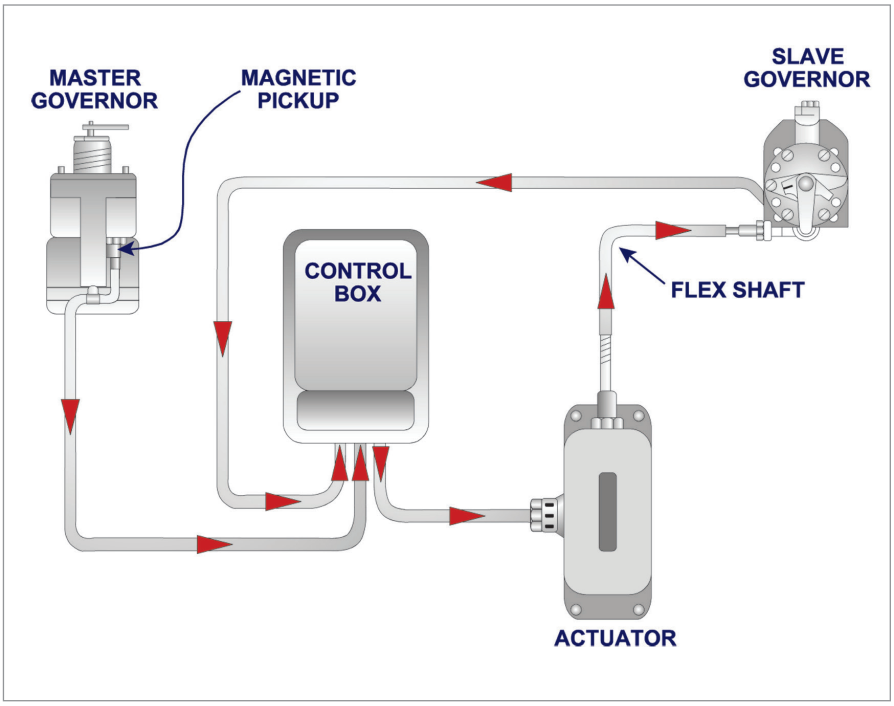


Figure 12.19 Woodward synchronization system for a light twin

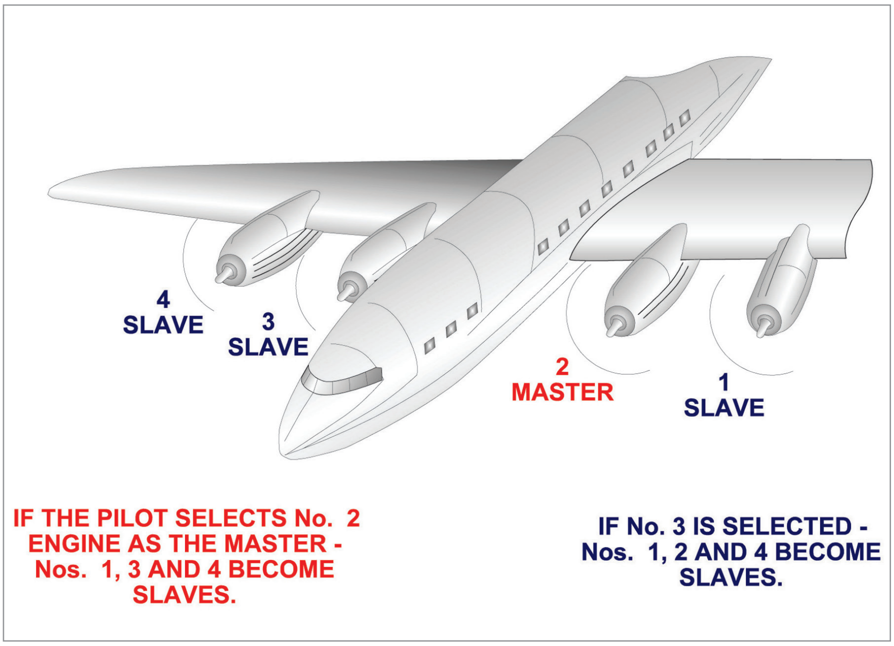


Figure 12.20 The master engine arrangement of a transport aircraft

Synchrophasing

A further significant improvement in noise levels can be obtained by ensuring that adjacent propeller tips are separated by some optimum angle to prevent noisy interference. Some aircraft provide the pilot with a means of manually "fine tuning" this angle to obtain the quietest result.

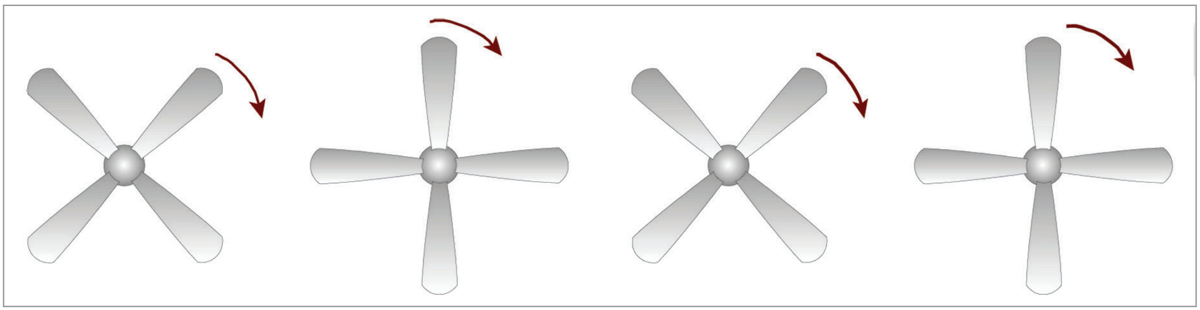


Figure 12.21 Synchrophasing positions

Reduction Gearing

Purpose
Where a powerful aero-engine needs a large propeller to convert its power into thrust, too large a diameter would bring the risk of sonic compressibility and blade flutter if the propeller were rotated too fast.

In order to be able to use a large diameter propeller, the engine, turning at its maximum rpm, cannot be directly connected to the propeller; so the drive speed must be reduced to a more suitable level by a reduction gear placed in the driveline between engine and propshaft.

Reduction Gear Types

Parallel Spur Gear
This type of reduction gear, while mechanically simple and relatively cheap to produce, takes up a lot of room at the front of the engine as the axes of the gears are parallel. It has been used mostly on V type, in-line, water-cooled engines. e.g. Rolls Royce Merlin and Griffon.

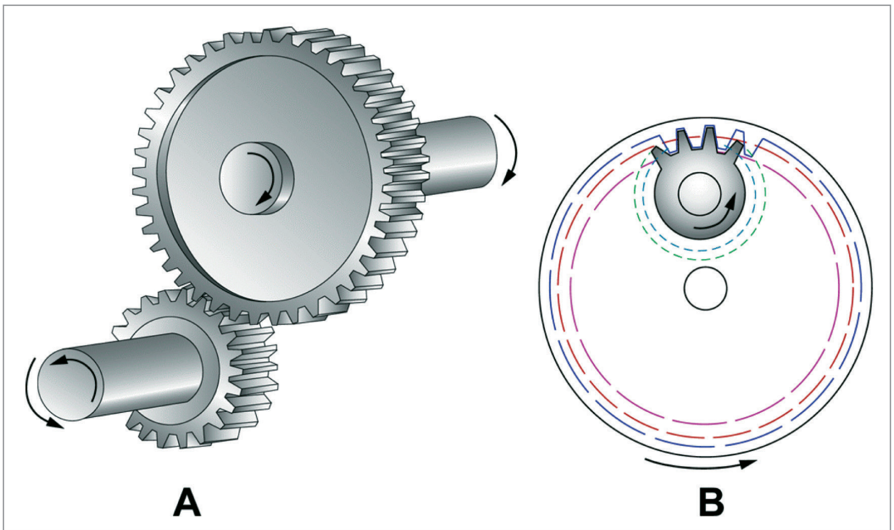


Figure 12.22 Two types of spur type reduction gear arrangement

Epicyclic Reduction Gear

This layout is quite compact and has the advantage of concentric layout. Everything rotating about the same centre line. The gears may be straight cut, bevelled, or helically cut to impart a degree of end-thrust which, being proportional to the torque passing through to the propeller, may be used to provide a torque indication system in the engine's instrumentation.

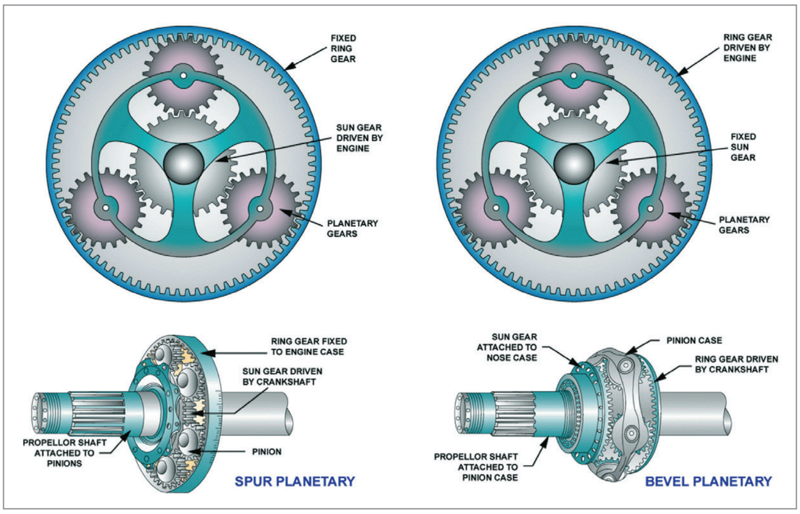


Figure 12.23 Spur & bevel planetary gears

Torque Meter

Purpose

The torque meter is provided to give the pilot information about the amount of power he is deploying from his engines during any phase of flight. It may be calibrated in torque units such as pounds feet (lb.ft) or newton metres (Nm), Percentage (%) or pounds per square inch (psi), or any other suitable unit of power.

Operation

There are two main varieties of torque signalling systems:

- **Electronic** - where the twist of an intermediate drive shaft, being proportional to the transmitted power, is measured electronically and the angle signal used to drive the torque meter. This is inherently lighter and more reliable than other types.

- **Oil pressure** - where the end thrust of a helically cut planet wheel or the torque reaction of a ring gear is used to alter the oil pressure of the torque transmission system. This pressure is then read off on the torque meter gauge. *Figure 12.24* shows the ring gear system.

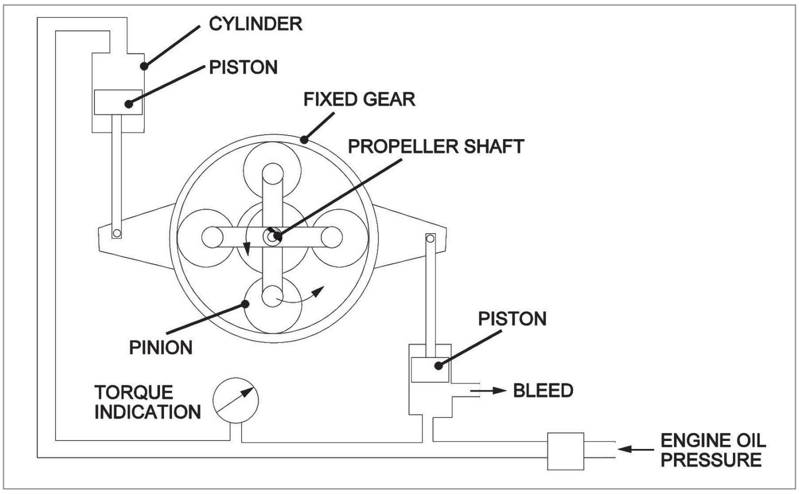


Figure 12.24

When the engine is running, the pinions (planet gears) are being driven around the stationary gear by the central input shaft from the engine. The thrust reaction to the pinion's movement will try to rotate the stationary gear backwards.

The stationary gear is allowed to float, its movement being opposed by oil pressure generated by the torque meter pump. Within cylinders, exposed to torque meter pump output, two pistons are operated by lever arms attached to the "stationary" gear. One of the pistons partially covers a bleed port.

Under low power conditions, the bleed orifice is at maximum area so that torque meter oil pressure is balancing the thrust on the stationary gear. Increased power tends to try to rotate the stationary gear, forcing the pistons further into the cylinders. This reduces the bleed orifice area as well as physically pressurizing the oil. The effect being to raise oil pressure as a function of propeller torque to balance the thrust on the stationary gear.

Checks to Be Carried out on a Propeller after Engine Start

Introduction

The checks to be carried out and the methods used will vary from aircraft type to aircraft type and from propeller type to propeller type. In addition to the checks to be described, it should be remembered that there are many other checks carried out on propellers. Most of them are maintenance orientated, but of course, a pilot is responsible for a thorough pre-flight visual inspection of the propeller before engine start-up.

Single Acting Propeller - PA34-200T SENECA Aircraft

After start-up, the engine oil must be warmed up to the level prescribed in the operating manual before any checks are commenced. The checks form part of the normal "after start" and "before take-off" checks.

The first check is a part of the "Power Check":

Throttle . . . . 1900 rpm

Propeller (rpm lever) . . . . EXERCISE
Check - rpm drops when min rpm selected.
rpm returns to 1900 when max rpm selected.
Repeat.

Throttle . . . . 1500 rpm

Propeller Feathering. . . . . CHECK

Throttle . . . . CLOSE/SET 1200 rpm

"Before Take-off"

Propellers . . . . MAX rpm

Propeller De-icing . . . . AS REQUIRED

If icing condition expected during or immediately after take-off:

Select - ON

Check - Propeller de-icing ammeter.

- Both alternator ammeters.

Double Acting Propeller

The checks to be carried out are much the same. There will, of course, be detail differences in basic rpm settings etc., but the object will be the same. To ensure rapid response to rpm control lever signals.

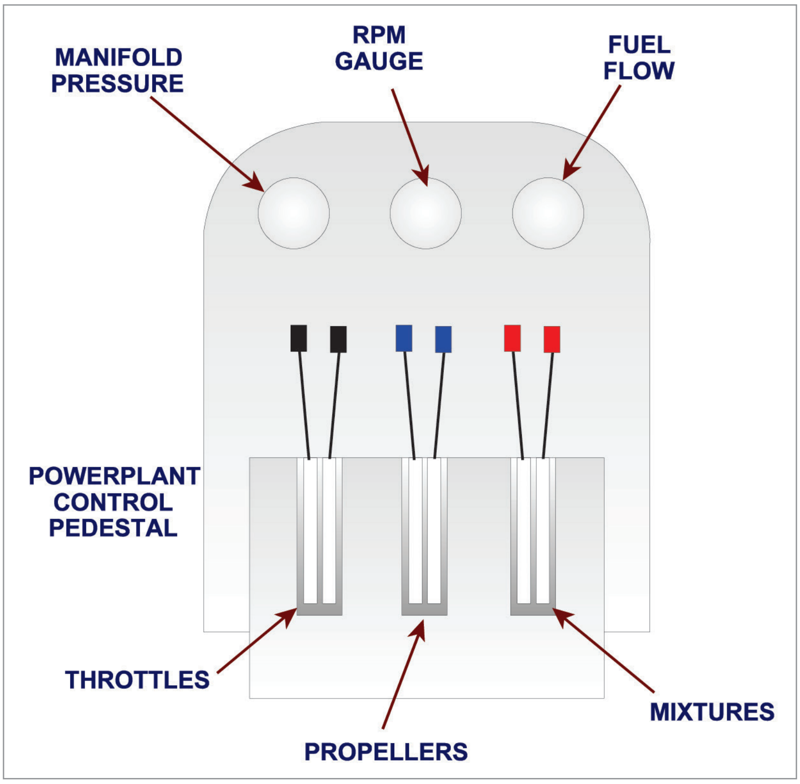


Figure 12.25 A typical light twin powerplant controls arrangement

It is necessary, once the lubricating oil in the main engine has warmed sufficiently, to exercise the pitch change mechanism. This will evacuate the cold, sluggish oil from the pitch change cylinder and purge it from the CSU and oil passages.

As with the Seneca, once the oil has warmed, there will be an engine test procedure which will involve causing the pitch change piston to traverse from the fine-pitch stop to the feathering stop more than once. With a double acting propeller, there is not only double the amount of actuating oil in circulation, but also an extra system to check. The correct functioning of the feathering pump may have to be ascertained, along with the functioning of the pressure operated cut-out switch.

Diesel Engines

The diesel engine generally runs at a lower rpm and higher torque than a conventional engine. The good torque outputs translate into greater static-thrust values allowing the aircraft greater take-off performance levels.

These features also allow the use of Constant Speed Propellers with typically more blades than a conventional gasoline powered unit.

Gearboxes may be used to ‘step-down’ the engines output rpm to match engine/propeller performances. Propeller-control in the modern diesel is co-ordinated with the fuel delivery by means of a ‘single-lever’ concept similar in principle to the turbo-prop.

Fuel scheduling, propeller pitch, torque-monitoring and other parameters are controlled electronically by the FADEC unit.

Questions - Propellers

1. **The blade angle of a propeller is the angle between:**

   a. the root chord and the tip chord of the propeller
   b. the chord and the airflow relative to the propeller
   c. the chord of the propeller and the longitudinal axis of the aircraft
   d. the propeller chord and the plane of rotation of the propeller

2. **The blade angle:**

   a. is constant along the propeller blade
   b. decreases from root to tip
   c. increases from root to tip
   d. varies with changes in engine rpm

3. **The geometric pitch of a propeller is:**

   a. the distance it would move forward in one revolution at the blade angle
   b. the angle the propeller chord makes to the plane of rotation
   c. the distance the propeller actually moves forward in one revolution
   d. the angle the propeller chord makes to the relative airflow

4. **A right hand propeller:**

   a. rotates in a clockwise direction when viewed from the rear
   b. is a propeller fitted to the right hand engine
   c. rotates in an anti-clockwise direction when viewed from the rear
   d. is a propeller mounted in front of the engine

5. **The angle of attack of a fixed pitch propeller:**

   a. depends on forward speed only
   b. depends on forward speed and engine rotational speed
   c. depends on engine rotational speed only
   d. is constant for a fixed pitch propeller

6. **During the take-off run a fixed pitch propeller is:**

   a. at too coarse an angle for maximum efficiency
   b. at too fine an angle for maximum efficiency
   c. at the optimum angle for efficiency
   d. at the optimum angle initially but becomes too coarse as speed increases

7. **For an aircraft with a fixed pitch propeller, an increase in rev/min during the take-off run at full throttle is due to:**

   a. an increase in propeller blade slip
   b. the engine overspeeding
   c. a more efficient propeller blade angle of attack
   d. the propeller angle of attack increasing

8. An aircraft with a fixed pitch propeller goes into a climb with reduced IAS and increased rev/min. The propeller:

a. angle of attack will decrease
b. pitch will decrease
c. angle of attack will increase
d. angle of attack will remain the same

9. For an aircraft with a fixed pitch propeller, propeller efficiency will be:

a. low at low speed, high at high speed
b. high at low speed, low at high speed
c. constant at all speeds
d. low at both low and high speed, and highest at cruising speed

10. The blade angle of a fixed pitch propeller would be set to give the optimum angle:

a. during take-off
b. during the cruise
c. at the maximum level flight speed
d. for landing

11. Propeller torque results from the forces on the propeller:

a. caused by the airflow, giving a moment around the propeller's longitudinal axis
b. caused by centrifugal effect, giving a moment around the propeller's longitudinal axis
c. caused by the airflow, giving a moment around the aircraft's longitudinal axis
d. caused by centrifugal effect, giving a moment around the aircraft's longitudinal axis

12. The thrust force of a propeller producing forward thrust:

a. tends to bend the propeller tips forward
b. tends to bend the propeller tips backward
c. tends to bend the propeller in its plane of rotation
d. causes a tension load in the propeller

13. A propeller which is windmilling:

a. rotates the engine in the normal direction and gives some thrust
b. rotates the engine in reverse and gives drag
c. rotates the engine in reverse and gives some thrust
d. rotates the engine in the normal direction and gives drag

14. For an aircraft with a right hand propeller the effect of slipstream rotation acting on the fin will cause: (see Chapter 16, Book 13 Principles of Flight).

a. yaw to the left
b. roll to the left
c. yaw to the right
d. nose up pitch

15. **To counteract the effect of slipstream rotation on a single engine aircraft:**

a. the fin may be reduced in size
b. a “T” tail may be employed
c. the fin may be off-set
d. the wings may have washout

16. **The gyroscopic effect of a right hand propeller will give: (see Chapter 16, Book 13 Principles of Flight)**

a. a yawing moment to the left whenever the engine is running
b. a yawing moment to the left when the aircraft rolls to the right
c. a nose-up pitch when the aircraft yaws to the right
d. a yaw to the right when the aircraft pitches nose up

17. **The alpha range of a variable pitch propeller is between:**

a. feather and flight fine pitch stop
b. feather and ground fine pitch stop
c. flight fine pitch stop and reverse stop
d. ground fine pitch and reverse stop

18. **When the CSU is running “on speed”:**

a. the governor weight centrifugal force balances the CSU spring force
b. the CSU spring force balances the oil pressure
c. the governor weight centrifugal force balances the oil pressure
d. the supply of oil to the CSU is shut off

19. **If the engine power is increased with the propeller lever set then:**

a. the governor weights move out, blade angle decreases, rpm decreases, weights remain out
b. the governor weights move in, blade angle increases, rpm decreases, weights move out
c. the governor weights move out, blade angle increases, rpm decreases, weights move in
d. the governor weights move out, blade angle increases, rpm decreases, weights move in, blade angle decreases again

20. **The purpose of the centrifugal feathering latch on a single acting propeller is to prevent:**

a. CTM turning the propeller to fine pitches
b. the propeller from accidentally feathering at high rpm
c. the propeller from feathering on shutdown
d. the propeller from overspeeding if the flight fine pitch stop fails to reset

21. **A hydraulic accumulator may be fitted to a single acting propeller to provide pressure for:**

a. normal constant speed operation of the propeller
b. operation of the propeller in the event of failure of the CSU pump
c. feathering and unfettering the propeller
d. unfettering the propeller

22. If it is required to increase the rpm of a variable pitch propeller without moving the power lever, the propeller lever must be moved:

a. forward, the governor weights move inwards, blade angle increases
b. backward, the governor weights move outwards, blade angle decreases
c. forwards, the governor weights move inwards, blade angle decreases
d. forwards, the governor weights move outwards, blade angle decreases

23. The CSU incorporates an oil pump. Its purpose is:

a. to provide pressure to feather the propeller
b. to provide pressure to unfeather the propeller
c. to increase the engine oil pressure to a higher pressure to operate the propeller pitch change mechanism
d. to ensure adequate lubrication of the CSU

24. A propeller blade is twisted along its length:

a. to compensate for the Centrifugal Twisting Moment
b. to maintain a constant angle of attack from root to tip of the blade
c. to increase the thrust given by the tip
d. to maintain constant thrust from root to tip

25. Propeller torque is:

a. the tendency of the propeller to twist around its longitudinal axis
b. the helical path of the propeller through the air
c. the turning moment produced by the propeller about the axis of the crankshaft
d. the thrust produced by the propeller

26. The greatest stress on a rotating propeller occurs:

a. at the tip
b. at about 75% of the length
c. at the mid point
d. at the root

27. The Beta range of a propeller is from:

a. the feather stops to the flight fine pitch stop
b. the feather stops to the ground fine pitch stop
c. the feather stops to the reverse pitch stop
d. the flight fine pitch stop to the reverse pitch stop

28. An 'auto-feathering' system senses:

a. low rpm
b. decreasing rpm
c. high torque
d. low torque

29. **What happens to the pitch of a variable pitch propeller in order to maintain constant rpm when (i) IAS is increased and (ii) Power is increased?**

	(i)	(ii)
a.	increases	decreases
b.	decreases	increases
c.	increases	increases
d.	decreases	decreases

30. **Propellers may have an 'avoid' range of rpm:**

a. to avoid resonance peaks which could lead to fatigue damage to the propeller
b. to avoid excessive propeller noise
c. because the engine does not run efficiently in that rpm range
d. to avoid the possibility of detonation occurring in the engine

Questions - Piston Engine General Handling

1. **What is the preferred direction for aircraft parking prior to start-up?**

   a. Tail into wind
   b. Nose into wind
   c. 1st engine to be started on windward side
   d. Facing towards the duty runway threshold to enable easy taxi-out

2. **Prior to starting a piston aero-engine (in-line inverted) and after ensuring that the ignition is "OFF", which check may have to be carried out?**

   a. Check that the pilot's flying licence is still in-date
   b. No further checks are necessary
   c. Obtain start-up permission from the Tower
   d. Carry out a check for engine hydraulicing

3. **When an engine starts up and the starter key is released, to what position does the key return?**

   a. "OFF"
   b. "ON"
   c. "BOOSTER"
   d. "BOTH"

4. **Immediately an engine has started up, what is the first instrument reading to be checked?**

   a. Oil pressure
   b. Battery volts
   c. Gyro erection
   d. Vacuum

5. **What would be the likely effect of prolonged running with a weak mixture?**

   a. Overheating
   b. Failure to come up to correct running temperature
   c. Carburettor icing
   d. High oil pressure

6. **Should over-priming cause a fire to start in the engine's carburettor during starting, what is the best immediate action?**

   a. Evacuate the aircraft and make a "flash" call to the airport fire services
   b. Shut down the engine. The fire will extinguish itself
   c. Keep the engine turning on the starter motor and select "idle cut-off". The fire should be drawn through the engine
   d. Select weak mixture on the mixture control and rapidly increase rpm

7. **When is the "Reference rpm" of an engine established?**

   a. Before the first flight of the day
   b. During engine warm-up
   c. By the engine's manufacturer during "Type Testing"
   d. When the engine is first installed in an aircraft

8. **When is "Static Boost" noted?**

   a. Before engine start
   b. Just after engine start, while warming up
   c. It is permanently marked on the boost gauge
   d. It must be calculated from the airfield QNH

9. **At what rpm is a magneto "dead cut" check carried out?**

   a. At ground warm-up rpm
   b. At reference rpm
   c. At take-off rpm
   d. During the "Mag. drop" check

10. **If, during a "Mag. drop" check the engine cuts, what action must be taken?**

   a. Immediately switch to "Both" and recheck
   b. A grounding wire has broken and not earthing the primary circuit
   c. The engine must be stopped
   d. Decrease rpm to idle for no more than 1 minute. Reselect reference rpm and recheck

11. **If, during a "Mag. drop" check there is no drop in rpm, what is the most likely cause?**

   a. A really good ignition system
   b. One of the switches being seized in the open circuit position
   c. One of the switches being seized in the closed circuit position
   d. The plug leads from that magneto have not been connected

12. **What are the main reasons to exercise a propeller from fine to coarse pitch after warm-up?**

   a. In order that a pilot may practise propeller control technique before take-off
   b. To pre-set the feathering signal before take-off, in case of an emergency
   c. To check that a full range of control is available at take-off boost
   d. To replace the cold oil in the pitch change mechanism and check rpm control

13. **At what mixture and carb. heat setting is a take-off normally carried out?**

   a. Fully weak and carb. heat fully off
   b. Fully rich and carb. heat fully on
   c. Fully rich and carb. heat fully off
   d. Fully weak and carb. heat fully off

14. **Why, when climbing, is the engine temperature monitored carefully?**

   a. A low temperature will be the only sign that pre-ignition is occurring
   b. Decreasing air density will reduce the engine cooling system's efficiency
   c. A low engine temperature can give rise to poor atomization of fuel, and thus adversely affect Specific Fuel Consumption
   d. Use of high power at relatively low speed can allow engine temperature to creep up

15. When cruising in a fixed-pitch propeller equipped aircraft, what, from the list below, would be the symptoms of carburettor icing?

1. Increase in manifold temperature
2. Decrease in rpm
3. Loss of airspeed
4. Increase in engine temperature
5. Loss of altitude
6. Loss of oil temperature
7. Increase in rpm

Choose from the following:

a. 2, 3 and 5
b. 1, 2 and 7
c. 4, 5, 6 and 7
d. 3, 4, 5 and 7

16. What is the main danger from using a weak mixture at a high power setting?

a. Low cylinder head temperature
b. Low fuel pressure
c. Pre-ignition
d. Detonation

17. What are the most likely effects on an engine of a low power, high speed descent?

a. Engine overspeeding and consequent damage
b. Engine overcooling and carburettor icing
c. Engine overheating and oil cooler coring
d. High oil temperature and piston ring gumming up

18. What problem is prevented by the use of the correct running down procedure?

a. Spark plug fouling
b. Oil cooler coring
c. Very high rate of piston ring wear
d. Over high temperatures on next start-up

19. What is the correct way to shut down an engine?

a. Switch off both magnetos together
b. Switch off the fuel booster pump
c. Move the mixture control to ICO
d. Feather the propeller when at idle rpm

20. What are the two main symptoms of an excessively rich mixture?

a. Loss of power and a drop in cylinder head temperature
b. Gain in power and a drop in cylinder head temperature
c. Loss of power and a rise in cylinder head temperature
d. Gain in power and a rise in cylinder head temperature

Answers - Propellers

1	2	3	4	5	6	7	8	9	10	11	12
d	b	a	a	b	a	c	c	d	b	c	a

13	14	15	16	17	18	19	20	21	22	23	24
d	a	c	d	a	a	c	c	d	c	c	b

25	26	27	28	29	30
c	d	d	d	c	a

Answers - Piston Engine General Handling

1	2	3	4	5	6	7	8	9	10	11	12
b	d	d	a	a	c	d	a	a	c	b	d

13	14	15	16	17	18	19	20
c	d	a	d	b	a	c	a

CAE Oxford Aviation Academy

GAS TURBINES

ATPL GROUND TRAINING SERIES

Chapter

13

Gas Turbines - Introduction

The History of the Gas Turbine Engine

Simply stated, jet propulsion can be described as the force which is generated in the opposite direction to the flow of gas or liquid under pressure which is escaping through an opening or hole.

The force that makes a lawn sprinkler rotate when water flows through it is one example of jet propulsion that is readily apparent in everyday life, and the thrust that sends rockets into the night sky on Guy Fawkes Night is another.

Whatever the form that the device utilizing jet propulsion takes, it is essentially a Reaction Engine which operates on the principle of the Third Law of Motion as stated by the English physicist, Sir Isaac Newton, in 1687.

The first known use of a reaction engine was by Hero of Alexandria in 250 BC. Hero's engine, *Figure 13.1*, consisted of a sphere into which steam was introduced under pressure.

The steam was introduced through apertures which also formed the bearings upon which the sphere was allowed to rotate.

When the steam was allowed to escape through two bent tubes mounted opposite one another on the surface of the sphere, it created a thrust which caused the sphere to rotate around its axis.

Figure 13.1

The idea to use a jet reaction engine for aircraft is not new. In 1913 a design for an Aerodynamic Thermal Duct (Athodyd) was suggested by a French engineer named Lorin but it was not until 1941 that Sir Frank Whittle's jet engine powered an aircraft in flight.

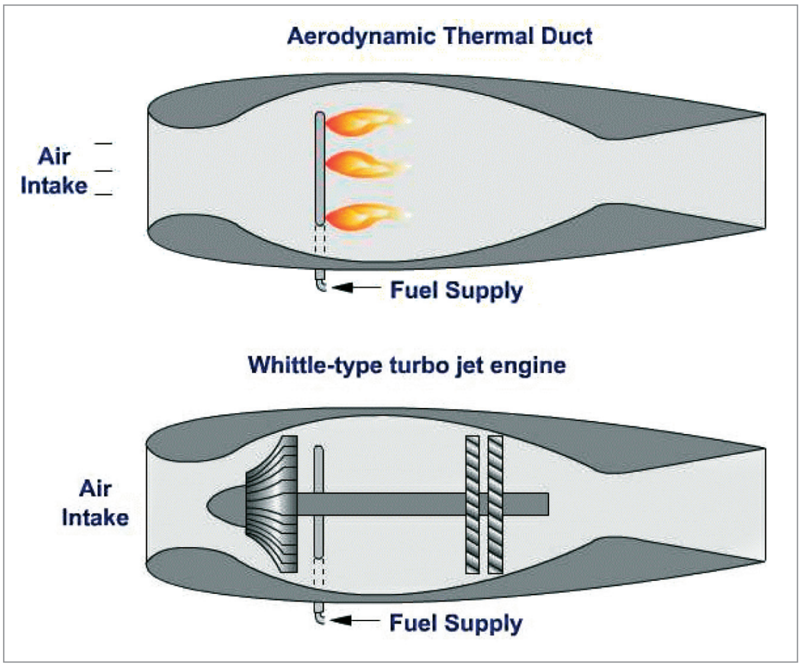


Figure 13.2 Athodyd and Whittle Engine.

The Principles of the Gas Turbine Engine

The principle of the Gas Turbine Engine is basically the same as that of the piston engine/ propeller combination, they both propel a mass of air backwards.

From: Force = Mass × Acceleration.

In a gas turbine engine the Mass is the air delivered by the compressor. Acceleration is the difference in the outlet velocity Vo of the air, to that of its inlet velocity V_I, due to the addition of heat energy.

Thrust Force is therefore m × $(V_o - V_i)$ + Pressure Thrust

Written scientifically as Thrust = $W(V_o - V_i)$ + Pressure Thrust (See Chapter 20)

The propeller drives a relatively large mass backwards fairly slowly, while the gas turbine throws a small mass of air backwards relatively quickly.

Newton's Third Law states:

For every force acting on a body, there is an equal and opposite reaction.

In the two cases quoted earlier, the propeller and the gas turbine engine, the force created by the mass of air and its velocity generates a reaction in the opposite direction driving the aircraft forwards.

It must be remembered that the jet reaction does not result from the pressure of the jet on the atmosphere, in all instances the resultant reaction or thrust exerted on the engine is proportional to the mass or weight of air expelled by the engine and the velocity change imparted to it.

The Working Cycle of the Gas Turbine Engine

The working cycles of both the four-stroke piston engine (the Otto cycle) and the gas turbine engine (the Brayton cycle) are very similar, see *Figure 13.3*.

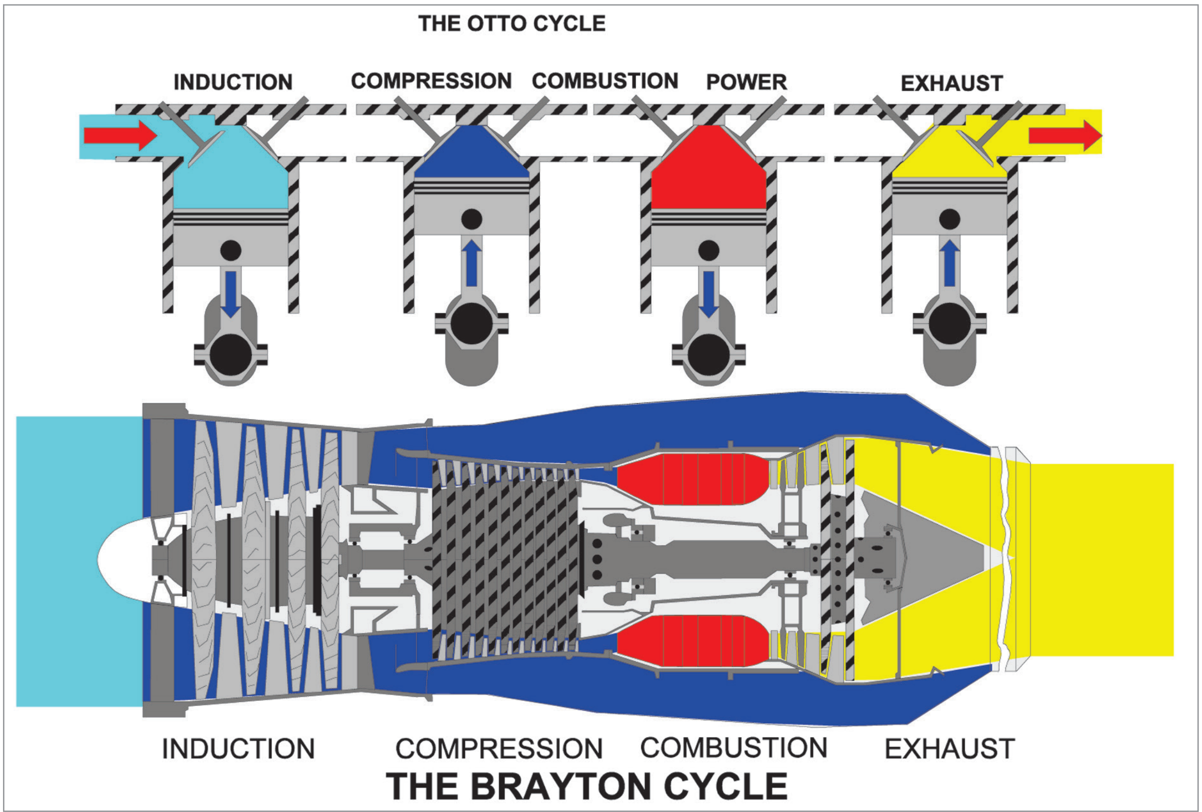


Figure 13.3 A comparison of the working cycles of the piston engine & the gas turbine engine.

The induction, compression, combustion, power and exhaust of the Otto cycle is matched by induction, compression, combustion and exhaust in the Brayton cycle.

In the gas turbine engine however, combustion theoretically occurs at a constant pressure, whereas in the piston engine it occurs at a constant volume. Power is developed in the turbine of the engine.

Other differences concern the continuous manner in which these processes occur in the gas turbine engine as opposed to the intermittent procedure occurring in the piston engine.

Only one of the strokes is utilized in producing power in the piston engine, the other three effectively absorbing power, while in the gas turbine engine the three ‘idle’ strokes have been eliminated, thus allowing more time for the burning of fuel.

This is one of the reasons why the gas turbine engine has a greater power/weight ratio than the piston engine.

A Pressure Volume Diagram of the Working Cycle

The pressure volume diagram shown in *Figure 13.4*, The Brayton Cycle, represents the working cycle of the gas turbine engine in its simplest form.

Air at atmospheric pressure enters the engine at point A and is compressed along the line A-B.

Fuel is added in the combustion chambers signified by point B and burnt, in theory at a **constant pressure.**

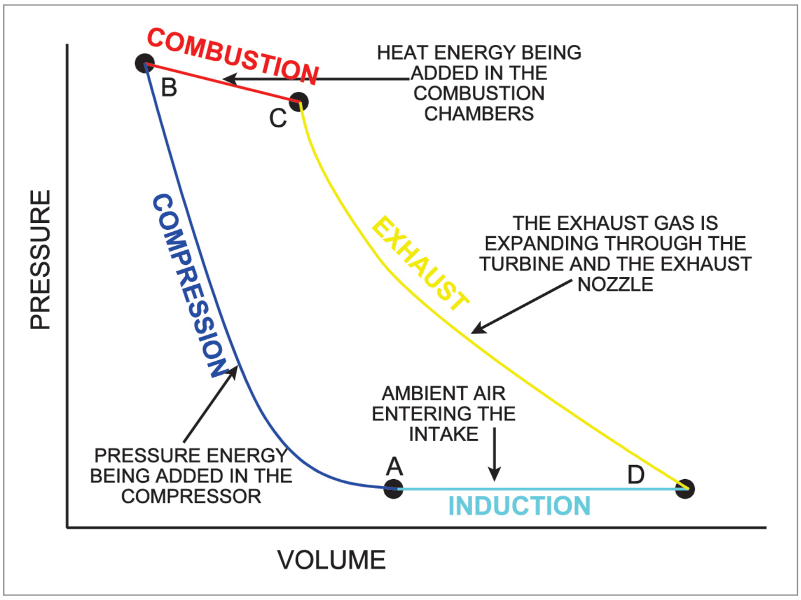


Figure 13.4 A pressure volume diagram of the working cycle of a gas turbine engine.

In actual fact, there are pressure losses in the combustion chamber created by having to produce swirl and turbulence, this causes a pressure drop throughout its length of between 3-6%. Nevertheless, a considerable increase in the volume of the air is generated within the combustion chamber.

Between points C and D the gas generated through combustion expand in the turbine and the jet pipe, theoretically attaining a value equal to atmospheric pressure before being ejected.

Constant Pressure Combustion

As previously stated, theoretically combustion occurs at a constant pressure in the gas turbine engine. This is achieved partly through the continuous process of the Brayton cycle and the fact that the combustion chamber is not an enclosed space.

These circumstances ensure that there are no fluctuations of pressure in the engine as there are in the piston engine, where peak pressures greater than 1000 lb per square inch have to be accommodated. These pressures necessitate utilizing extremely strong and heavy construction in the piston engine and if detonation is to be avoided, the use of high octane fuels.

In contrast, in the gas turbine engine, the use of low octane fuels and relatively light construction methods are the rule rather than the exception.

The Temperature Limit of the Engine

The turbojet is a heat engine, the higher the temperature attained in combustion the greater the expansion of the gases and hence the greater efficiency of the engine. There is however a limit to the amount of heat that can be released into the turbine from combustion.

This limit is imposed by the materials from which we manufacture the nozzle guide vanes and the turbine blades.

The use of modern materials and extremely efficient cooling methods in the nozzle guide vanes and the turbine blades have enabled the use of much higher gas temperatures in the latest engines with the consequence that they have a higher thermal efficiency than their predecessors.

Application of the Gas Laws in the Gas Turbine Engine

The air, which is the working fluid of the gas turbine engine, experiences various changes in its pressure, temperature and volume due to its receiving and giving up heat during the working cycle of the engine.

These changes conform to principles inherent in a combination of Boyle's Law and Charles's Law.

Boyle's Law states that:

If a given mass of gas is compressed at a constant temperature, the absolute pressure is inversely proportional to its volume.

or $P \times V = K$

In isolation, this law is not much use to us because in practice we cannot compress a gas at a constant temperature, however, if we use it in conjunction with Charles's Law it becomes more useful.

Charles's Law $\frac{V}{T} = K$ states that:

If a gas is heated at a constant pressure, the change in volume will vary directly with the change in the absolute temperature, the change being the same for all perfect gases.

Thus, the volume of a given mass of gas which remains at a constant pressure is directly proportional to the absolute temperature of that gas.

This law on its own is a little better, at least in theory we have combustion occurring at a constant pressure in the gas turbine engine, but as we have seen, it does not happen in practice.

Combined Gas Law states that:

The product of the pressure and the volume of a quantity of gas divided by its absolute temperature is a constant.

or: $$\frac{P \times V}{T} = K$$

Simply stated, this means that the product of the pressure and volume of the air throughout each stage of the working cycle is proportional to the absolute temperature of the air at that stage.

The three main stages when these conditions change are during compression, combustion and expansion.

During compression

Work is done to increase the pressure and decrease the volume of the air. There is a corresponding rise in its temperature. Higher compression ratios give higher thermal efficiency and low specific fuel consumption. Changes in outside air temperature will affect the density of the air. A decrease in temperature will increase air density and the compressor will have to work harder on the air; this will be indicated by a drop in engine rpm, if not compensated by the fuel control unit.

During combustion

The addition of fuel to burn with the air increases the temperature and there is a corresponding rise in its volume at an almost constant pressure.

During expansion

When some of the energy in the gas stream is being converted to mechanical energy by the turbine, there is a decrease in the pressure and temperature of the gas with a corresponding increase in its volume.

These changes in the temperature and pressure of the gas, as well as the changes in the velocity of the gas can be seen in *Figure 13.5.*

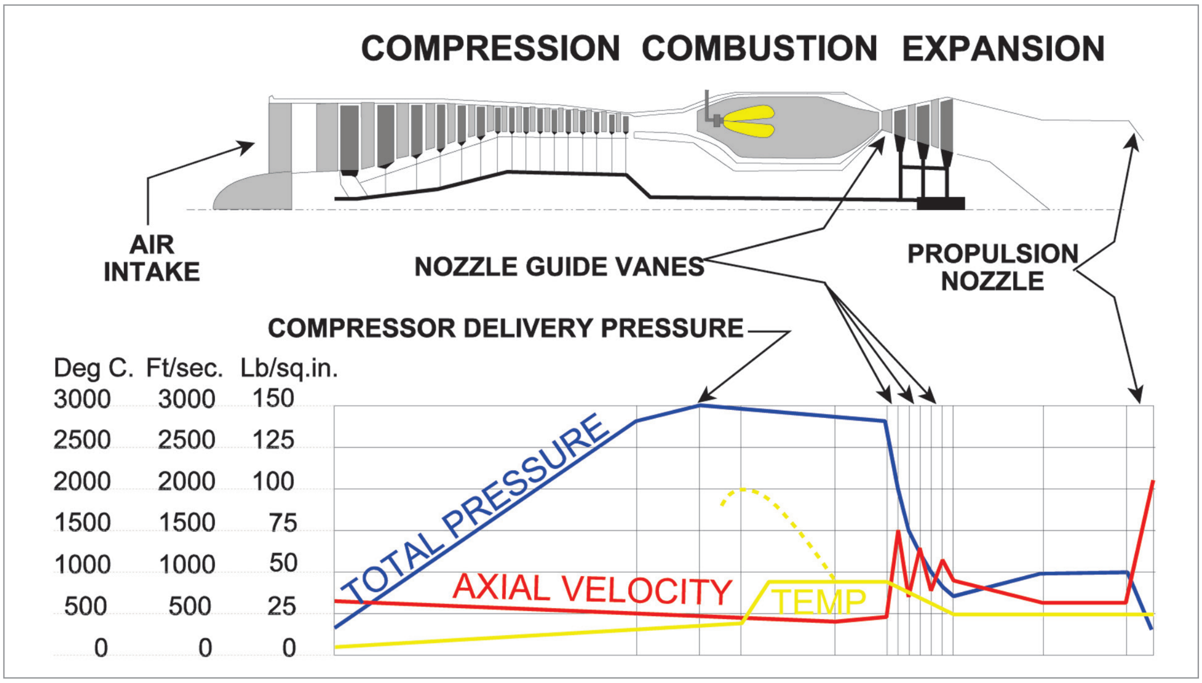


Figure 13.5 Changes in pressure, temperature & velocity in a single spool axial flow engine.

Duct Design

As the air passes through the engine there are various changes demanded in its velocity and pressure. For example, throughout the compression stage, the air must be compressed but without any appreciable increase in its velocity.

Another example is at the exhaust nozzle, where the pressure of the gas is dropped to that of ambient with a considerable increase in its velocity.

These changes in pressure and velocity are accomplished by the different shaped passages or ducts through which the air must pass before it exits the engine. The design of these ducts is extremely important because the efficiency with which the changes from velocity (kinetic) energy to pressure (potential) energy and vice versa occur are reflected in the overall efficiency of the engine. The illustrations in *Figure 13.6* show two examples of the use of different duct shapes used within the engine.

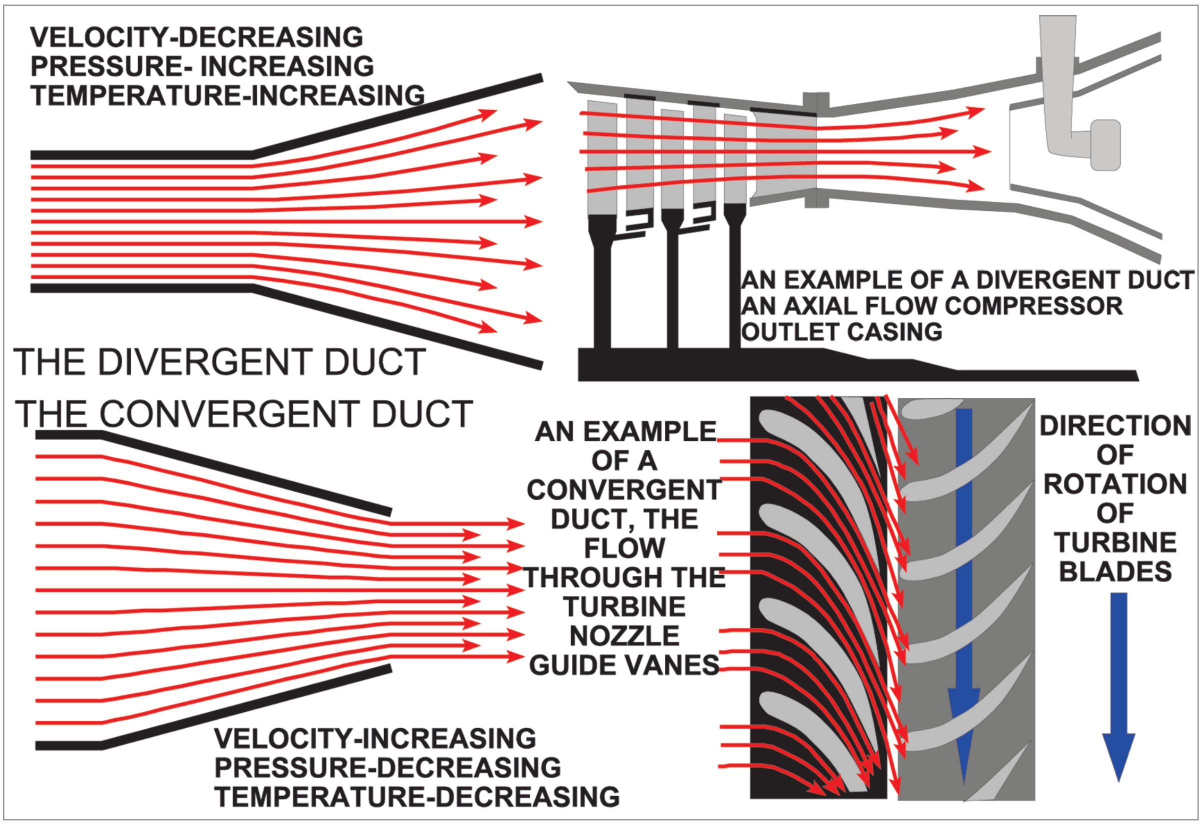


Figure 13.6 The use of divergent & convergent ducts to control the passage of airflow through the engine.

In the top example it can be seen that the use of a divergent duct will increase the pressure of the air after it leaves the final stage of the compressor and before it enters the combustion chamber. This air, sometimes called **'compressor delivery air'**, is the highest pressure air in the engine *(see Figure 13.5)*. The advantage here is twofold, first an increase in pressure with no expenditure of energy in driving the compressor, secondly, a decrease in velocity which will serve in making the task of the combustion chamber less difficult.

The bottom example in *Figure 13.6* shows how the use of a convergent duct is used to accelerate the gas as it passes through the nozzle guide vanes on its way to the turbine blades.

The torque applied to the turbine blade is dependent, among other things, upon the rate of gas flow into it, it follows then that the faster we can make the gas flow into the turbine, the more torque we can transfer to it.

Logically therefore, if we convert some of the considerable pressure energy of the gas stream into kinetic energy, it will be more efficient in imparting a turning effect upon the turbine and its shaft.

Airflow Through a Pure Straight Turbojet Engine

Figure 13.7 shows a single **spool** axial flow compressor turbojet engine.

When a compressor and turbine are joined on one shaft the unit is called a spool. This type was for a long time considered to be the most useful where an engine with a small frontal area was required, such as in fighter aircraft where a high forward speed was the main criterion.

There were however problems with the control of the smooth flow of air through the engine throughout its rotational speed range, more of this later.

The flow follows conventional patterns, from the compressor the air is fed into the combustion chambers as with the turboprop engine, and similarly fuel is now added to give the substantial increase in volume required.

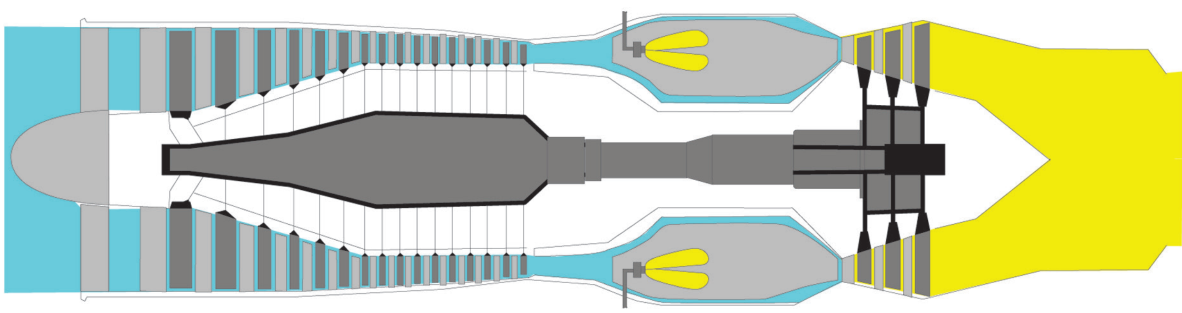


Figure 13.7 A single spool axial flow compressor turbojet engine.

The energy required to drive the compressor is now extracted from the gases as they pass through the turbine, the remaining energy is extracted to act as thrust as the gases pass to atmosphere via the end of the jet pipe.

Airflow Through a Turboprop Engine

Figure 13.8 illustrates both a centrifugal compressor turboprop engine and an axial flow compressor turboprop engine.

The output from a turbo-propeller engine is the sum of the shaft power developed at the turbine and the residual jet thrust. This is called Equivalent Shaft Horsepower (ESHP).

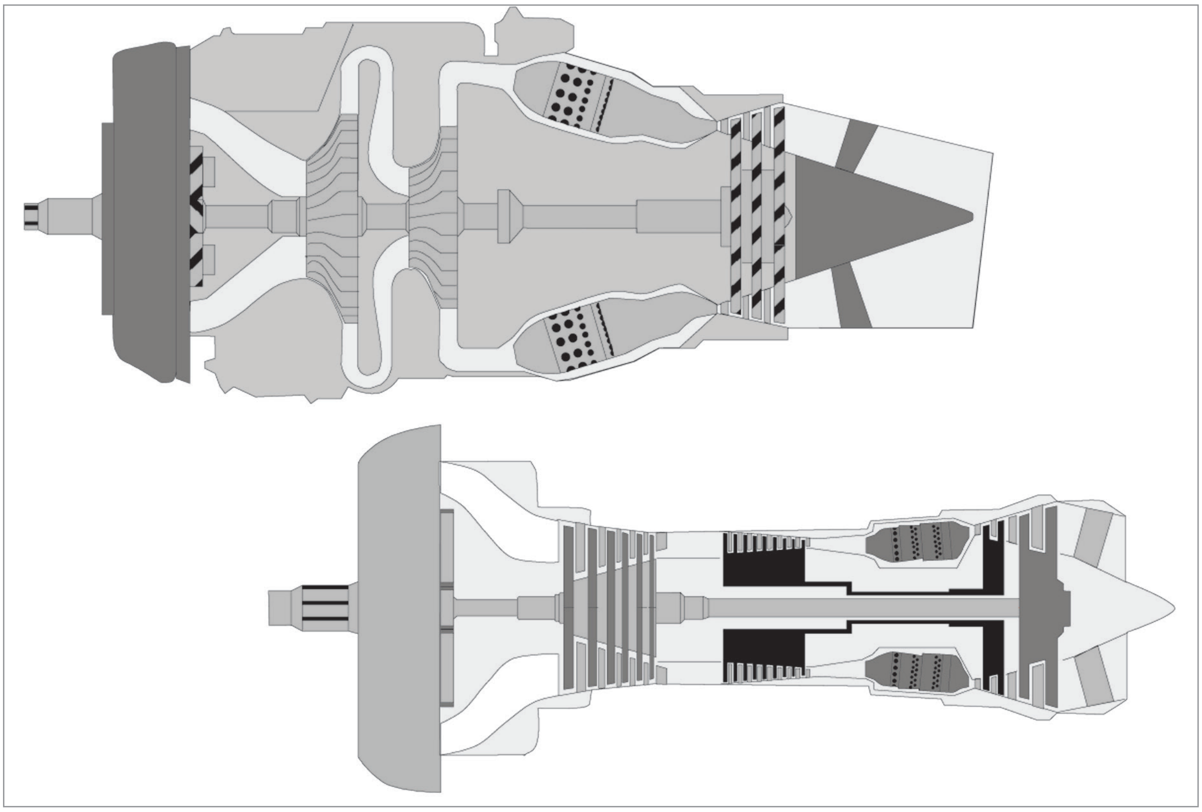


Figure 13.8 Centrifugal and axial compressor turboprop engines.

The major difference between the turboprop and the turbojet is how in the former almost all the energy in the gas stream is converted into mechanical power.

In the turbojet a high proportion of the gas stream energy is utilized to drive the compressor as it is in the turboprop, but whereas in the turbojet the energy that remains is used as thrust, the energy that remains in a turboprop engine is used to drive the propeller. Only a small amount of 'jet thrust' is available from the exhaust system of a turboprop with an efficient turbine, it can be described as 'residual thrust only'.

Apart from this difference, the airflow through the engine is virtually the same in either case. The compressor passes the air to the combustion chamber where the fuel is added and a substantial increase in the volume of the air is obtained at a nominal constant pressure.

The gas is now expanded in the turbine where a drop in the temperature, pressure and velocity is exchanged for the mechanical energy to drive the compressor/s and the propeller through its reduction gear.

Airflow Through a Turboshaft Engine

The turboshaft engine can be thought of as a turboprop engine with the propeller replaced by a shaft. Turboshaft engines can be used to drive helicopter rotors.

They can also used in applications where a compact supply of electrical power is required, their output shaft being attached to an alternator. This is the type of engine normally used as the Auxiliary Power Unit (APU) on most modern transport aircraft.

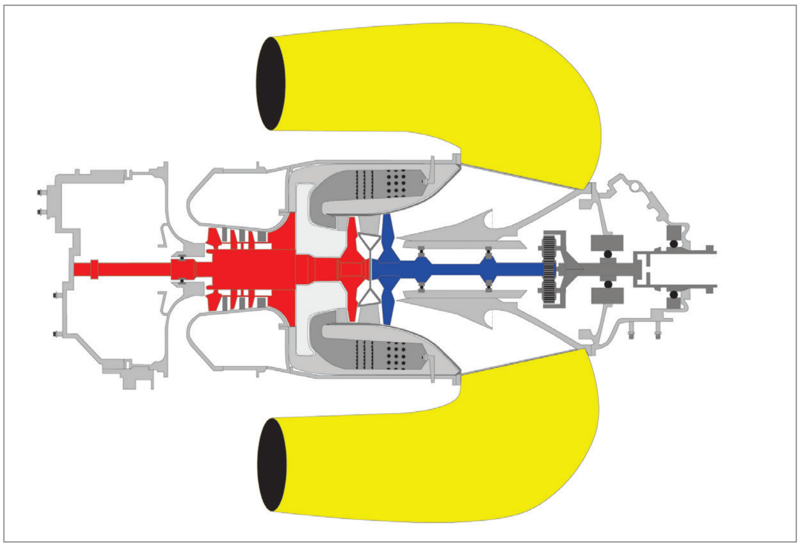


Figure 13.9 A single spool turboshaft engine incorporating a free power turbine.

Most, if not all, turboshaft engines incorporate a **Free Power Turbine.**

A free power turbine is one that is not connected to any of the compressors. This frees it from the constraint of having to rotate at a speed that suits the compressor and this gives it a much wider operating speed range.

The single spool turboshaft engine illustrated in *Figure 13.9* has a reverse flow combustion chamber system. This allows the engine to be much shorter, stiffer and lighter than it otherwise would, but does add the requirement for a centrifugal compressor to be used in the high pressure stage. This allows for the air to be thrown out radially in order that it can enter the combustion chamber in the correct direction.

Other than this deviation, the airflow follows that previously described for the turbojet engine up to the point where it leaves the high and low pressure turbines. Having converted sufficient energy to drive the two compressors, the gas now passes through the free power turbine where all of the remaining energy can be used to drive whatever is attached to it.

Airflow Through a Low Bypass Ratio Engine

The Bypass Ratio is the ratio of the mass airflow which flows through the fan-duct (bypass duct) to the mass of air which is directed through the hot core. A low ratio is considered to be in the region of about 1 or 2:1, whereas a high ratio would be around 5:1.

Example: Fan Mass-flow 1500 lb Bypass Ratio = $\frac{1200}{300}$ = 4:1

Core Mass-flow 300 lb

The engine shown in *Figure 13.10* is a twin spool, low bypass ratio engine. The airflow as far as the end of the low pressure compressor is identical to that of a pure turbojet, but then the airflow splits into two. An amount depending on the bypass ratio will flow down the bypass duct and the remainder continues into the high pressure (HP) compressor.

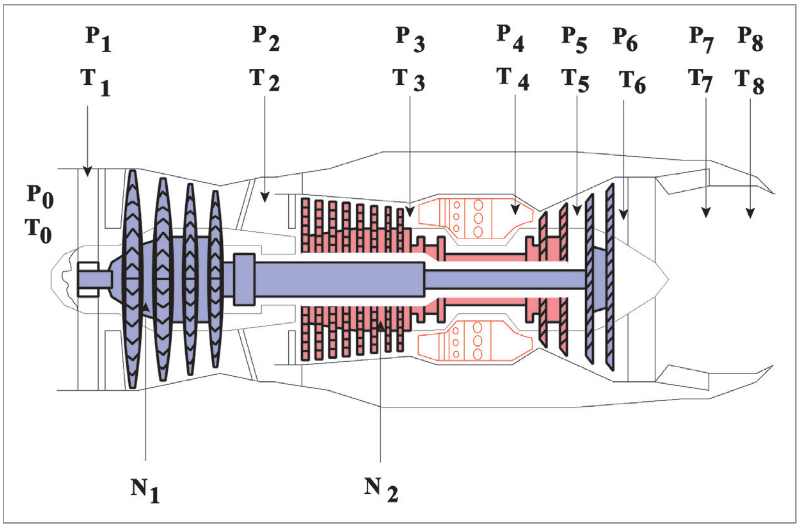


Figure 13.10 A twin spool low ratio bypass turbojet

P = Gas Pressure

T = Gas Temperature

N = Rotating Assembly

Each symbol is accompanied by a number which identifies its position from the front to rear of the engine.

Rolls Royce have historically used the designations listed below and shown in *Figure 13.10*.

P_0 T_0 = Ambient

P_1 T_1 = Inlet

P_2 T_2 = LP Compressor Delivery

P_3 T_3 = HP Compressor Delivery

P_4 T_4 = Turbine Entry

P_5 T_5 = HP Turbine Exit

P_6 T_6 = LP Turbine Exit

P_7 T_7 = Exhaust

P_8 T_8 = Propelling Nozzle

N_1 = LP Compressor/Turbine

N_2 = HP Compressor/Turbine

From the HP compressor the air follows the now familiar path through the combustion chambers and into the turbine before it rejoins the bypass air in the mixer unit of the exhaust system.

The propulsive efficiency of both the low and high ratio by-pass engines is much greater than that of the pure turbojet at the speeds normally associated with jet transport aircraft. Propulsive efficiency was explained earlier

This also follows for the specific fuel consumption which is appreciably lower for the high ratio bypass engine.

Airflow Through a High Bypass Ratio (Turbofan) Engine

The experience gained through manufacturing and operating the low bypass ratio type of engine proved that engines dealing with larger comparative airflows and lower jet velocities could give propulsive efficiencies comparable to those of turboprops and greater than turbojets at normal cruising speeds. The advent of the fan jet engine had arrived.

The triple spool front fan turbojet engine shown in *Figure 13.11* represents probably the most successful example of this type of engine, the Rolls Royce RB 211.

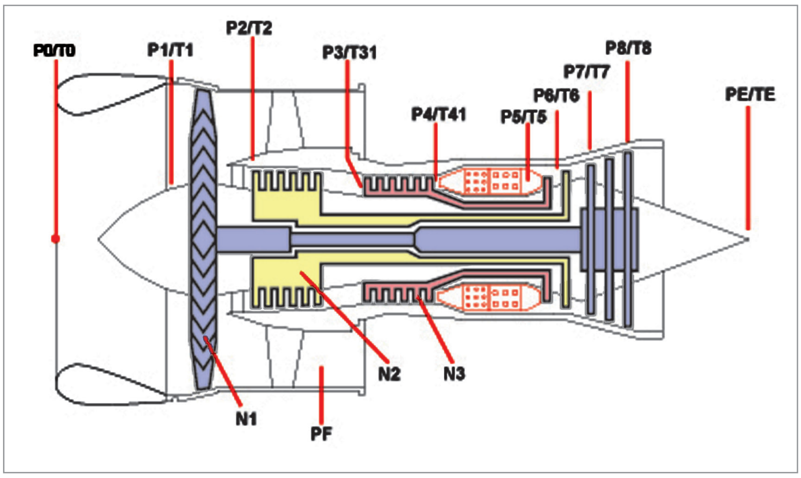


Figure 13.11 Triple spool front fan turbojet

The air enters the intake and passes immediately into the low pressure compressor, more commonly called the fan. Here its pressure is raised before it splits to go either through the bypass duct or into the intermediate pressure compressor, the amount depending upon the bypass ratio.

The thrust of this type of engine is almost completely dependent on the bypass airflow which has a high mass and relatively low velocity, hence its good propulsive efficiency. The air which passes through the intermediate and high pressure compressors has a great deal of energy added in the combustion chambers, but this energy is required to drive the compressors.

The rearmost, or the low pressure turbine, is responsible for extracting virtually all of the energy that remains in the gas stream to drive the front fan.

If it is efficient in doing its job then there should be only residual thrust remaining when the hot gases emerge from the turbine.

Propulsive Efficiency

Thrust is the product of mass times acceleration. It can be demonstrated that the same amount of thrust can be provided either by imparting a low acceleration to a large mass of air, or by giving a small mass of air a large acceleration. In practice the former is preferred, since it has been found that the losses due to turbulence are much lower and the propulsive efficiency is higher. The levels of propulsive efficiency for several different types of gas turbine engine are shown in *Figure 13.12*, below.

The efficiency of conversion of kinetic energy to propulsive work is termed propulsive or external efficiency. This is affected by the amount of kinetic energy wasted by the propelling mechanism.

Propulsive Efficiency = $\dfrac{\text{Work Done on Aircraft}}{\text{Work Done on Airflow + Work Wasted in Exhaust}}$

Propulsive Efficiency formula is written as: PE = $\dfrac{2V}{V+V_J}$ where *V* is aircraft Speed and V_J is Jet Velocity

Example 1.

A low bypass turbojet engine has a forward velocity (V) of 200 mph and a jet velocity (V_J) of 1000 mph.

$$\frac{2V}{V+V_J} = \frac{2 \times 200}{200 + 1000} = \frac{400}{1200} = \frac{1}{3} \times \frac{100}{1} = 33\%$$

Example 2.

A low bypass turbojet engine has a forward velocity (*V*) of 600 mph and a jet velocity (V_J) of 1000 mph.

$$\frac{2V}{V+V_J} = \frac{2 \times 600}{600 + 1000} = \frac{1200}{1600} = \frac{3}{4} \times \frac{100}{1} = 75\%$$

It can be seen from these examples that the closer the aircraft speed comes to the speed of the jet efflux, the more efficient the propulsion unit becomes.

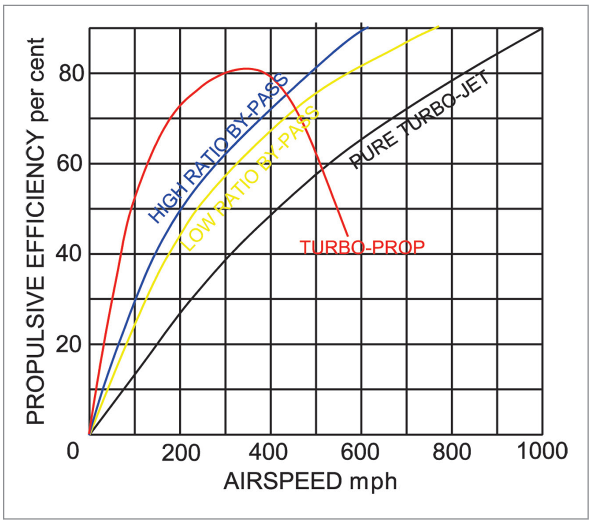


Figure 13.12 The propulsive efficiencies of gas turbine engines.

The highest propulsive efficiency at low airspeeds is offered by the turbo-propeller engine combination. However, above about 350 miles per hour, the propeller's efficiency does drop off quite rapidly due to the disturbance of the airflow at the tips of the blades.

In comparison with the turboprop, the propulsive efficiency of the pure turbojet appears quite poor at the lower airspeeds.

As the airspeed increases in excess of 800 miles per hour however, the propulsive efficiency starts to improve beyond the capability of the turboprop engine to match it, and from then on there is no comparison, the eventual outcome being a propulsive efficiency close to 90%.

Cruising speeds in the order of 800 miles per hour are at present out of the reach of most transport aircraft and this fact means that in the mid-speed range, where most of the world's transport aircraft operate, there is a niche for the bypass type of engine.

This type, which includes the ducted fan or turbofan engine, has a propulsive efficiency which fits neatly between that of the turboprop and the pure turbojet. By dealing with comparatively larger mass airflows at lower jet velocities the bypass type engine attains a propulsive efficiency which exceeds that of both the turboprop and the pure turbojet at the speeds normally associated with jet transport aircraft.

To summarize. The closer the aircraft speed comes to the speed of the jet efflux exiting the engine, the higher the Propulsive Efficiency of the engine/propeller combination.

Modular Construction Methods

The use of larger and larger aircraft has meant that air travel has become less and less expensive. This concept works well as long as the aircraft themselves work well. If however one restricting component on a large aircraft, such as an engine, becomes unserviceable, then the expense involved in keeping three or four hundred passengers fed, accommodated and happy becomes exorbitant.

Engine manufacturers, in an attempt to minimize the financial burden imposed upon the users of their equipment in the event of failure, have started to use Modular Construction Methods which facilitate changing sections of an engine rather than the whole engine. *Figure 13.13* shows how the engine is split into several modules.

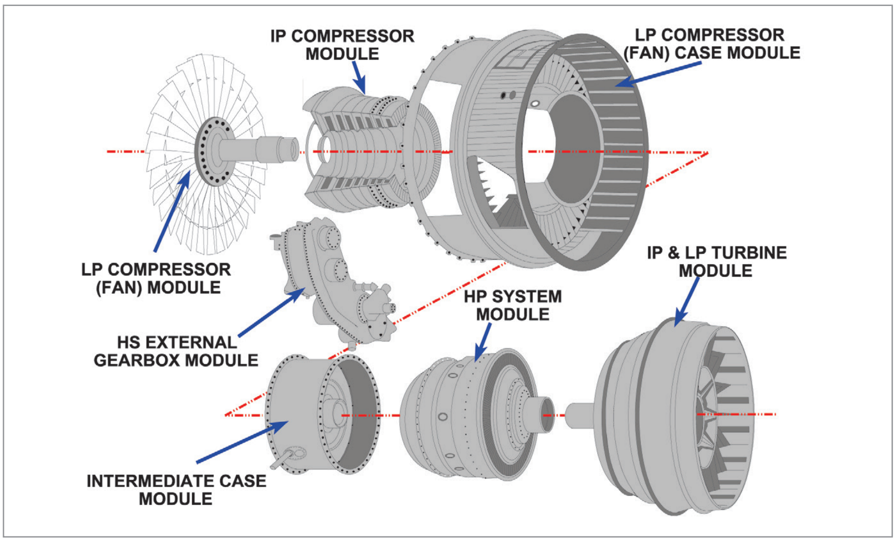


Figure 13.13 Modular construction units.

Questions

1. **When gases pass through a convergent duct their:**

   a. velocity and temperature increase and their pressure decreases
   b. their velocity increases and their temperature and pressure decrease
   c. their velocity decreases and their temperature and pressure increase
   d. they expand adiabatically

2. **Select the correct order of best propulsive efficiency, from low to high airspeed.**

   a. High bypass ratio turbojet, Low bypass ratio turbojet, Pure turbojet, Turboprop
   b. Low bypass ratio turbojet, Pure turbojet, Turboprop, High bypass ratio turbojet
   c. Pure turbojet, Turboprop, High bypass ratio turbojet, Low bypass ratio turbojet
   d. Turboprop, High bypass ratio turbojet, Low bypass ratio turbojet, Pure turbojet

3. **The highest pressure in a gas turbine engine occurs:**

   a. between the compressor and the combustion chamber
   b. in the combustion chamber
   c. in the jet pipe
   d. at the P1 probe

4. **In a turbofan engine, the fan speed is controlled by:**

   a. a reduction gear
   b. a wastegate
   c. the turbine
   d. varying the pitch

5. **In a High Bypass Ratio engine:**

   a. all of the air goes through both the low and high pressure compressors
   b. not all the air goes through the high pressure compressor
   c. not all the air goes through the low pressure compressor
   d. all the air goes through the high pressure compressor

6. **Modular construction:**

   a. is only used on turboprop engines
   b. cannot be used on high ratio engines
   c. has a weight saving function
   d. enables malfunctioning sections of the engine to be changed without changing the whole engine

7. **The Bypass Ratio of an engine is the ratio of:**

   a. primary air to tertiary air
   b. cold stream air to that flowing through the hot core of the engine
   c. exhaust gas pressure to air intake pressure
   d. primary air to secondary air

8. **The Gas Turbine Engine uses the principle of:**

a. Newton's Third Law of motion
b. creating thrust equal to the weight of the aircraft
c. expelling air at the same speed as that of the aircraft
d. the fluid flywheel

9. **The addition of heat in a combustion chamber allows a:**

a. large expansion at a substantially constant pressure
b. large expansion at a constant volume
c. large expansion at a decreasing static pressure
d. minimum expansion at a constant volume

10. **In a divergent duct:**

a. the pressure decreases and the temperature and velocity increases
b. the pressure, velocity and temperature increases
c. the pressure temperature increases and the velocity decreases
d. the pressure decreases, the temperature increases and the velocity remains constant

11. **In a twin spool engine:**

a. the LP compressor is connected to the HP compressor
b. the HP turbine is connected to the LP compressor, the LP turbine is connected to the HP compressor
c. the LP turbine is connected to the LP compressor, the HP turbine is connected to the HP compressor
d. the HP turbine is connected to the LP turbine, the HP compressor is connected to the LP compressor

12. **A Bypass Ratio of 5:1 means that:**

a. 5 pounds of air is bypassed for every 10 pounds entering the engine intake
b. 5 pounds of goes through the HP compressor for every 10 pounds that enters the intake
c. 10 pounds of air goes through the bypass for every 5 pounds that enters the intake
d. 5 pounds of air is bypassed for every 1 pound that goes through the hot core of the engine

13. **Aft of the compressor:**

a. the velocity of the airflow remains the same
b. the velocity of the airflow decreases before the combustion chamber
c. the velocity increases before the combustion chamber
d. the air pressure decreases before the combustion chamber

14. **The fan in a ducted fan engine, is driven by:**

a. the high pressure turbine
b. the rearmost turbine
c. the intermediate pressure turbine
d. all of the above

15. **In a bypass engine, the bypass air:**

a. increases the air mass flow and therefore increases the propulsive efficiency
b. cools the combustion chamber and therefore increases the thermal efficiency
c. reduces the air mass flow and therefore increases the propulsive efficiency
d. increases the air mass flow and therefore reduces the propulsive efficiency

16. **The majority of the thrust of a:**

a. turbofan engine comes from the turbine exhaust
b. turboprop engine comes from the turbine exhaust
c. turboshaft engine comes from the free power turbine exhaust
d. turbofan engine comes from the bypass air

17. **A pure turbojet engine gives:**

a. a small acceleration to a large mass of air
b. a large acceleration to a large mass of air
c. a small acceleration to a small mass of air
d. a large acceleration to a small mass of air

18. **During the Brayton cycle, combustion takes place:**

a. continuously
b. once every revolution
c. once every other revolution
d. only during the start cycle

Answers

1	2	3	4	5	6	7	8	9	10	11	12
b	d	a	c	b	d	b	a	a	c	c	d

13	14	15	16	17	18
b	b	a	d	d	a

Chapter

14

Gas Turbines - Air Inlets

Air Inlet

The engine air inlet is built into the airframe or the forward part of the nacelle installation. It is so designed to provide a relatively turbulent free supply of air to the face of the low pressure compressor or fan. The design of the intake duct is vital to the performance of the engine under all airspeeds or angles of attack to avoid compressor stall.

The simplest form of intake is a single entrance circular cross-section 'pitot' type. It is normally straight in wing mounted engines, but can be shaped to form an 'S' shaped duct for tailcone mounted engines (727, TriStar). Unstable airflow in an S duct can be a common occurrence particularly during crosswind take-offs.

The pitot type of intake maximizes the use of ram effect and suffers the minimum loss of ram pressure as altitude increases. Efficiency of this type of intake reduces as the aircraft approaches sonic speed due to the formation of a shock wave at the intake lip.

The air inlet is usually divergent in a subsonic intake and this divergence allows a reduction of velocity and an increase of pressure at the compressor face as the airspeed increases.

The pressure within the intake of a gas turbine engine while it is being run on a stationary aircraft is below ambient pressure. This is because of the high velocity airflow through the intake. As the aircraft begins to move the pressure within the inlet starts to rise. The point when inlet pressure returns to ambient is known as **ram pressure recovery.**

This point is usually reached at about Mach 0.1 to Mach 0.2. As the aircraft speed increases even further the inlet produces more and more ram compression which allows the engine compression ratio to increase. This in turn generates more thrust without costing any increase in fuel flow. This is illustrated below.

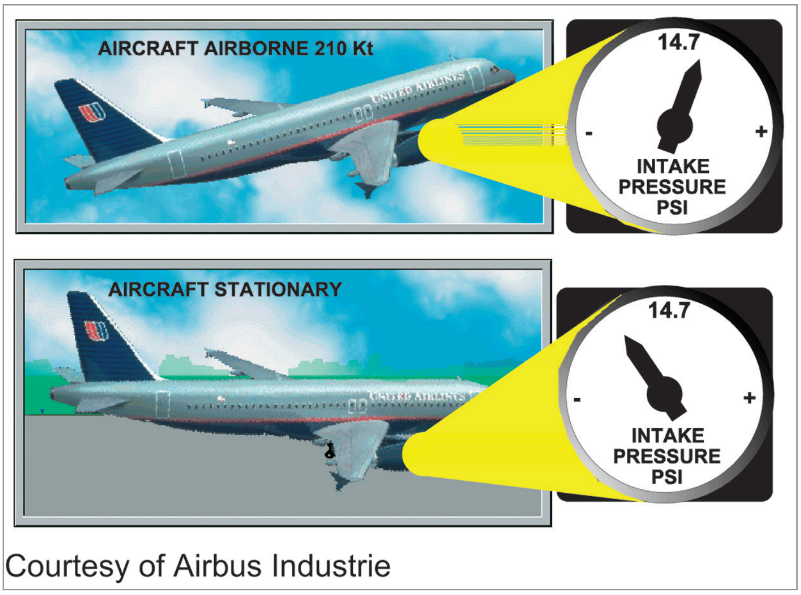


Figure 14.1 Ram recovery pressure

Operational Considerations

Take-off
The engine air inlet is designed to maintain a stable airflow to the compressor face, anything that disrupts the airflow and causes it to be turbulent may cause he compressor to stall or surge.

The intake cannot cope with high angles of attack and be expected to maintain a stable airflow. One of the most critical times is during acceleration of the engine to take-off power. Any crosswind may affect the airflow into the intake, particularly those aft body mounted engines having an ‘S duct’ type of intake, (TriStar, 727). To avoid the possibility of stall and surge the procedure defined in the operating manual must be followed which typically is to get the aircraft moving forwards before smoothly increasing the power setting to the take-off value by 60 - 80 knots approx. (rolling take-off).

Icing
Inlet icing can occur if conditions are conducive, typically this would be if the ambient temperature is below +10°C, there is visible moisture, standing water on the runway or the RVR is less than 1000 metres. If these conditions exist the pilot should activate the engine anti-icing system.

Damage
Damage to the intake or any roughness internally in the intake may cause the incoming air to be turbulent and may disrupt the airflow into the compressor causing stall or surge. Be particular during intake inspection to notice damage, uneven skin panels, surface roughness etc.

Foreign Object Ingestion
Damage to compressor blades is invariably caused by ingestion of foreign objects while the aircraft is on or close to the ground. Pay particular attention to the area on the ground in front of the engine intakes prior to engine start to ensure that it is free of loose stones and other debris. This is particularly important for wing mounted engines whose intake is close to the ground. It is no coincidence that aft body mounted engines whose intake is above the aircraft fuselage suffer much less with foreign object ingestion.

In-flight Turbulence
Heavy in-flight turbulence can not only spill the coffee but can seriously disrupt the airflow into the engines. Using the operating handbook turbulence penetration speed and the correct rpm or Engine Pressure Ratio (EPR) will reduce the possibility of compressor malfunction. It may also be prudent or a requirement to activate the continuous ignition to reduce the probability of engine ‘flame out’.

Ground Operations
The vast majority of compressor damage is caused by Foreign Object Damage (FOD). Damage to the compressor blades leads to changes in the geometry of the system which can cause performance deterioration, compressor stall and even engine surge. To prevent such damage being caused it is essential that the operators of gas turbine engines should take precautions which preclude the entry of debris into the area of the ramp. Further to this the pilot should ensure during his external pre-flight checks that the engine intakes are free from any such debris. The responsibility does not end there, after flight, intake and exhaust covers should be fitted to prevent ingress of contaminants and windmilling.

During start up, taxi and reverse thrust operation debris can be sucked into the intake and power should be kept to a minimum to avoid potential damage.

Several deaths and many serious injuries have been caused through personnel being sucked into the intakes of gas turbine engines while they have been operating, great care must be exercised whenever it is necessary to function in close proximity to running engines.

Questions

1. In a high bypass engine with a 'pitot' intake, with the engine running and the brakes on, what will P_1 be in relation to P_0?

a. Same.
b. Greater.
c. Less.
d. 14.7 psi.

2. A pitot intake forms a .... duct .... the fan to ensure that the airflow .... to .... and achieves a ....

a.	convergent	before	speeds up	subsonic	pressure rise
b.	divergent	after	slows down	subsonic	pressure rise
c.	divergent	before	speeds up	sonic	pressure drop
d.	divergent	before	slows down	subsonic	pressure rise

3. What effect will severe icing in the intake have on a high bypass engine?

a. The axial velocity of the air will increase with a reduction in the angle of attack of the airflow with the compressor blades and a possible stall.
b. The axial velocity of the air will decrease with a reduction in the angle of attack of the airflow with the compressor blades and a possible stall.
c. The axial velocity of the air will decrease with an increase in the angle that the resultant airflow forms with the compressor blades chord line and a possible stall.
d. The axial velocity of the air will increase with an increase in the angle of attack of the airflow with the compressor blades and a possible stall.

4. Which of the following would be classed as prudent when carrying out Engine Ground Runs?

a. Only carry out engine runs with a tailwind.
b. Fit debris guards when running.
c. Only do ground runs on tarmac.
d. Only do ground runs on concrete.

5. With an 'S' type intake, if the pilot selects max rpm while standing still, there is a strong possibility that:

a. the angle, which the relative airflow forms with the compressor blades, will become too small, which will cause the engine to stall and surge.
b. the angle, which the relative airflow forms with the compressor blades, will become too small, which will cause the engine to surge then stall.
c. the angle which the relative airflow forms with the compressor blades will become too large, which will cause the engine to stall and surge.
d. the angle, which the relative airflow forms with the compressor blades, will become too large, which will cause the engine to surge then stall.

6. The purpose of an air inlet is to provide a relatively .... supply of air to the .... of the .... compressor.

a.	turbulent free	face	low pressure
b.	turbulent	face	low pressure
c.	turbulent free	rear	low pressure
d.	turbulent free	face	high pressure

7. In a pitot intake the term 'Ram Pressure Recovery' refers to the time when:

a. EPR has attained the take-off setting.
b. the HP Compressor has reached its maximum.
c. the EPR has recovered to its optimum figure.
d. intake pressure has been re-established to ambient pressure.

Answers

1	2	3	4	5	6	7
c	d	c	b	c	a	d

Chapter

15

Gas Turbines - Compressors

Types of Compressor

The air must be compressed before having fuel added to it in the combustion chambers and subsequent expansion in the turbines.

There are basically two types of compressor in use in engines presently available, one allows axial airflow through the engine while the other creates centrifugal flow.

In both cases the compressors are driven by a turbine which is coupled to it by a shaft.

The Pros and Cons of the Centrifugal Compressor

The centrifugal compressor is much more robust than the axial flow compressor. That and the fact that it is the easiest and cheapest of the two types to manufacture made it a popular choice in early gas turbine engines.

It does however have one or two disadvantages which have relegated it to the second position in terms of large modern engines. If we compare two compressors with the same frontal area, one centrifugal and the other axial, we would first of all find that the axial flow compressor can consume far more air than the centrifugal compressor and secondly that much higher compression ratios can be attained in the axial flow compressor.

Since the amount of thrust generated by an engine depends partly upon the mass of air flowing through it, it can be demonstrated that the centrifugal compressor engine will have less thrust than an axial flow compressor with the same frontal area.

The Principles of the Centrifugal Flow Compressor

The action of the turbine rotates the impeller of the compressor at high speed. Air is introduced continuously into the eye (centre) of the impeller by rotating guide vanes and centrifugal force causes it to flow outwards towards the tip.

Because of the divergent shape of the vanes the pressure of the air increases as it flows outwards, and because we are adding energy into the equation, the air’s velocity also increases.

The air leaves the tip of the impeller and passes into the diffuser section, a system of stationary divergent ducts designed to convert the kinetic energy (velocity) into potential energy (pressure).

In practice approximately 50% of the pressure rise across the compressor occurs in the impeller and the other 50% in the diffuser section.

The compression ratio of a single stage centrifugal compressor would be in the region of 4:1. That means that the outlet pressure of the compressor stage would be approximately four times greater than the inlet pressure.

To attain greater engine compression ratios using centrifugal compressors two of them would have to be used in series with each other.

In practice it has not been found feasible to use more than two centrifugal compressor stages together, excessive impeller tip speeds and extreme centrifugal loading prohibit efficient operation of a third stage.

As a result of this, engine compression ratios of greater than 15:1 are not considered possible using centrifugal compressors.

At the elbows of the compressor outlet casing cascade vanes are fitted.

These enable the air to be turned through large angles with the minimum of loss, and they are also used to complete diffusion.

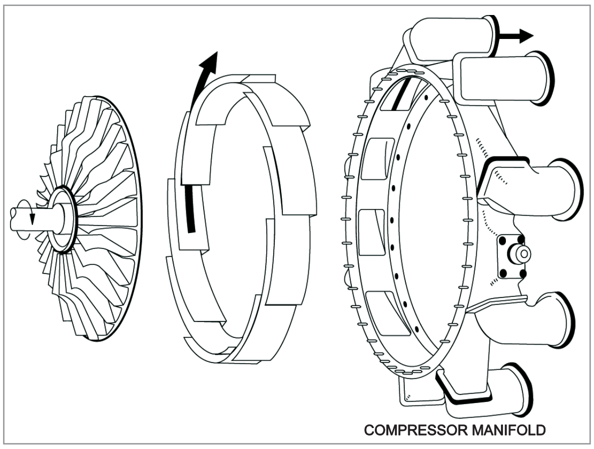


Figure 15.1

The Principles of the Axial Flow Compressor

The principle of the axial flow compressor is basically the same as that of the centrifugal flow compressor, it converts kinetic energy into pressure (potential) energy. The means which it uses to achieve this conversion are however different.

The axial flow compressor, as shown in *Figure 15.2*, consists of several rows of rotating (rotor) blades of aerofoil section interspersed with rows of stationary diffuser (stator) blades, also of aerofoil section.

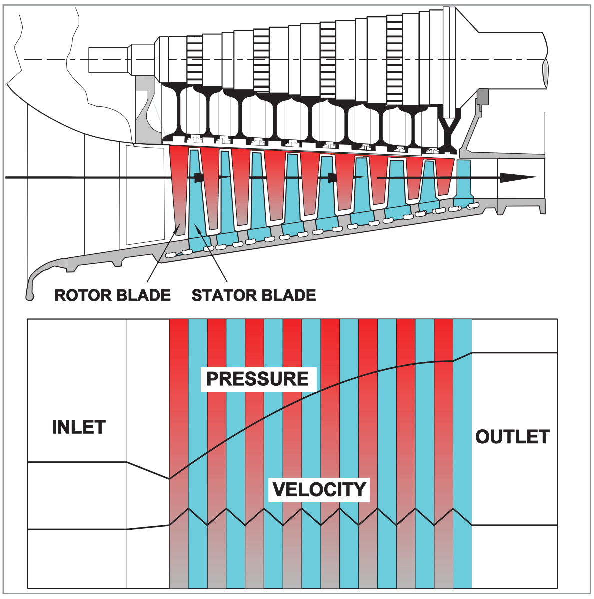


Figure 15.2 The changes in pressure & velocity through an axial flow compressor.

A stage consists of one row of rotor blades, fastened to discs on a rotor drum, followed by a row of stator blades, which are fastened to the compressor outer casing.

On both the rotor and the stator the spaces between the blades form divergent passages.

In the rotor, which is turned continuously at high speed by the turbine, mechanical energy is added and converted into both kinetic (velocity) energy and potential (pressure) energy.

Within the stator, the pressure is increased by the conversion of the kinetic energy into pressure energy. This process is illustrated in *Figure 15.2.*

Simply stated, the rotor stages can be seen as doing the same job as the impeller in a centrifugal compressor, while the stator stages can be compared to the diffuser in a centrifugal compressor. The pressure rise across each stage is only quite small, the ratio being about 1.1 or 1.2:1. This means that in the first stage the pressure might only increase by about 3 psi. As a consequence of this, in order to gain the compression ratios demanded by modern engines, many stages may be used on the same spool *(see Figure 15.3)*, and an engine may have up to three spools. So effective is this method of compression that in an engine like the RB 211 compression ratios as great as 35:1 can be attained. In this engine, the pressure rise over the last stage can be as much as 80 psi.

These high pressures can result in compressor outlet temperatures of up to 600°C.

Some engines now use a combination of centrifugal and axial compressors.

Maintaining the Axial Velocity of the Airflow

The space between the rotor drum and the compressor outer casing is called the air annulus. To maintain the axial velocity of the air as it is compressed into a smaller and smaller volume, the air annulus must be reduced.

This gradual convergence is achieved by either tapering the compressor outer casing or the rotor drum, or in some cases a combination of both. This is shown in *Figure 15.3.*

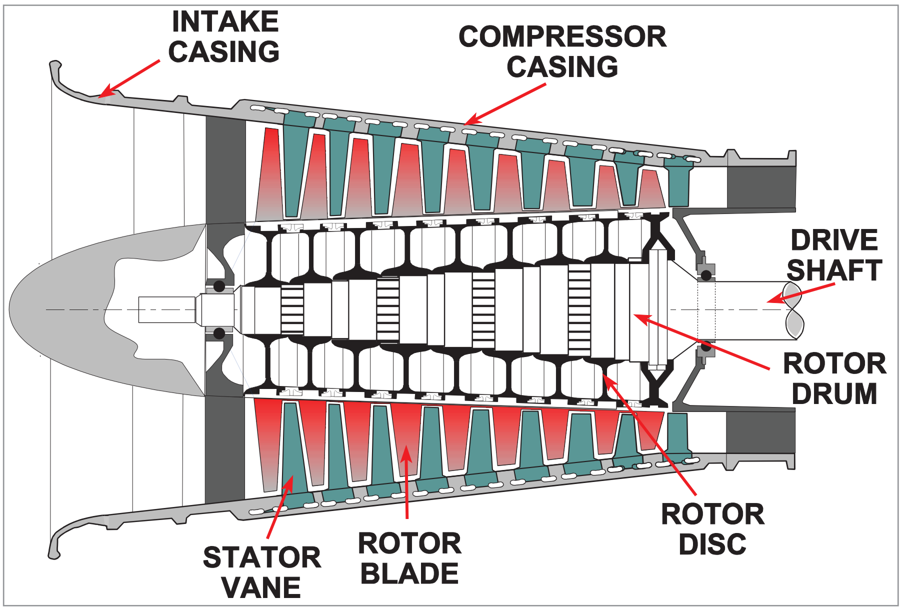


Figure 15.3 A single spool compressor.

Airflow Control

Increasing the compression ratio of a compressor makes it progressively more difficult to ensure that it operates efficiently over the whole of its speed range. This is caused by the fact that the compression ratio of the engine falls as the speed of rotation of the compressor falls. Therefore, as the engine slows down, the volume which the air takes up gets greater and greater, because it is not being compressed so much.

The increased volume of air at the high pressure end of the compressor makes it difficult for it to pass through the space available and so it slows down and in some cases can cause choking and turbulence.

This reduction in axial velocity happens throughout the compressor and can cause a phenomenon called stall, which if not checked can progressively worsen to produce surge, a situation where, in the worst case, the airflow through the engine can instantaneously reverse its direction of flow.

Stall

The angle of attack of a compressor blade is the result of the axial velocity of the air passing across it and the rotational speed of the blade.

These two velocities combine to form a vector which gives the actual angle of attack of the airflow over the blade.

A compressor stall can be described as an imbalance between these two velocities which can occur through various causes, some of which are as follows:

a) **Excessive fuel flow caused by abrupt engine acceleration** (the axial velocity is reduced by increasing combustion chamber back pressure).

b) **Engine operation above or below the engine design rpm parameters** (increases or decreases the rotational speed of the compressor blade).

c) **Turbulent or disrupted airflow to the engine intake** (the axial velocity is reduced).

d) **Contaminated or damaged compressor components** (decreased axial velocity because of decreased compression ratio).

e) **Contaminated or damaged turbine** (loss of power to the compressor causing decreased axial velocity because of decreased compression ratio).

f) **Excessively lean fuel/air mixture caused by abrupt engine deceleration** (the axial velocity is increased by the decreasing combustion chamber back pressure).

Any of the above conditions can cause **compressor stall** to commence, and as soon as it does there **is a partial breakdown of airflow through the engine.**

The indications of compressor stall are an increase in the vibration level of the engine and an increase in the Exhaust Gas Temperature (EGT).

This latter effect (the increase in EGT) is caused by the fact that there is less air going to the combustion chambers, hence there is less air to cool the products of combustion, the exhaust gases.

Compressor stall is then a progressive phenomenon, it could initially in theory occur at just one blade, worsening to encompass the whole of one stage, and then, if nothing is done to prevent it, affect the whole engine.

Surge

The progressive deterioration of the situation will eventually cause **a complete breakdown of airflow through the engine called a surge.** In severe cases this could cause an instantaneous reversal of the gases in the engine, with air being expelled through the engine intake with a loud bang. **If surge does occur, the throttle of the affected engine must be closed slowly.**

This situation is most commonly caused by fuel system malfunction or mishandling and in extreme cases could inflict such large bending stresses on the compressor rotor blades that they contact the stator blades with potentially catastrophic results.

Apart from the loud noise that usually accompanies a surge, there is a large rise in the EGT and the resulting loss of thrust may cause the aircraft to yaw.

Prevention of Stall and Surge

Operation of the engine outside the optimum rpm and axial velocity range is inevitable, design criteria are, after all, aimed at producing the greatest efficiency near maximum rpm, and operation at levels below that point has to occur if we are to be able to throttle the engine back.

This means that we are committed to altering the rotational speed of the compressor, and also the axial velocity of the air as it passes through the engine, by doing so we are encouraging the onset of stall and surge.

Methods of ensuring that this does not happen have to be fitted to the engine, the following is a list of some of those methods:

a) Variable Inlet Guide Vanes (VIGVs)

b) Variable Stator Vanes.

c) Compressor Bleeds.

d) Multi-spool Compressors.

e) Active Clearance Control.

Variable Inlet Guide Vanes

Variable inlet guide vanes (VIGVs) are fitted to engines which have a particular problem with inherent compressor stall at low rpm or during engine acceleration or deceleration. The vanes are fitted just in front of the first rotor stage, they can be automatically pivoted around their own axis to vary the path of the airflow going into the compressor, so maintaining the proper relationship between compressor rotational speed and airflow in the front compressor stages.

At low compressor speeds the VIGVs are angled to impart the greatest amount of swirl to the air, thereby correcting the relative airflow to obtain the optimum angle of attack over the rotor blades. This optimum angle of attack allows a smooth and rapid engine acceleration.

Variable Stator Vanes

After the first rotor stage has been successfully negotiated, the airflow may still have problems further down the compressor when the engine is operating at other than optimum conditions. To minimize these problems, some engine are fitted with variable stator vanes, see *Figure 15.4*

These vanes can be pivoted automatically, so that as the compressor speed is reduced from the optimum design value, they are progressively closed to maintain an acceptable angle of attack onto the following rotor blades.

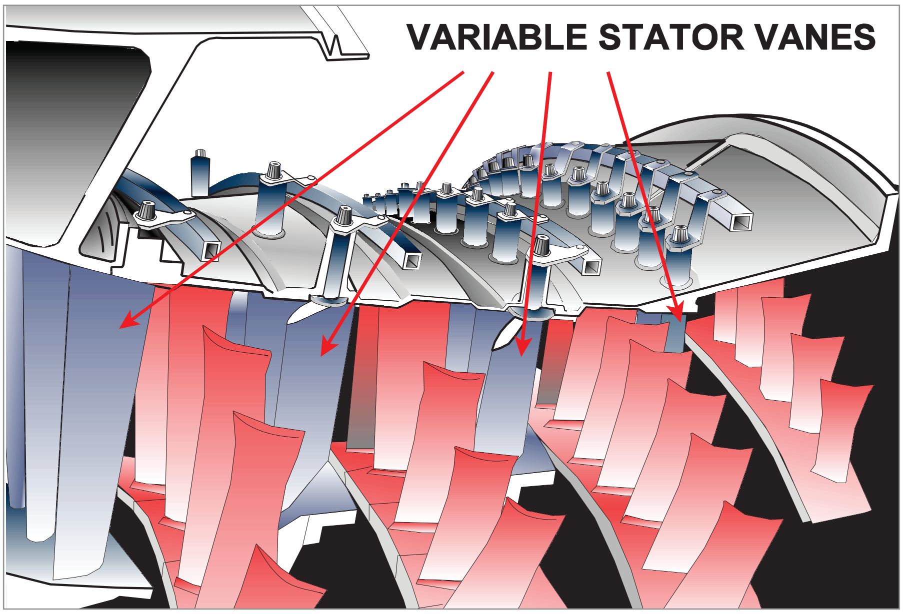


Figure 15.4 Typical variable stator vanes

Compressor Bleeds

As explained earlier, when the engine slows down, its compression ratio will decrease and the volume of air in the rear of the compressor will be greater.

This excess volume causes choking in the rear of the compressor and a decrease in the mass flow. This in turn causes a decrease in the velocity of the air in the front of the compressor and increases the tendency to stall.

If a compressor bleed valve, as shown in *Figure 15.5,* is introduced into the intermediate stages of the compressor, it can be opened at low rpm or during engine acceleration to allow some of the excess volume of air to escape.

This will have the effect of increasing the velocity of the air in the earlier stages of the compressor and reducing the choking effects in the rear of the compressor.

This combination will ensure that compressor stall is less likely to occur during the conditions while the bleeds are open, but there are disadvantages to the use of the system.

Opening compressor bleeds, whether they are stall preventive measures or bleeds used to supply air for aircraft services, decreases the mass flow through the engine.

This will cause a drop in thrust for a given throttle position which raises the engine's specific fuel consumption (sfc) and also raises the EGT because of the drop in the amount of cooling air available.

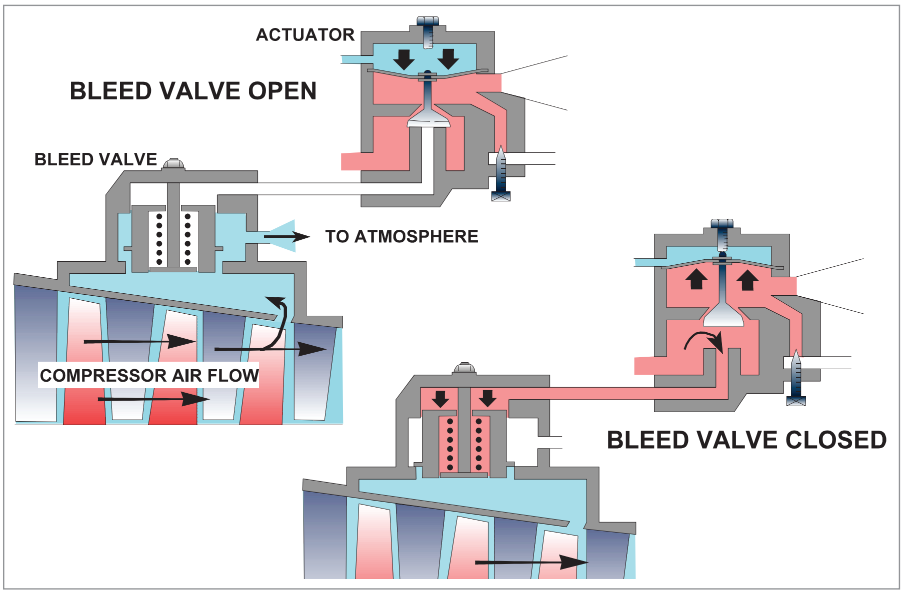


Figure 15.5 The operation of a compressor bleed valve.

Multi-spool Compressors

Early axial flow engines were developed by adding more compressor stages on one shaft to obtain higher and higher compression ratios.

This made it increasingly difficult to retain operational flexibility in terms of engine speed. Compressor blade angles are arranged to give peak performance around maximum rpm, when the axial velocity of the airflow and the rotational speed of the blade produce the optimum angle of attack of the airflow over the blade.

Any reduction of engine rpm changes the symmetry of the vector diagram relating it to the axial velocity, and the angle of attack no longer retains its optimum value, stall became an ever present problem at lower engine speeds.

To overcome this, the compressor was split, initially into two, and subsequently into three, sections, each section being driven through a shaft by its own turbine. The speed of rotation of each successive compressor increases, the HP compressor rotating faster than the LP.

The whole unit, compressor, shaft and turbine, forms a spool.

By designing the engine so that, upon closing the throttle, the speed of the low pressure spool falls off more rapidly than the high pressure spools, it can be arranged that the symmetry of the vector diagram relating to angle of attack can be maintained over a much greater range, thus reducing greatly the chance of compressor stall.

Active Clearance Control

A later development designed to control the airflow through the engine is that of active clearance control. The basic problem with all cases of stall is that the angle of attack of the airflow over the blade is no longer at its optimum value.

This can be the result of changes in either the axial velocity of the airflow over the blades or their rotational speed.

If the axial velocity can be controlled over the whole of the engine speed range, then the chances of stall or surge happening are diminished.

One method of accomplishing this is to vary the size of the air annulus at the high pressure end of the compressor, something which was considered technically impossible not too long ago.

By cooling the compressor casing we can cause it to shrink and so achieve the desired clearance between it and the blade tips. The cooling medium most often used at present is air, which is introduced into tubing running through the exterior of the compressor casing.

Compressor Surge Envelope

Compressor stall/surge has been shown to be caused by an imbalance between the flow of air through the compressor and the pressure ratio. *Figure 15.6* illustrates how the designer ensures the relationship between pressure rise and rpm follows a path known as the working line or design line. Built-in airflow control devices such as bleed valves, allow a safety margin between the working line and the surge line.

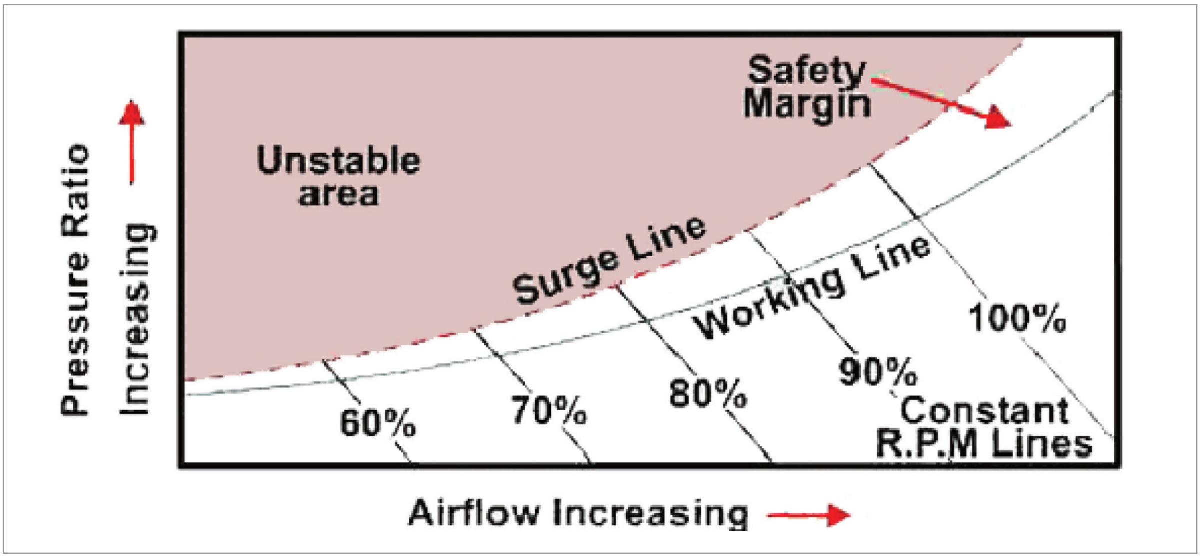


Figure 15.6

Construction

Figure 15.3 shows the basic methods of construction commonly used in compressor assembly. The rotor shaft is supported in bearings and is coupled to the turbine shaft so that minor variations in alignment are allowed for.

The centrifugal load imposed on the compressor dictates that the rotor blades are fixed to a disc which itself is fitted around the rotor shaft.

The types of fixing methods vary, the most common being that where the root of the blade is shaped into a dovetail joint and secured to the disc by a pin or locking tab.

On smaller engines it becomes more and more difficult to design a practical fixing method and at the same time maintain minimum disc weight.

One way of getting over the problem is to produce blades integral with the disc, this type of blade and disc combination has been called the 'blisk'.

The compressor casing is constructed of aluminium alloy at the front stages with the intermediate stage casing being manufactured from steel alloys.

In the high pressure section of the compressor the temperatures are so high that nickel based alloys are the only materials capable of withstanding them.

Rotor Blades

The rotor blades are of aerofoil section and are normally made from drop forged stainless steel, machined to a close tolerance before being attached to the rotor disc.

The blades reduce in size from the front to the rear of the compressor, to accommodate the convergent shape of the air annulus, see *Figure 15.3*.

Some of the low pressure stages may have blades manufactured from titanium where the temperatures of compression are not too high.

The method of fixing, usually the dovetail system, see *Figure 15.7*, does not ensure that the blade is held immovable in the disc, in fact the blades are quite loose until firmly seated by centrifugal force during engine operation, so that when windmilling on the ground the blades rattle loosely and sound somewhat like a bag of nails being shaken.

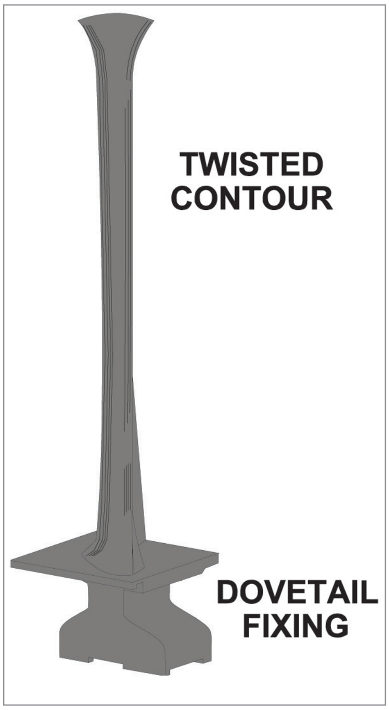


Figure 15.7 A typical compressor rotor blade.

Stator Vanes

The stator vanes are also aerofoil shaped and are fixed to the compressor casing either directly or into stator vane retaining rings, which are themselves fastened to the casing.

The vanes may be assembled in segments in the earlier stages, and the longer ones are shrouded at their inner ends to prevent vibration which can be induced by the velocity flow over them, see *Figure 15.8*.

Early engines used aluminium alloys in the manufacture of stator vanes but it did not withstand foreign object ingestion damage at all well.

Steel or nickel based alloys have a high fatigue strength and are less easily cracked or eroded by impact. Titanium is sometimes used for the vanes in the early stages, but it is not suitable further down the engine where the high temperatures can affect it.

Another problem which may happen is that of rub, an excess of which might occur through mechanical failure, sufficient heat from friction would then be generated to ignite the titanium causing at best expensive repairs, or at worst an airworthiness hazard.

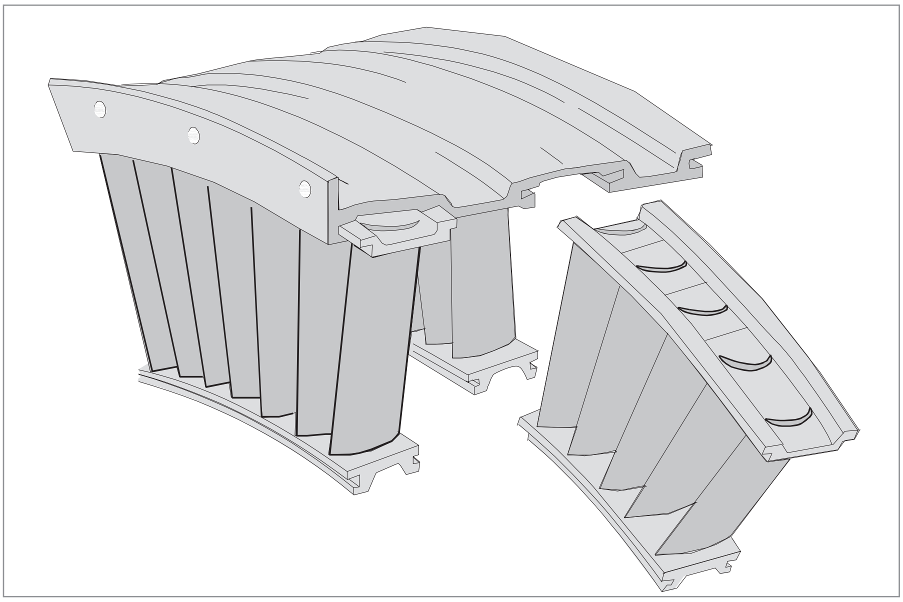


Figure 15.8 Segments of shrouded stator vanes.

Fan Blades

The high bypass ratio engine's low pressure compressor blades, more commonly known as the fan blades, were initially manufactured from solid titanium, this material having the properties of strength with lightness.

A low blade weight is essential if the fan is to be able to withstand the out of balance forces which would occur if a blade failed. Notwithstanding the enormous strength of titanium, the blades had to have incorporated into their design a snubber.

This was a support fitted at mid-span which prevented aerodynamic instability, unfortunately it also added weight, and, particularly when two of them were required, as shown in *Figure 15.9*, it interfered with the supersonic flow characteristics of the air at the extremities of the blade.

Figure 15.9 A high bypass ratio engine low pressure compressor or fan.

Experiments with new materials, particularly carbon fibre, were carried out, but its flexibility greatly reduced its effectiveness and its use has largely been discontinued.

The greatest advancement has been achieved by fabricating the blade from a honeycomb core sandwiched between two outer skins of titanium, see *Figure 15.10.*

This method gives added strength with less weight, enabling the introduction of the wide chord fan blade. The stability of the blade is ensured as a result of its wider chord and therefore the snubber is no longer necessary.

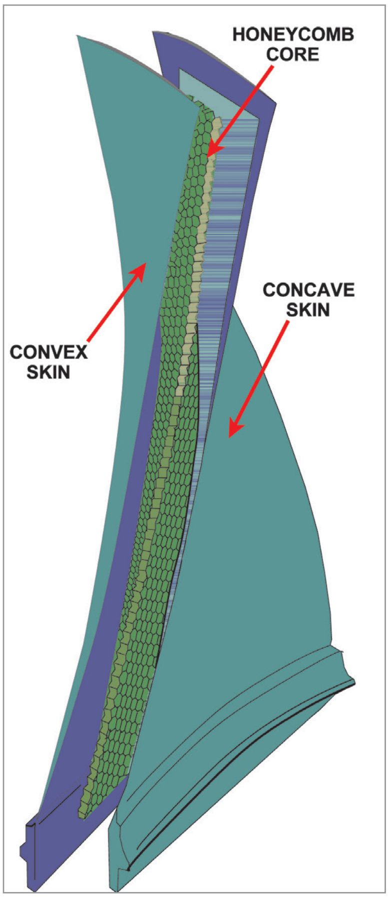


Figure 15.10 Wide chord fan blade construction.

Compressor (and Turbine) Contamination

Accumulation of contaminants in both the compressor and the turbine section of the engine reduces the efficiency of the unit and can seriously affect its performance.

The contaminants on the compressor, which are mostly salt and pollution from industrial areas, reduce the aerodynamic efficiency of the blades.

In the turbine the contamination takes the form of sulphidation, a build up of sulphur deposits from the burning fuel which destroys the aerodynamic shape of the turbine blades and the nozzle guide vanes and which will, over a period of time, erode their surface finish.

If the major cause of contamination is salt ingestion, then a timely rinsing of the compressor with fresh water can avoid the harsher treatment which otherwise will be required. This can be carried out either while motoring the engine over on the starter, or while running the engine at idle speed. This procedure is known as a desalination wash.

If the contamination has reached the stage where a desalination wash is not sufficient, then the application of an emulsion type surface cleaner may be necessary, this is sprayed into the engine intake under the same conditions as the desalination wash. This procedure is known as a performance recovery wash.

The turbine also benefits from this treatment, frequent applications allowing an extension of service life for some engines.

A more vigorous treatment, perhaps more applicable to centrifugal compressor engines, is that of the injection of an abrasive grit into the engine intake while it is running at an idle power setting.

The grit takes the form of broken walnut shells, (the Americans use the broken stones from apricots), unfortunately, because the grit is mostly burnt in the combustion chambers, this method does not clean the turbine components as well as the fluid cleaning method.

Questions

1. **The pressure ratio of a gas turbine engine compressor is:**

   a. equal to the number of compression stages
   b. the ratio between compressor outlet and compressor inlet pressure
   c. the ratio between exhaust inlet and exhaust outlet pressure
   d. never greater than 5 to 1

2. **The compressor idling speed of an uncompensated gas turbine engine will increase:**

   a. at higher ambient temperature
   b. with higher than sea level density
   c. at altitudes lower than sea level
   d. at lower ambient temperature

3. **One stage of an axial flow compressor consists of:**

   a. one rotor assembly and one row of stator vanes
   b. one stator assembly and one row of guide vanes
   c. one rotor and one impeller assembly
   d. one impeller and one diffuser assembly

4. **The pressure rise across each stage of an axial flow compressor is:**

   a. greater than that of a centrifugal compressor
   b. between 3 and 5 to one
   c. twice the inlet pressure
   d. between 1.1 and 1.2 to one

5. **The ring of blades which sometimes precede the first rotor stage of an axial flow compressor are called:**

   a. the first stage stator blades
   b. variable inlet guides vanes
   c. first stage diffuser blades
   d. nozzle guide vanes

6. **As air passes through an axial flow compressor, a pressure rise takes place in:**

   a. the impeller and the diffuser
   b. the rotor blades only
   c. both the rotor blades and the stator vanes
   d. the stator vanes only

7. **In the event of a surge occurring the correct action to be taken is:**

   a. to close the throttle quickly
   b. to close the throttle slowly
   c. to open the throttle fully
   d. to close the LP fuel valve

8. **Shrouding of stator blade tips is designed to:**

a. prevent tip turbulence
b. ensure adequate cooling
c. minimize vibration
d. prevent tip losses

9. **The cross-sectional area of the air annulus is reduced as it approaches the combustion chamber:**

a. to maintain the volume of the air under rising pressure
b. to prevent an increase of the velocity of the air under rising pressure
c. to maintain the axial velocity of the air toward the combustion chamber
d. to allow longer blades to be used towards the latter stages of the compressor

10. **The attachment of blades to the compressor disc:**

a. allows slight movement to relieve stress concentration
b. is rigid
c. prevents them being contaminated by the atmosphere
d. allows slight movement because of the different expansion rates of the blades and the disc, which would otherwise cause centre line closure

11. **Compressor blades are designed to produce:**

a. a given pressure and velocity rise
b. a constant flow over the engine speed range
c. a steady velocity with a pressure rise over the engine speed range
d. turbulent flow into the combustion chamber

12. **A compressor blade will stall when:**

a. the air axial velocity and rotational speed relationship is disturbed
b. the mass airflow and speed relationship is constant
c. the speed of the gas flow through the turbine falls below Mach 0.4
d. the compression ratio exceeds 10 to 1

13. **Compressor surge will occur when:**

a. all stages are at maximum efficiency
b. all stages are at maximum rpm
c. there is a partial breakdown of airflow through the compressor
d. all stages have stalled

14. **Cascade vanes are fitted in which part of the centrifugal compressor?**

a. the air inlet
b. the outlet elbow
c. the impeller
d. the diffuser

15. **The purpose of the diffuser vanes in a centrifugal compressor is to:**

    a. increase the charge temperature
    b. convert pressure energy into kinetic energy
    c. increase the air velocity
    d. convert kinetic energy into pressure energy

16. **The pressure rise across a centrifugal compressor:**

    a. occurs in the impeller only
    b. occurs in the diffuser only
    c. is shared almost equally by the impeller and the diffuser
    d. is always greater in the diffuser than in the impeller

17. **To gain a greater pressure ratio than 4:1:**

    a. two centrifugal compressors can be placed in parallel
    b. the compressor diameter must be reduced
    c. the cascade vanes must be convergent
    d. two centrifugal compressors can be placed in series with each other

18. **The major disadvantage of a centrifugal compressor is that:**

    a. it cannot cope with a large mass flow of air
    b. it cannot be used for a turbo jet engine
    c. a larger turbine must be used
    d. it is more prone to damage than the axial flow compressor

19. **The purpose of cascade vanes is to:**

    a. increase the velocity of the airflow prior to it entering the combustion chambers
    b. turn the air smoothly through 90 degrees and complete diffusion
    c. remove swirl from the airflow
    d. swirl the air, ready for the next compression stage

20. **The type of compressor used to create radial airflow would be:**

    a. positive displacement
    b. axial
    c. centrifugal
    d. constant volume

21. **Under ideal conditions the pressure rise across a single-stage centrifugal compressor can be:**

    a. 1.1 or 1.2 to 1
    b. not more than 4 to 1
    c. 1.5 to 1
    d. 30 to 1

22. **An advantage of a centrifugal compressor is that it is:**

    a. dynamically balanced
    b. more robust and is easier to manufacture
    c. unaffected by turbulence
    d. able to handle a larger mass of air than an axial flow compressor

23. A compressor stall causes:

a. the vibration level to increase with a decrease in the turbine gas temperature
b. an increase in the turbine gas temperature and the vibration level
c. the rotation of the engine to stop suddenly
d. the airflow through the engine to stop suddenly

24. Air passing through a convergent duct experiences:

a. a decrease in temperature and pressure with an increase in velocity
b. an increase in temperature and velocity with a decrease in pressure
c. an increase in temperature and pressure with a velocity decrease
d. adiabatic expansion

25. Fuel is regulated on rapid engine acceleration:

a. to prevent detonation in the combustion chambers
b. because the rapid response of the compressor might cause a flame out
c. because the cooling effect of too much fuel would cause a drop in pressure in the combustion chamber
d. to prevent inducing a compressor stall and surge

26. A compressor stall:

a. is overcome by increasing the fuel flow
b. is a complete breakdown of the airflow through the compressor
c. may only affect one stage or several stages of a compressor
d. is mechanical failure of the compressor

27. Compressor blades increase in size:

a. from the root to the tip to increase the temperature
b. from the high pressure section of the compressor to the low-pressure section
c. from the low-pressure section of the compressor to the high-pressure section to maintain a constant airflow velocity
d. from the tip to the root to decrease the temperature

28. The occurrence of compressor stalls is limited by:

a. bleed valves
b. nozzle guide vanes
c. swirl vanes
d. cascade vanes

29. Bleed valves are automatically opened:

a. at maximum rpm to prevent compressor stall
b. at low rpm to prevent the turbine stalling
c. during engine acceleration to prevent turbine surge
d. at low engine rpm to prevent the compressor stalling

30. **To prevent compressor stall at the rear of the compressor, bleed valves must be positioned:**

a. at the rear stages of the compressor
b. at the front stages of the compressor
c. at the mid stages of the compressor
d. at the intake of the engine

31. **A complete breakdown of airflow through a compressor is known as:**

a. compressor turbulence
b. compressor buffet
c. compressor surge
d. compressor seizure

32. **One indication that a compressor bleed valve has stuck closed at low rpm is:**

a. possible compressor stall
b. an inability to achieve full power
c. that bleed air is reduced
d. that the engine will stop

33. **Within the compressor:**

a. bleed valves are set to open at high rpm
b. pressure decreases
c. temperature decreases
d. temperature increases

34. **Bleeding compressor air for anti-icing will cause:**

a. an increase in EGT, a decrease in thrust and an increase in SFC
b. a decrease in EGT, an increase in thrust and a decrease in SFC
c. an increase in rpm and fuel flow
d. an increase in rpm and a decrease in fuel flow

35. **Variable inlet guide vanes:**

a. deflect air past the compressor
b. adjust the relative airflow position
c. deflect air past the turbine
d. induce air into a centrifugal compressor

36. **Compressor blades are twisted from root to tip:**

a. to decrease the pressure
b. to maintain a correct angle of attack
c. to reduce the relative airflow
d. to give added rigidity to the blade structure

37. **In a compressor:**

a. the air temperature is steady with a pressure rise
b. the air temperature falls with a pressure rise
c. the drop in air temperature is inversely proportional to the pressure rise
d. the air temperature rises with a pressure rise

38. A stall in a gas turbine engine is most likely to occur with:

	Pressure Ratio	Location in Compressor
a.	high	front
b.	high	back
c.	low	back
d.	low	front

39. Contamination of the compressor:

a. is not likely to prove a problem if the aircraft is not flown at low level over the sea
b. will not decrease the performance of the engine if the fuel sulphur content does not exceed 0.001%
c. can seriously reduce the efficiency of the engine
d. can be reduced by periodically flying through thunderstorms

40. The low pressure compressor of a high ratio bypass engine:

a. is driven by the high pressure turbine
b. rotates faster than the high-pressure compressor
c. is always a centrifugal compressor
d. is driven by the rearmost turbine

Answers

1	2	3	4	5	6	7	8	9	10	11	12
b	a	a	d	b	c	b	c	c	a	c	a

13	14	15	16	17	18	19	20	21	22	23	24
d	b	d	c	d	a	b	c	b	b	b	a

25	26	27	28	29	30	31	32	33	34	35	36
d	c	b	a	d	c	c	a	d	a	b	b

37	38	39	40
d	c	c	d

Chapter

16

Gas Turbines - Combustion Chambers

The Task of the Combustion Chamber

The combustion chamber must contain the burning mixture of air (from the compressor) with fuel (from the fuel spray nozzles), to allow the maximum heat release at a substantially constant pressure, so that the turbine receives a uniformly expanded, heated and accelerated stream of gas. This is not an easy task, but advancements are constantly being made in combustion chamber design to enable more efficient use of fuel with less and less pollution of the atmosphere.

Efficient combustion has been made increasingly more important because of the rise in the cost of the fuel itself, and the increasing awareness of the general public of the dangers of atmospheric pollution from the exhaust smoke.

The Temperature Increase Allowed

There is a limit to the maximum temperature of the gas from the combustion chamber, this is imposed by the materials from which the nozzle guide vanes and the turbine are manufactured. The slightest excursion above that limit will mean the possible disintegration of the turbine with probably catastrophic results.

The Temperature Increase Required

Modern materials will allow a gas temperature initially in the combustion chamber of 2000°C plus. When it exits the combustion chamber the temperature must be reduced to 1000 to 1500°C. Considering that the air may already have been heated to around 600°C due to compression, sufficient fuel must be added to raise the temperature further.

This of course would be the temperature at full power, lower power settings would require lower fuel flows so the combustion chamber has to be capable of maintaining stable and efficient combustion over a wide range of engine operating conditions.

The Flame Rate of Kerosene

Air enters the combustion chamber at approximately the same rate at which it enters the intake of the engine, speeds of up to 500 feet per second are not unusual.

The flame rate of kerosene, the speed at which the leading edge of the flame travels through the vapour, is 1 to 2 feet per second. If burning kerosene was exposed in an airstream which was travelling at 500 feet per second it would be extinguished immediately.

Something must be done to slow down the speed of the airflow after it leaves the compressor and before it reaches the primary zone, the zone inside the combustion chamber where it is mixed with the fuel and burnt.

Figure 16.1 shows how the air is slowed down and its pressure is increased after it leaves the compressor and before it enters the combustion chamber.

In fact the pressure attained at this point is the highest in the whole of the engine. The reduction in velocity is still not enough however, further decreases must be achieved if the flame is not to blow out.

Figure 16.1 shows how the air entering the primary zone passes through the snout before being divided to go through the perforated flare and the swirl vanes.

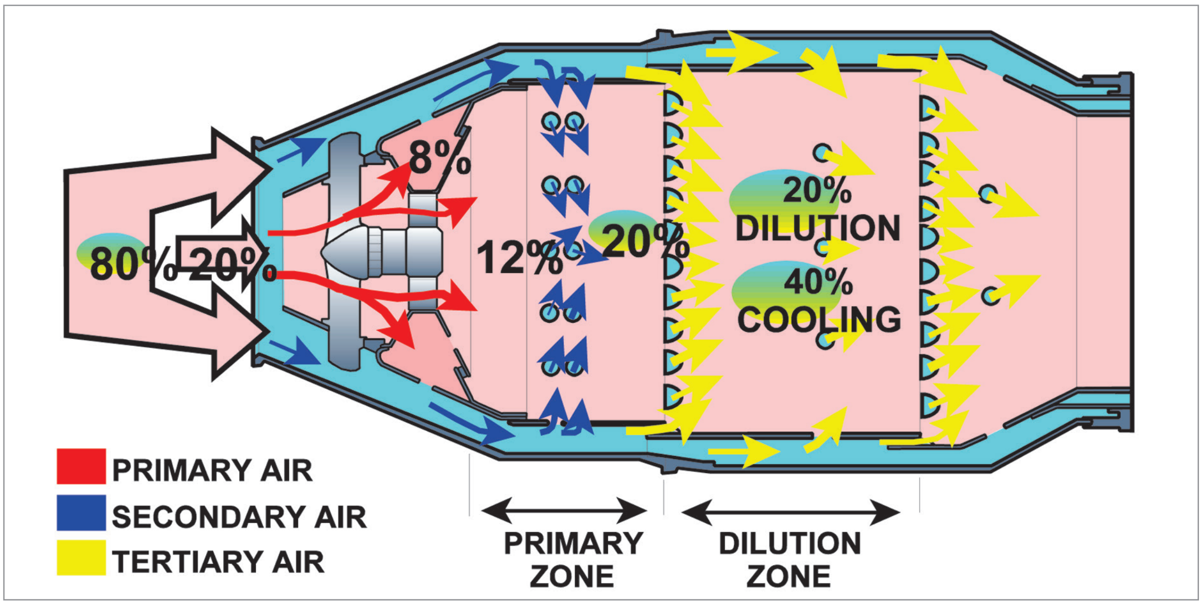


Figure 16.1 The division of airflow through the combustion chamber.

Primary Air

The primary air is then 20% of the flow coming into the combustion chamber, this is basically the air which is mixed with the fuel and burnt.

By being passed through the flare and the swirl vanes, the velocity of this air is reduced, and it also starts the recirculation which is required if the flame is not to be extinguished.

Secondary Air

The air which has not been picked up by the snout goes into the space between the flame tube and the air casing. Some of this air is allowed into the flame tube through secondary air holes. Secondary air, about 20% of the total, reacts with the primary air flowing through the swirl vanes to form a toroidal vortex, a region of low velocity airflow which resembles a doughnut or a smoke ring. This stabilizes and anchors the flame and prevents it being dragged down the flame tube away from the fuel nozzle area.

The temperature of the gases at the centre of the primary zone reaches about 2000°C, this is far too hot for the materials of the nozzle guide vanes and turbine blades so a further drop in temperature is required before the gases can be allowed to exit the combustion chamber.

Tertiary Air

The remaining 60% of the total airflow, tertiary air, is progressively introduced into the flame tube to cool and dilute the gases before they are allowed to go into the turbine assembly. Tertiary air is used to cool both the gas exiting the chamber and the walls of the air casing.

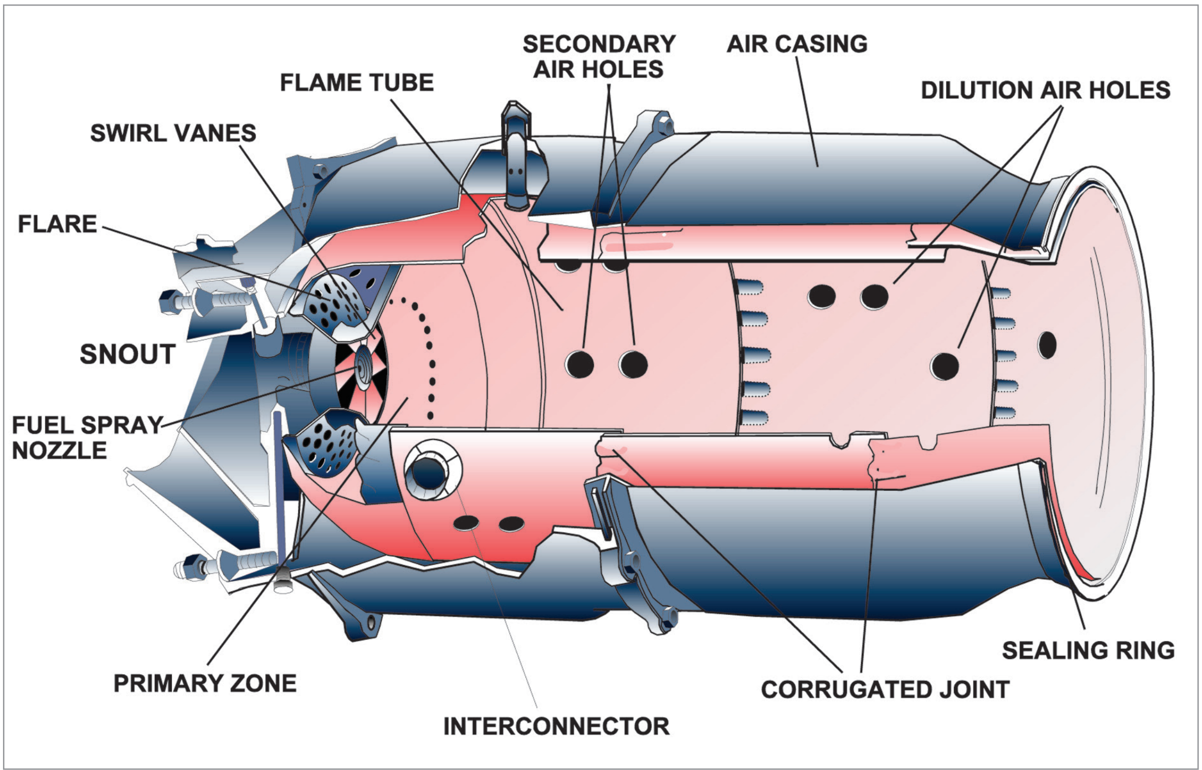


Figure 16.2 An early combustion chamber.

The combustion chamber shown in *Figure 16.2* is one of several which would have been used in an early multiple combustion chamber system, more modern designs use a different method of cooling the air casing, this is termed transpiration cooling, where a film of air flows between laminations which form the air casing wall.

The Combustion Chamber Components

Figure 16.2 shows several interesting features of a multiple combustion chamber.

Most gas turbine engines only have **two igniters**, in fact the engine would probably start quite readily with only one operating, however, because there are only two, another means of passing the starting flame between the combustion chambers has to be found, this is the inter-connector.

Immediately after **light up**, the flame in the chamber with the igniter causes an increase in the pressure within that chamber. The pressure differential between that chamber and the one adjoining it drives the burning gases through the inter-connector where they ignite the mixture.

This process is continued around the engine until the contents of all of the chambers is burning, whereupon the pressures within them are equalized and the flow through the inter-connectors ceases.

The **sealing ring** at the turbine end of the combustion chamber allows for elongation of the chamber due to expansion. The chamber is fixed at the compressor end by being bolted onto it, it cannot expand in that direction. The sealing ring allows the chamber to expand into the **nozzle box**, the portion of the engine immediately preceding the **nozzle guide vanes**, while maintaining a gas tight seal.

The **corrugated joints** allow the tertiary air to bleed into the flame tube, so causing a gradual drop in the temperature of the gases before they exit into the nozzle guide vanes.

The Multiple Combustion Chamber System

The straight through flow multiple combustion chamber system was developed from Sir Frank Whittle's original design. It was used on some earlier types of axial flow engine and is still in use on centrifugal compressor engines like the Rolls Royce Dart.

It consists of eight or more of the chambers illustrated in *Figure 16.2*, disposed around the engine to the rear of the compressor section, each chamber being made up of a flame tube with an individual air casing.

Shown in *Figure 16.3* is a multiple combustion chamber system similar to that used on the Rolls Royce Avon, which was a powerful (for its time) axial flow compressor engine used on many different types of aircraft, both military and commercial, for a considerable number of years.

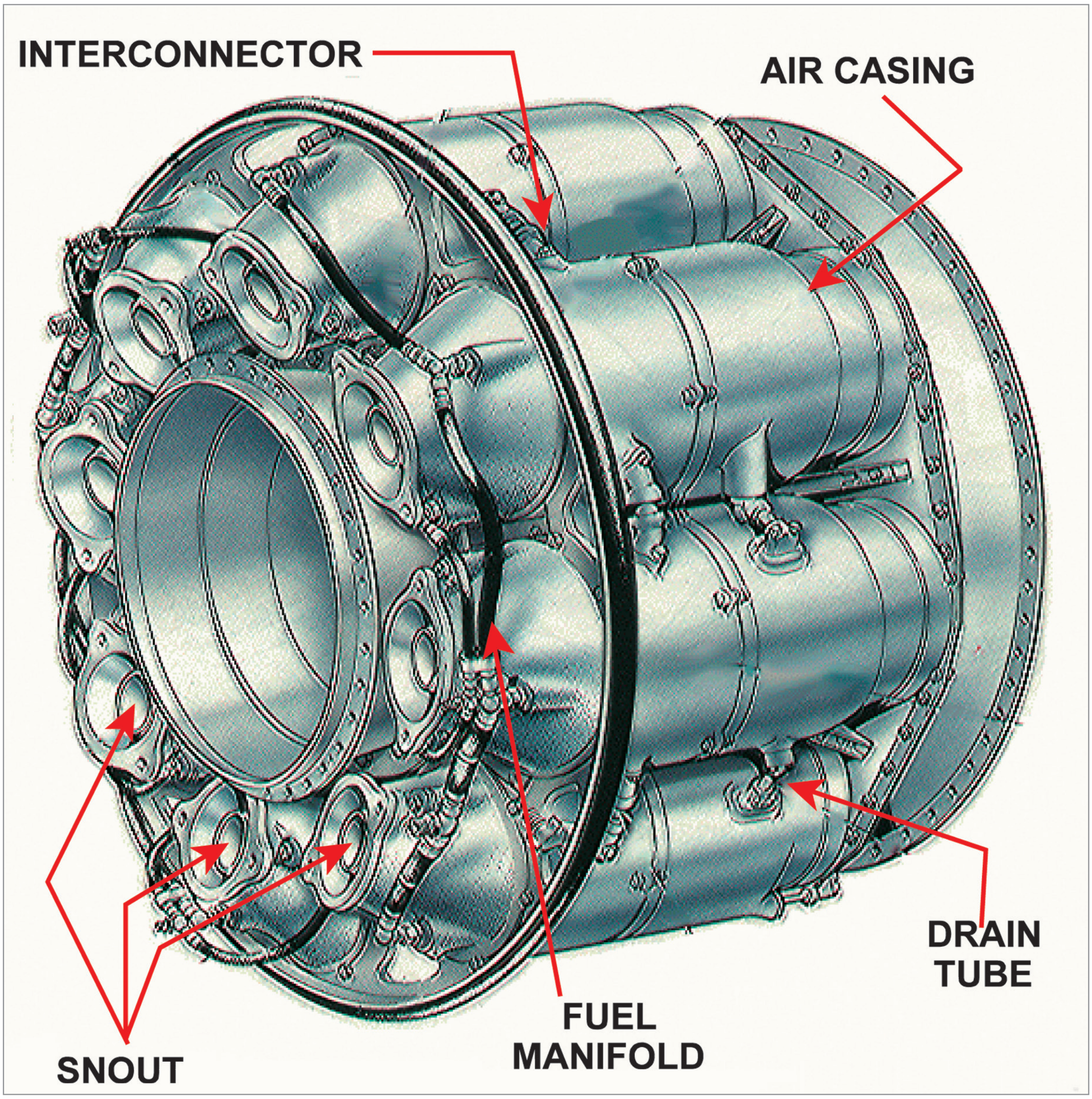


Figure 16.3 A multiple combustion chamber system.

Well defined in *Figure 16.3* are **the snout** (the primary air scoop), **the inter-connectors** and **the drain tubes.**

The drain tubes provide for the unlikely event of a failure to start, more commonly known as a wet start. This situation happens when the mixture in the combustion chamber fails to ignite during a start.

A considerable amount of fuel will have been fed into the engine and if it is not removed before the next attempt to start, the result will be a very long, very hot and very dangerous jet of flame from the rear of the engine.

The Fuel Drain System

Two means of getting rid of the fuel are open to us, first, the fuel drain system, and secondly a method of evaporating the remaining traces from the chambers and the jet pipe. The fuel drain system utilizes the drain tubes which connect the lowest part of each chamber with the next chamber below it.

Fuel remaining after a wet start will attempt to find its own level by flowing from the top of the engine to the bottom chamber. Once in the bottom chamber it exits via the drain valve located at the six o'clock position, which is spring loaded towards open. During normal engine operation internal pressure keeps the valve shut.

To evaporate any remaining traces of fuel from the chambers, the engine is then motored over on a blow out cycle.

Utilizing the starter motor, the engine is rotated for the time normally allocated to a full start cycle, with the HP fuel cock shut and the ignition system automatically de-selected. Compressed air will flow through the combustion chamber and assist in the evaporation of any fuel still remaining within.

The Tubo-annular Combustion Chamber System

The tubo-annular combustion chamber system, illustrated in *Figure 16.4* is sometimes also called the cannular or can-annular system.

It differs from the multiple combustion chamber system insofar as it does not have individual air casing for each of the flame tubes. A number of flame tubes are fitted within one common air casing which provides a more compact unit. This illustration is one of the few to show an igniter plug.

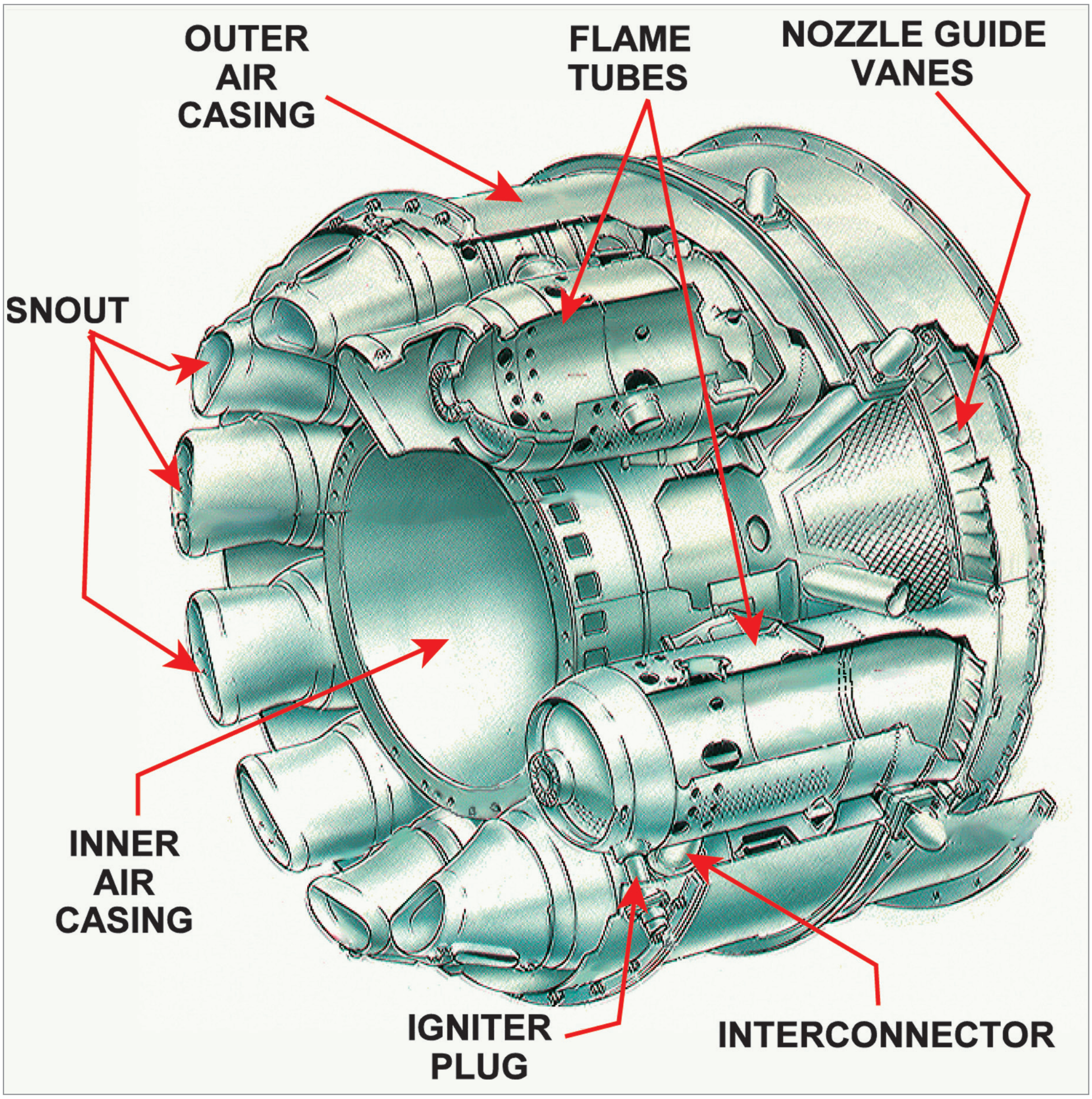


Figure 16.4 A tubo-annular combustion chamber system.

The Annular Combustion Chamber System

The annular combustion chamber system has only one flame tube which is contained by an inner and outer air casing. A typical example is shown in *Figure 16.5* and in further detail in *Figure 16.6*.

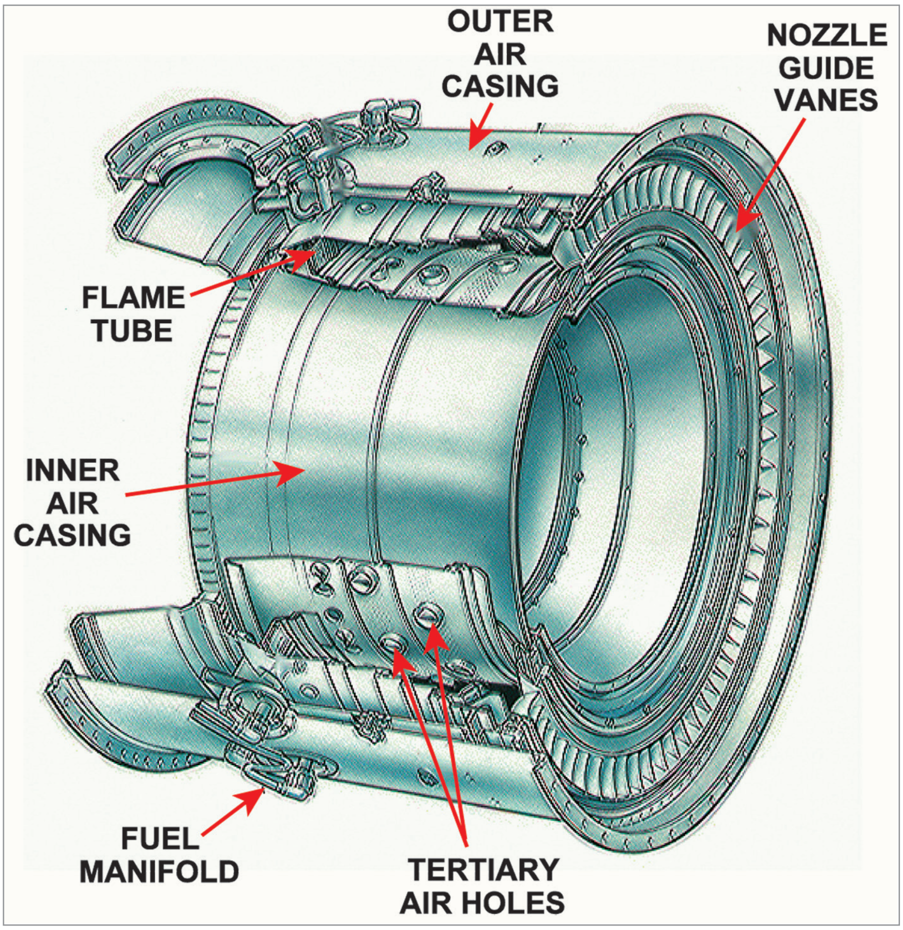


Figure 16.5 An annular combustion chamber.

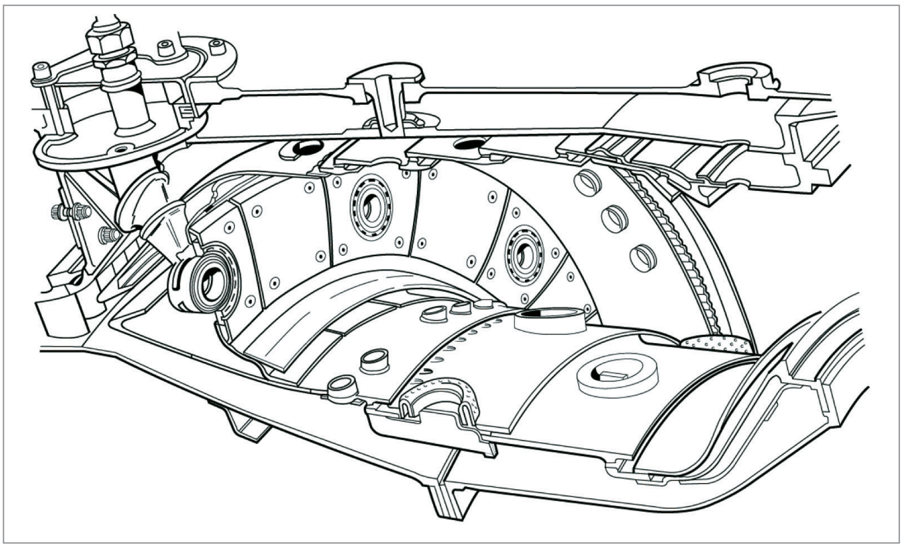


Figure 16.6 Details of annular combustion chamber (based on an original Rolls-Royce drawing).

The annular system has several advantages over the two other systems previously mentioned from which it was developed, they are:

a) For the same power output, the length of the annular chamber is only 75% that of a tubo-annular system of the same diameter.

b) There are no flame propagation problems.

c) Compared to a tubo-annular system, the air casing area is less, consequently less cooling air is required.

d) The combustion efficiency is raised to the point where unburnt fuel is virtually eliminated, allowing the oxidization of carbon monoxide to non-toxic carbon dioxide.

e) There is a much better pressure distribution of the gases impinging on the turbine so it has a more even load placed upon it.

The Air/Fuel (Stoichiometric) Ratio

To obtain the maximum heat release, the chemically correct air/fuel ratio of 15:1 must be used. Whereas in the piston engine the use of this ratio would cause detonation and dissociation to occur, in the gas turbine engine it poses no such problem because there are no peaks of pressure to assist in their generation.

The fuel and air are therefore mixed and burnt in the primary zone in the ratio of fifteen units of air to one unit of fuel, by weight. The addition of secondary and tertiary air will however dilute the mixture to the extent that the overall ratio may vary between 45:1 to as weak as 130:1.

Pressure Losses in the Chamber

It has been stated that combustion theoretically occurs at a constant pressure, in fact, as is shown in Chapter 13 *(Figure 13.5)* there is a small loss in pressure throughout the combustion chamber. This is caused by having to provide adequate turbulence and mixing. Losses vary from 3% to 8% of the pressure at the entrance to the combustion chamber.

Combustion Stability

During normal engine running conditions, combustion is self-supporting. Effectively the ignition system can be switched off as soon as the engine has attained self-sustaining speed, the speed at which, after start, it can accelerate without the assistance of the starter motor.

There may be certain engine operating conditions which do require ignition, for instance following a flame out, which is extinction of the flame due to various unusual occurrences, such as the ingestion of large amounts of water during take off from contaminated runways.

Another condition which can cause flame extinction is when the air/fuel ratio becomes too weak, a situation which is most likely to occur when the engine is throttled back during descent when a low fuel flow and high air mass flow will coincide.

Combustion stability means smooth burning coupled with the ability to remain alight over a large range of air/fuel ratios and air mass flows. *Figure 16.7* shows the limits of combustion stability.

It can be seen from *Figure 16.7*, that combustion stability will occur only between narrower and narrower limits as the air mass flow increases. The range between the rich and weak limits is reduced as the mass flow increases, beyond a certain point the flame is extinguished.

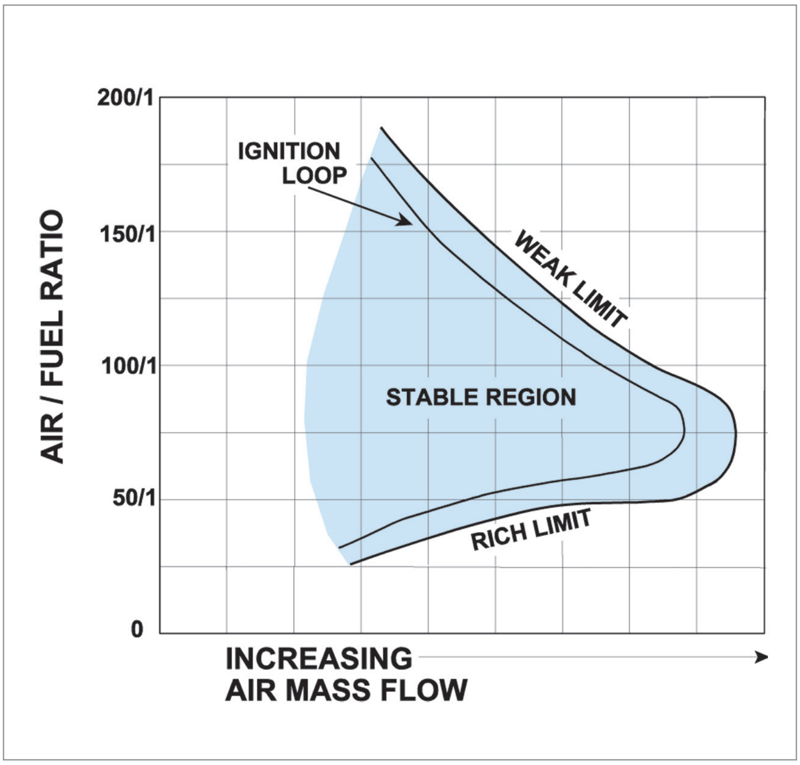


Figure 16.7 A typical combustion stability loop.

The ignition loop shown within the limits of the stable region illustrates that it is more difficult to start the combustion than it is to sustain it once it has started.

A consequence of this is that should the engine flame out at high speed or high altitude, it may be necessary to reduce both parameters before a successful relight can be obtained.

Relighting

As mentioned above, the ability of an engine to relight will vary according to the height and forward airspeed of the aircraft. *Figure 16.8* illustrates a notional relight envelope showing the flight conditions under which a serviceable engine would be guaranteed to relight.

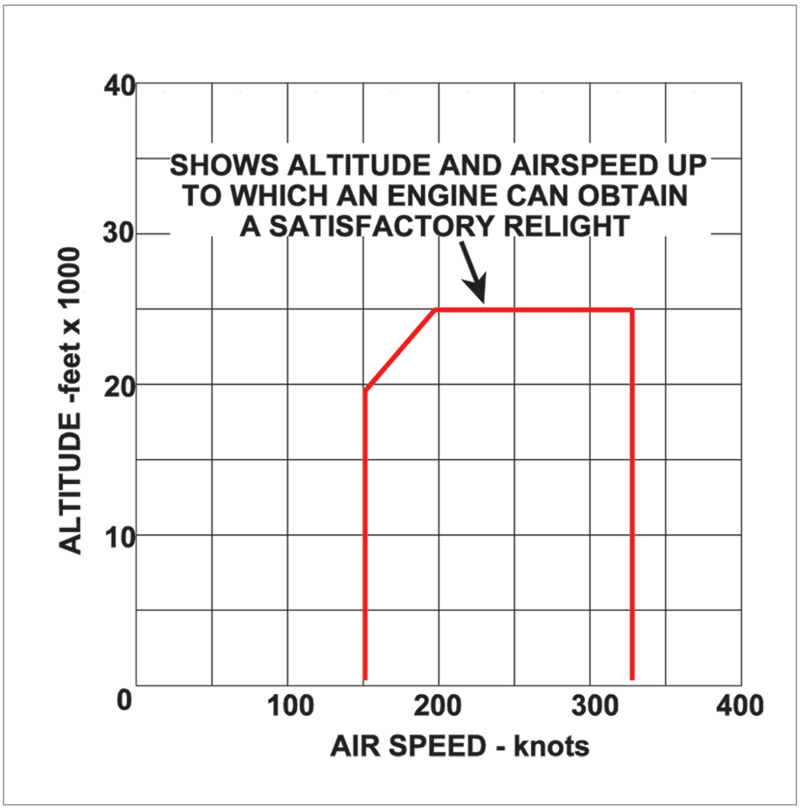


Figure 16.8 The relight envelope.

The airflow through the engine will cause it to rotate (windmill), so the compressor will supply sufficient air, all that is then required is the opening of the HP fuel cock and operation of the ignition system.

This is achieved by selection of the relight switch, which functions separately from the normal start circuit.

Combustion Efficiency

Combustion efficiency is the efficiency with which the combustor assembly extracts the potential heat actually contained in the fuel. Modern gas turbine engines have a very efficient combustion cycle.

At high power operating conditions combustion efficiencies as great as 99% are achievable, and at idle the systems will still give as much as 95%. This is illustrated in *Figure 16.9*, also shown is the overall air/ fuel ratio throughout the normal operating range of the engine.

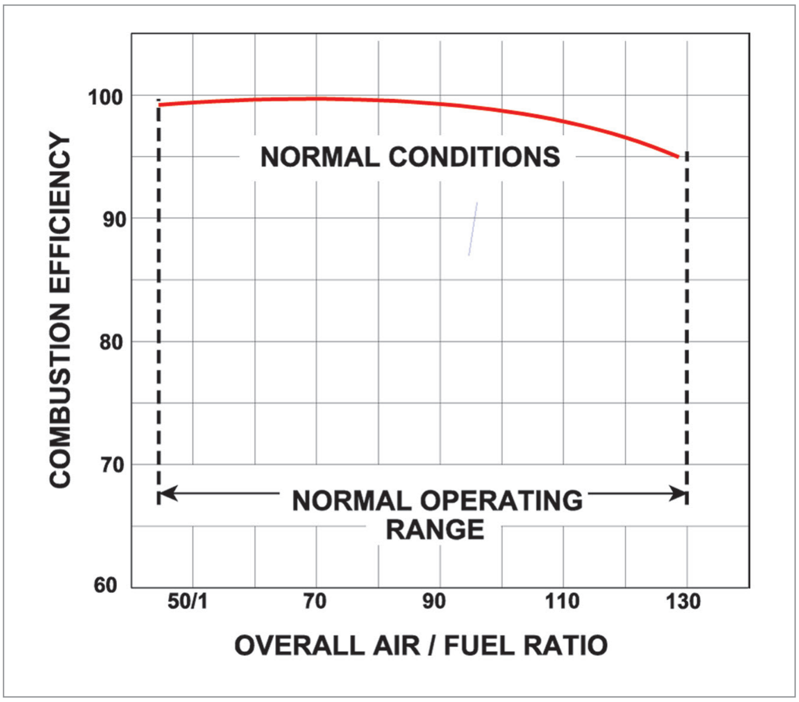


Figure 16.9 Combustion Efficiency and Air/Fuel Ratio.

Fuel Spray Nozzles

The very high combustion efficiency noted in the previous paragraph is due in no small part to the fuel spray nozzles which are used in large, modern, gas turbine engines. The nozzles have the task of atomizing or vaporizing the fuel to ensure that it is completely burnt. This is no easy job considering the velocity of the airstream from the compressor and the small distance allowed within the chamber for combustion to occur.

Other problems are a result of the relatively low pressures attainable by the engine driven high pressure fuel pump at engine start. The pumps, driven by the high speed gearbox, are only rotating at a minimal speed upon start selection and are

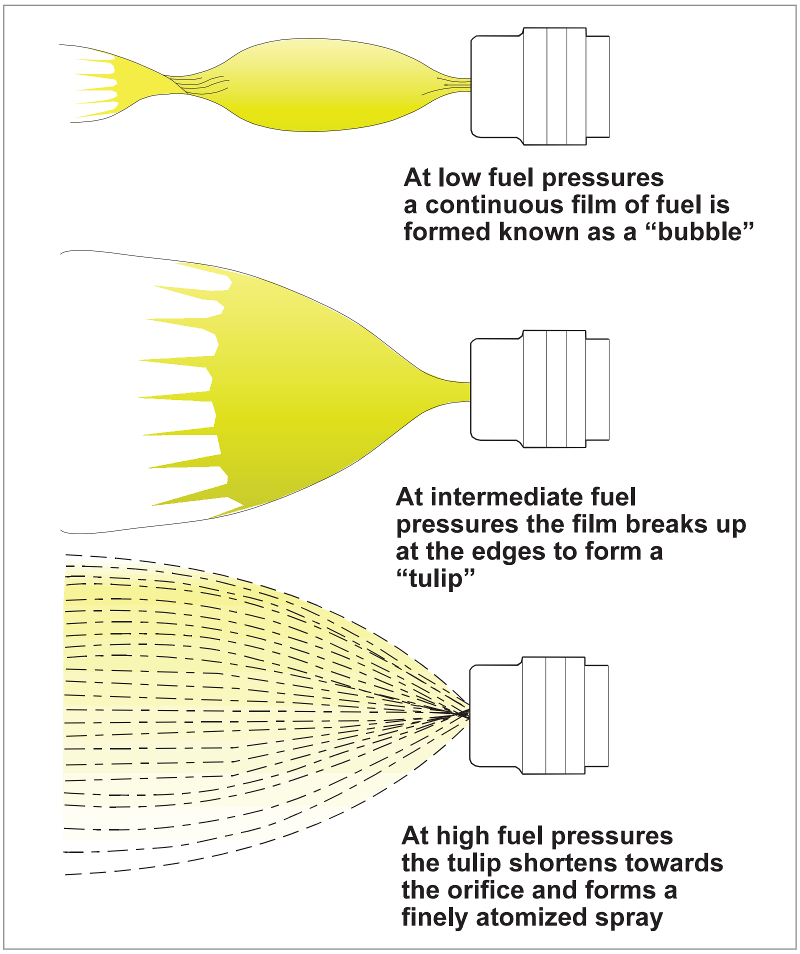


Figure 16.10 Fuel spray patterns at various pressures.

incapable, at that speed, of providing the high pressures (1500 - 2000 psi) required to give a good spray pattern, see *Figure 16.10*.

It can be clearly seen here that an orifice of fixed size will only provide a finely atomized spray at high fuel pressures, some other method must be found to give sufficient atomization at start when fuel pressures are low.

The Airspray System

One principle utilized in obtaining the required spray pattern is that of a high velocity airstream to break up the flow, this is the airspray system, it needs relatively low fuel pressures and so therefore can operate using a gear type pump which is much lighter than the more sophisticated plunger type pump.

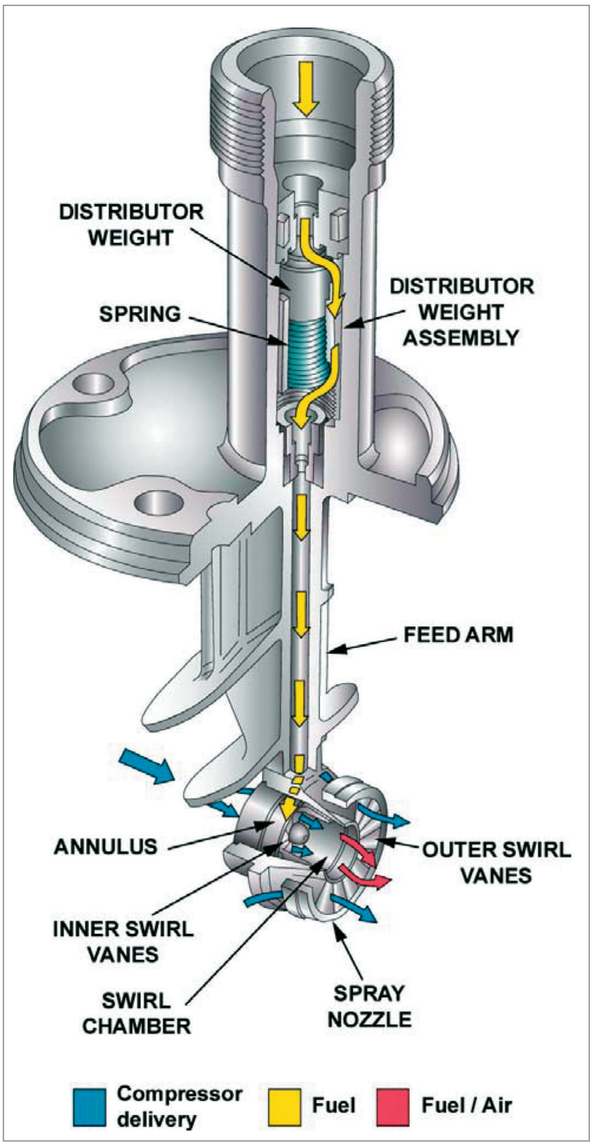


Figure 16.11 An airspray nozzle.

The Duplex System

The Duplex system, shown in *Figure 16.12*, effectively uses an orifice of variable size. At low fuel pressures, a pressurizing valve closes off the main fuel feed to the nozzle, the only supply coming from the primary fuel line.

The primary fuel line feeds the primary orifice, a much smaller hole which is capable of providing a fine spray at lower pressures. When the engine accelerates during start, fuel pressure builds until the pressurizing valve is opened, allowing fuel to flow to the main orifice to supplement that from the primary orifice.

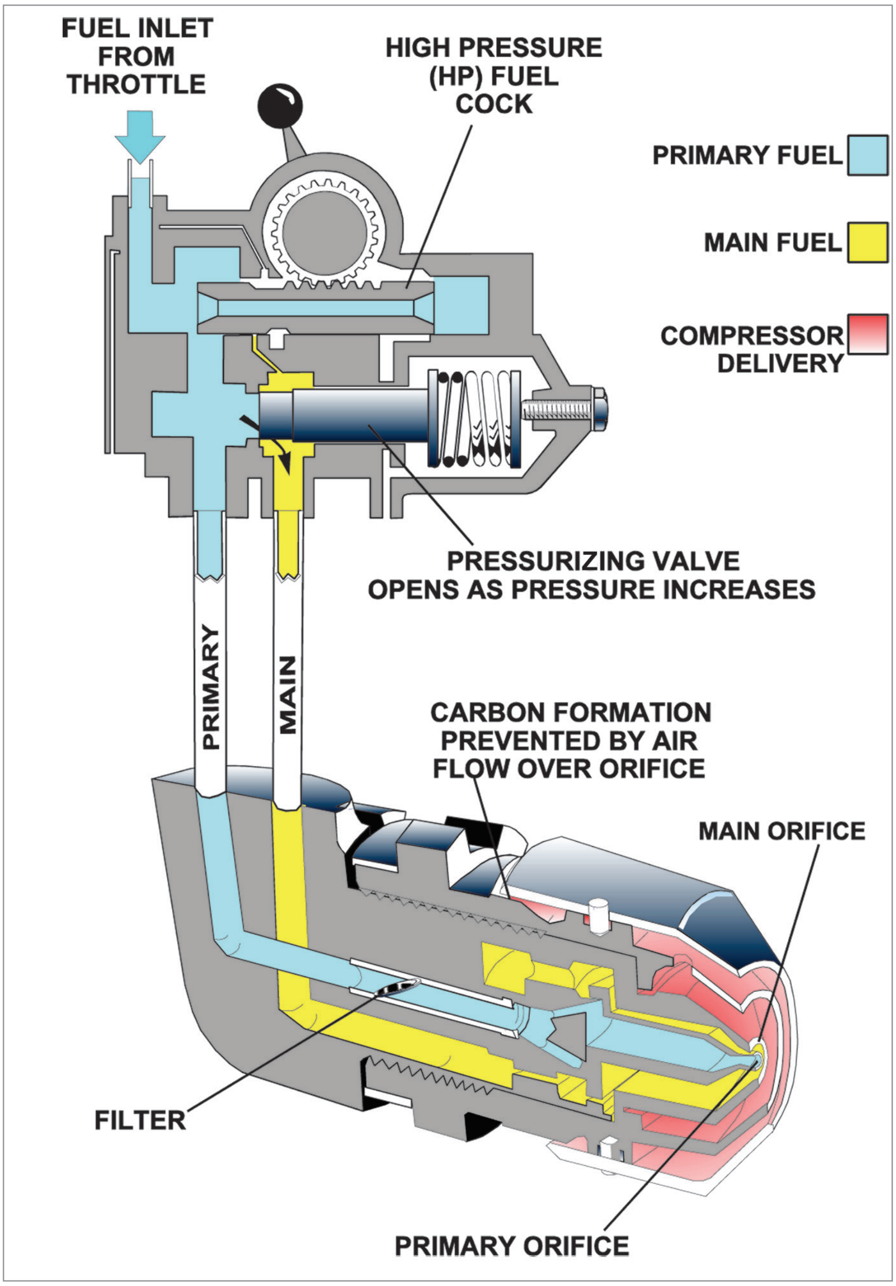


Figure 16.12 The duplex fuel spray nozzle.

The Vaporizing Tube System

In the vaporizing method, *Figure 16.13*, the fuel is sprayed from feed tubes into vaporizing tubes which are positioned inside the flame tube. Primary air is fed into the flame tube through the fuel feed tube opening and also through holes in the flame tube entry section. The fuel is turned through 180 degrees, and as the tubes are heated by combustion, it is vaporized before passing into the flame tube.

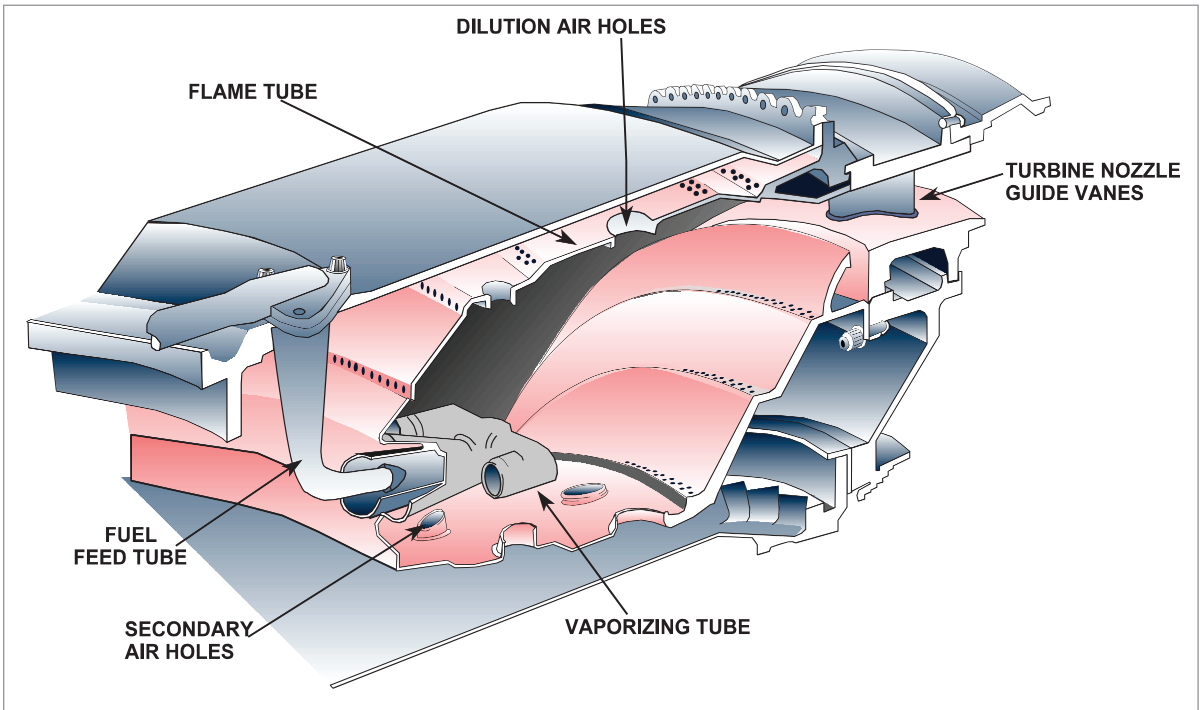


Figure 16.13 The vaporizing method of fuel feed.

Questions

1. **The ratio of air to kerosene to give the greatest heat release during combustion is:**

    a. 45:1
    b. 130:1
    c. 12.5:1
    d. 15:1

2. **One advantage of an annular combustion chamber system is that:**

    a. the diameter of the engine is reduced
    b. there is unrestricted airflow at maximum rpm
    c. there are no flame propagation problems
    d. the air casing area is greater

3. **Of the total airflow entering the combustion chamber the percentage that is mixed with the fuel and burnt is:**

    a. 10%
    b. 40%
    c. 20%
    d. 60%

4. **The combustion chamber drain valve is closed:**

    a. by combustion chamber gas pressure
    b. by a return spring
    c. by 12th stage compressor air pressure
    d. during a blow out cycle

5. **A cannular combustion system is:**

    a. a set of flame tubes, each of which is mounted in a separate air casing
    b. a set of flame tubes enclosed in a common air casing
    c. one common flame tube enclosed in a common air casing
    d. superior to the annular system because it only requires one igniter

6. **It is necessary to have a combustion drain system:**

    a. to prevent pressure build up in the combustion chamber
    b. to allow moisture content in the fuel to drain away
    c. to allow any unburnt fuel to drain after shutdown or a wet start
    d. to prevent the igniters becoming wetted by excess fuel

7. **The purpose of the tertiary airflow created in the combustion chamber is to:**

    a. reduce the gas temperature and cool the flame tube
    b. form a toroidal vortex, which anchors and stabilizes the flame
    c. reduce the gas temperature and cool the burner head
    d. ensure complete combustion of the fuel

8. **A relight envelope:**

   a. shows the flame stability limits
   b. shows airspeed and altitude limitations for an in-flight restart
   c. shows fuel/air mixture limitations for an in-flight restart
   d. contains the in-flight restart igniter plugs

9. **Swirl vanes in the combustion chamber:**

   a. increase the velocity of the airflow
   b. reduce the velocity of the airflow
   c. prevent compressor stall
   d. help to stabilize combustion

10. **The air entering the combustion chamber is divided; a small percentage is used in combustion, the rest:**

   a. is syphoned off for airframe anti-icing purposes
   b. is used only for cooling the gases before they exit the combustion chamber
   c. is used to reduce the oil temperature and cool the turbine blades
   d. is used to cool both the gases exiting the chamber and the walls of the air casing

Answers

1	2	3	4	5	6	7	8	9	10
d	c	c	a	b	c	a	b	b	d

Chapter

17

Gas Turbines - The Turbine Assembly

The Task of the Turbine Assembly

The turbine of a gas turbine engine can be likened to the axial flow compressor in reverse. Initially a stator section (nozzle guide vane) directs the air axially onto a rotor section. The turbine extracts energy from the hot gases that flow through it, and converts it into mechanical energy which it uses to drive the compressor and gearboxes. These can be used to operate accessories or, in the case of engines that do not use predominantly jet propulsion, to power propellers or rotors.

The energy available in the gases flowing through the turbine take the form of heat energy, potential (pressure) energy, and kinetic (velocity) energy. The conversion of all these into mechanical energy means that the value of all of them will be reduced as they pass through the turbine. However, the velocity of the gas in the combustion chamber is lower than the velocity of the gas in the exhaust unit.

The Stresses in the Turbine

During normal operation of the engine, the rotational speed of the turbine may be such that the blade tips travel at a rate in excess of 1500 feet per second. At the same time, the temperature of the gases driving the turbine can, in a modern engine, reach as high as 1700°C.

The speed of these gases is as high as 2500 feet per second, which is close to the speed of sound at these temperatures.

These factors mean that a small turbine blade weighing only 2 ounces when stationary can exert a load of two tons while working at top speed. This tensile loading, coupled with the tremendous heat, causes a phenomenon called creep, the stretching of the metal of the blade beyond its ability to reform back to its original length.

Whatever materials have been used to produce the turbine, and however carefully the temperature and rpm limits of the engine have been observed, creep will cause the length of the blade to increase over a period of time and engine operational cycles. A blade will have a finite life before failure occurs.

Low cycle fatigue describes relatively early turbine failure due to high operational demands. High cycle fatigue describes failure after longer turbine life due to lesser operational demands.

Turbine Blade Materials

The turbine blades of early gas turbine engines were manufactured from high temperature steel, this material imposed a severe limit upon the temperature at the rear of the engine, and as the gas turbine engine is a heat engine it follows that the power output was limited as a consequence.

The next advance in turbine technology was the use of nickel based alloys, and these were subsequently superseded by super alloys. These are a complex mixture of many different metals: chromium, cobalt, nickel, titanium, tungsten, carbon etc. Super alloys have a maximum temperature limit of approximately 1100°C or, if they are cooled internally, 1425°C.

A more recent practice is powder metallurgy, in which powdered super alloys are hot pressed into a solid state, but in the search for even stronger materials a procedure called single crystal casting is now being used in the most advanced engines. Traditional metal manufacturing processes produce a crystal lattice, or grain, in the material. The boundaries of the crystals create a weakness in the structure and are most likely to be the starting point of any failure. Single crystal material forms as only one grain in the mould, eliminating corrosion and creating an extremely creep resistant blade.

Ceramic materials are also being used in the production of turbine blades. Originally the ceramic was applied as a plasma spray, the coating giving very good protection against a corrosive condition caused by a reaction between the base metals of the blade, the sodium in the air and the sulphur in the fuel.

The Turbine Stage

It was shown in Chapter 15 that the compressor added energy to the air by increasing its pressure, in the turbine that energy is extracted by reducing the pressure of the gases flowing through it. This drop in pressure occurs both as it is converted to velocity in the nozzle guide vanes, and also as it is converted into mechanical energy in the turbine blades, see Chapter 13 *(Figure 13.5)*.

The turbine stage therefore consists of two elements, one row of stationary nozzle guide vanes and one row of rotating turbine blades. The complete turbine assembly comprises one or more turbine stages on one shaft, which, if coupled to a compressor, forms a spool.

Figure 17.1 shows a single shaft three stage turbine similar to that used on the Rolls Royce Dart turboprop engine.

There are certain features shown in this diagram which are worthy of special note.

The divergent gas flow annulus affords longer blades to be fitted moving backwards in the turbine to enable velocity to be controlled as the gas expands into the larger area.

The blade shroud is an attempt to minimize losses due to leakage across the turbine blade tips and also reduce vibration.

The clearance between the blade tips and the turbine casing varies because of the different rates of expansion and contraction of the materials involved. An abradable lining has been used in the casing area to reduce gas leakage through this clearance, but active clearance control, like that used in a modern compressor, is more effective at maintaining minimum tip clearance throughout the flight cycle, *Figure 17.2* shows its use on an American engine.

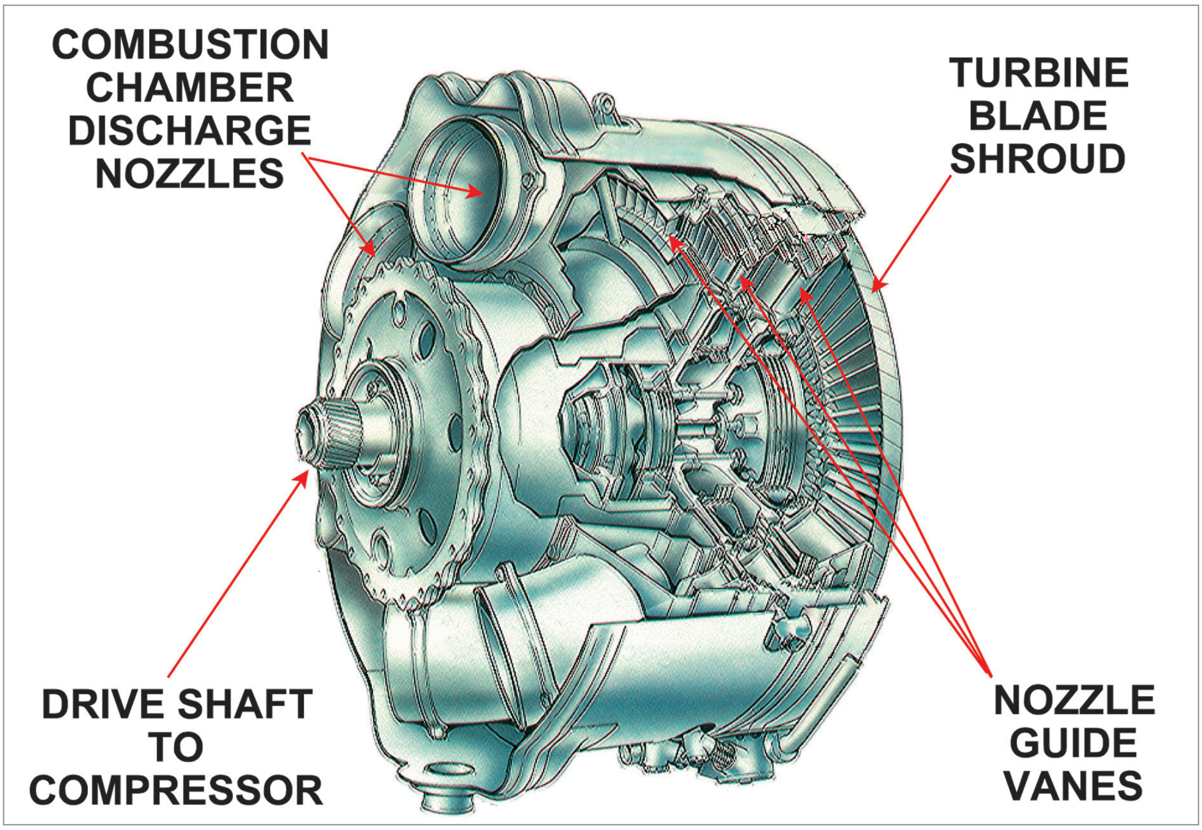


Figure 17.1 A three stage turbine assembly mounted on one shaft.

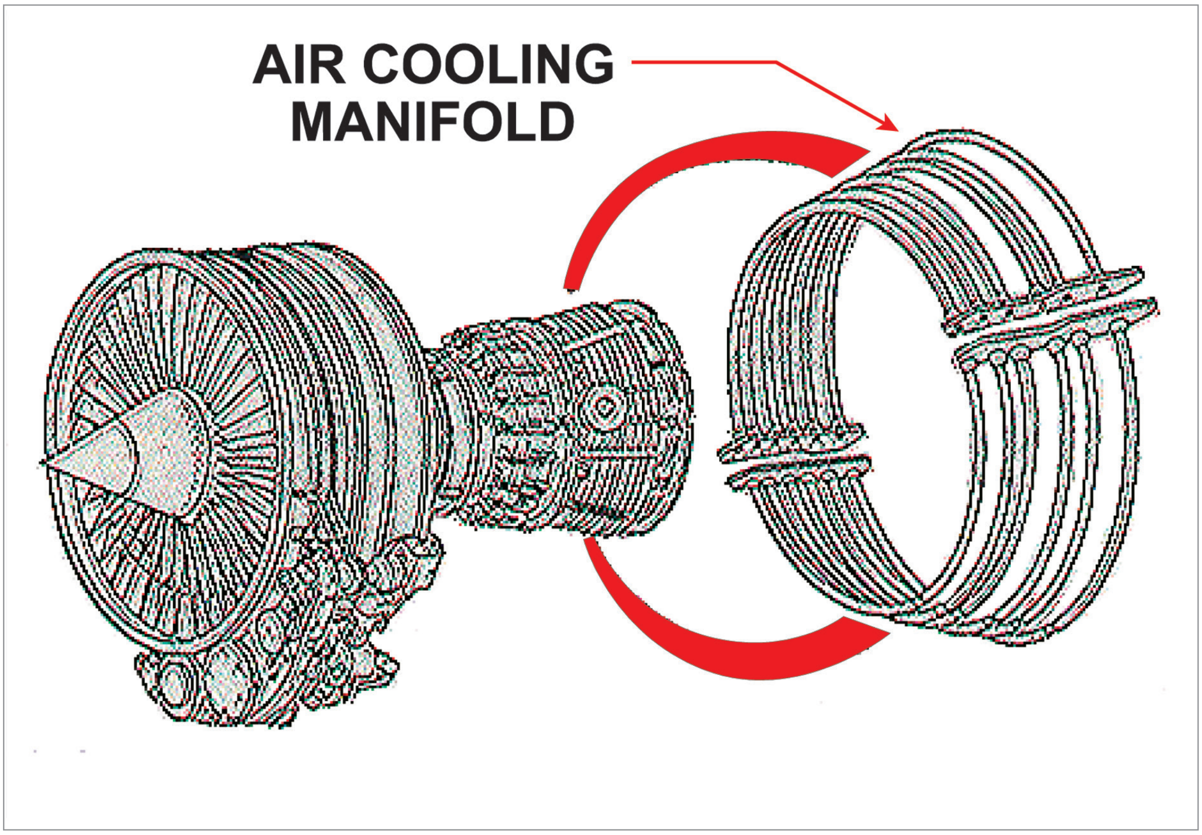


Figure 17.2 Active clearance control used in turbine case cooling.

The Free (Power) Turbine

When a turbine is coupled to a compressor to form a spool, it must rotate at a speed which conforms to the demanding requirements of the compressor, the speed of which is set at the point of best compression.

A free turbine is a turbine which is not connected to the compressor, it is connected only to the propeller or rotor reduction gearbox. This allows the turbine to seek its optimum design speed. There are further advantages to the free turbine, some of which are listed below:

- The propeller can be held at low rpm during taxiing, reducing noise pollution and wear on the brakes.
- Less starting torque required.
- A rotor parking brake can be fitted which eliminates the dangers inherent in having propellers rotating in windy conditions on the ground.

Multi-spool Engines

The power output of a turbine can be increased by increasing its diameter, but this of course would increase both the drag factor, because of the larger size of the engine, and the stresses imposed through the greater centrifugal forces created. A simpler method was shown in *Figure 17.1*, where an increase in the number of stages allowed an increase in power output with a reduction in turbine diameter.

It is a fact that the efficiency of a turbine blade increases as its rotational speed increases (the losses reduce in proportion to the square of the mean blade speed).

Unfortunately, the stresses on the blade increase in proportion to the square of the blade speed. It would seem that the engine designer is locked into a vicious circle where any attempt to increase engine efficiency by increasing turbine speed would require stronger blades, this would mean making them heavier which would mean greater stresses and so on.

The advent of the high ratio bypass engine with its much greater propulsive efficiency means that for a given thrust it can have a smaller turbine, this to some extent circumvents the vicious circle problems mentioned above.

This type of engine features three spools, see *Figure 17.3*, the high pressure (HP) turbine driving the high pressure compressor at relatively high speeds, and to the rear of that is the intermediate pressure (IP) turbine, driving the intermediate pressure compressor through a shaft inside that of the high pressure turbine.

The rearmost, or the low pressure (LP) turbine, the illustration features one with two stages, drives the fan, which is also the low pressure (LP) compressor. This rotates at the lowest speed of all.

The power developed by this turbine produces almost all the thrust of the engine through the reaction of the bypass air, which has a high mass flow moving at a speed which is relatively slow when compared with that of a pure turbojet engine. The shaft which connects the low pressure turbine to the low pressure compressor runs inside those connecting the HP and IP compressors and their turbines.

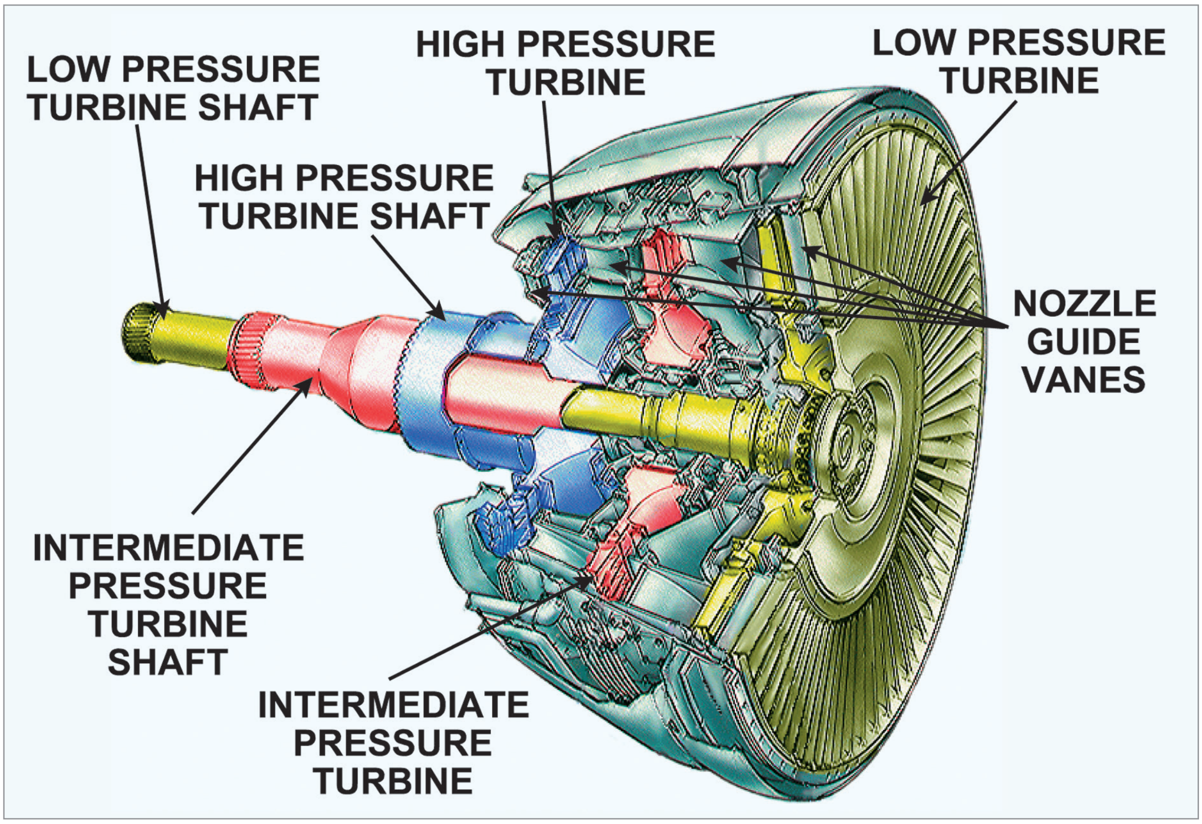


Figure 17.3 The turbine assembly of a triple spool engine.

Blade Shape

Nozzle guide vanes are of aerofoil shape and form convergent ducts where some of the potential (pressure) energy in the gas stream is converted to kinetic (velocity) energy. The turbine blades themselves can be:

a) Impulse type, like a water wheel.

b) Reaction type, which rotate as a reaction to the lift they create.

c) A mixture of the two called impulse/reaction.

The latter type is depicted in *Figure 17.4.*

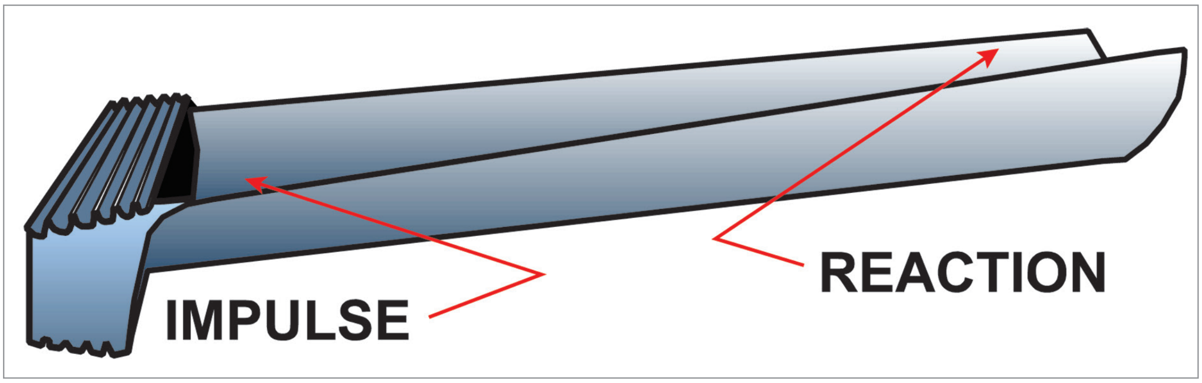


Figure 17.4 The combination impulse-reaction blade.

Figure 17.5 shows an end-on view of how the shape of the combination impulse/reaction blade changes from its base to its tip. The shape change is accomplished by the blade having a greater angle at the tip than at its base. This gives it a twist which ensures that the gas flow does equal work along the length of the blade and enables the gas flow to enter the exhaust system with a uniform axial velocity.

Normally gas turbine engines do not use the pure impulse or pure reaction type of blades. The proportion of each type of blade utilized is dependent upon the design requirements of the engine, in general the combination impulse/reaction is more commonly used. Impulse type turbine blades are used in air starter motors.

It is very rare to find pure reaction blading used, if it is, the nozzle guide vanes are designed to divert the gas flow direction **without altering the pressure of the gas.**

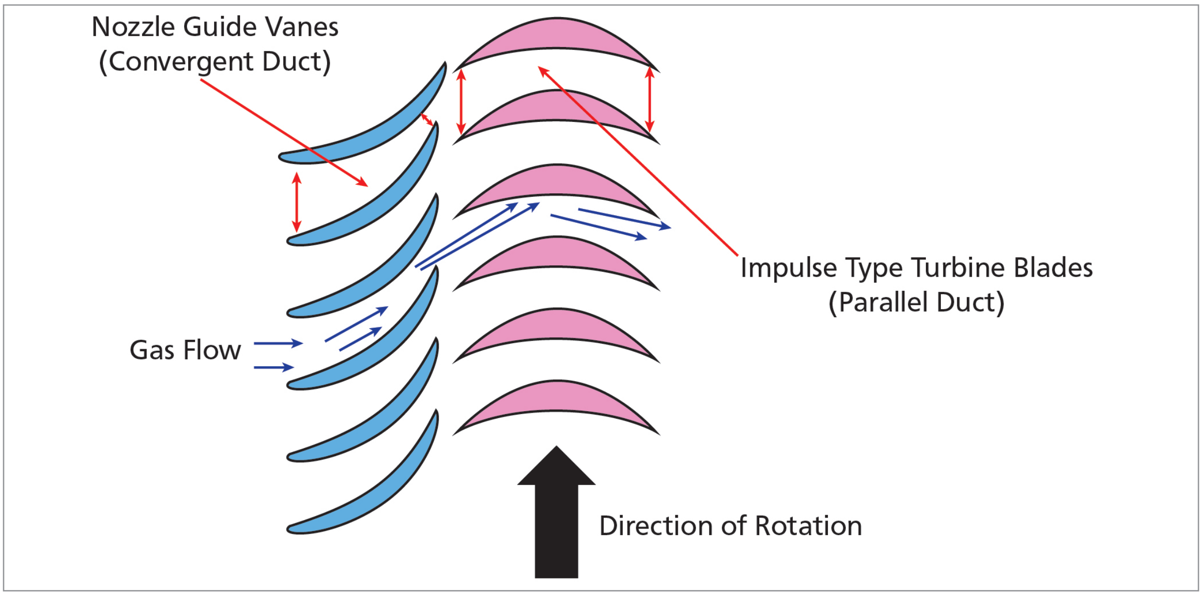


Figure 17.5 and Figure 17.6 How the twist of the blade changes it from impulse to reaction.

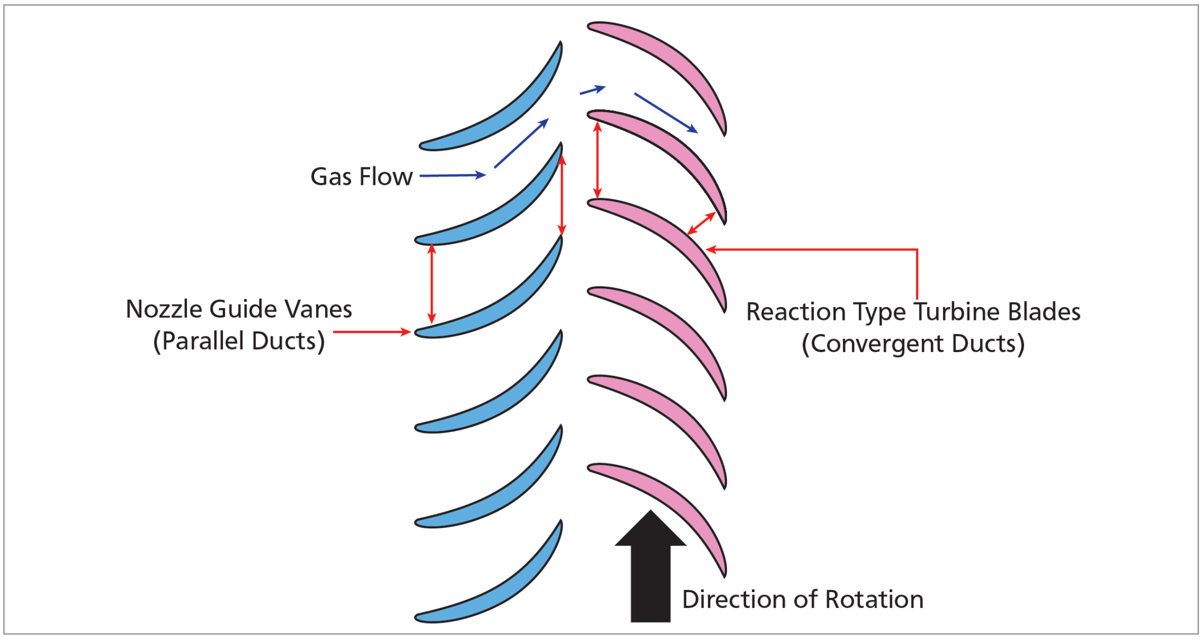


Figure 17.6

Turbine Blade Fixing

The considerable stress imposed upon the turbine blade and the turbine disc when the engine is rotating at working speed makes the method of fixing the blade to the disc extremely important.

The fir tree fixing is most commonly used on modern engines. The serrations which form the fir tree are very accurately machined to ensure that the enormous centrifugal load is shared equally between them.

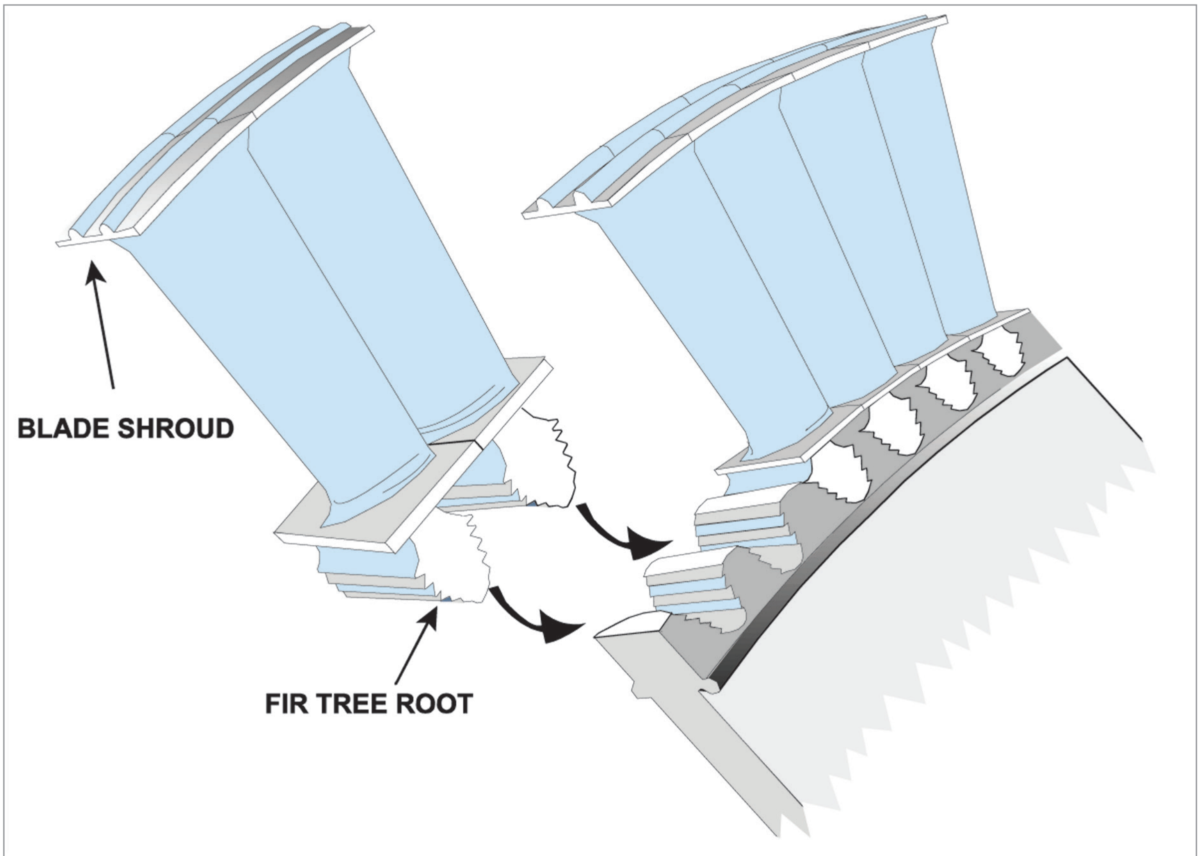


Figure 17.7 Fir tree root turbine blade attachment.

The blade is free in the serrations while the engine is not rotating, but the centrifugal force imposed during operation holds it firmly in place. *Figure 17.7* shows both the fir tree fixing and the turbine blade shroud, previously mentioned.

Losses in the Turbine

The turbine is a very efficient mechanical device, nevertheless it does suffer losses during its operation. On average these total about 8%. This is comprised of approximately 3.5% from aerodynamic losses in the turbine blades and 1.5% aerodynamic losses in the nozzle guide vanes, the rest is divided fairly equally between gas leakage over the blade tips and exhaust system losses.

Temperature Measurement

The maximum temperature that the turbine assembly can withstand limits the thrust or power available. Exceeding the maximum temperature will cause irrepairable damage to the engine, therefore monitoring the turbine temperature is imperative.

The temperature is measured by thermocouples placed in the gas flow somewhere in the turbine assembly, typically after the high or low pressure turbine and termed Exhaust Gas Temperature (EGT). The thermocouples are connected electrically in parallel. This has an added advantage that if one probe is damaged, the temperature reading on the gauge, (a slight drop) is virtually unaffected.

Other terms for gas temperature you may come across for older engines are: Turbine Inlet Temperature (TIT), Turbine Gas Temperature (TGT), Jet Pipe Temperature (JPT). So named because of the position of the thermocouples.

In modern engines the thermocouple probes are fitted **inside** selected fixed nozzle guide vanes to enable temperature to be sensed without the probe being battered by the high velocity gas flow. As the engine is accelerated to produce more thrust (or more SHP) the EGT will increase in proportion with the extra fuel flow and vice-versa.

Questions

1. **The effect on the temperature and pressure of the gases as they pass across the turbine is:**

    a. their temperature decreases and their pressure rises.
    b. both their temperature and pressure increase.
    c. both their temperature and pressure decrease.
    d. their temperature increases and their pressure falls.

2. **Nozzle guide vanes are fitted before the turbine:**

    a. to increase the velocity of the airflow.
    b. to decrease the velocity of the gas flow therefore increasing its pressure.
    c. to increase the velocity of the gas flow therefore reducing its pressure.
    d. to increase the temperature of the gas flow.

3. **One reason for shrouding turbine blades is:**

    a. to reduce "creep" which may occur in the blades.
    b. to improve efficiency and reduce vibration.
    c. to enable thinner blades to be used.
    d. to minimize blade end erosion.

4. **The blades are usually attached to the turbine disc by a "Fir Tree" root. A tight fit is ensured during operation:**

    a. by the action of centrifugal force.
    b. by thermal expansion of the disc.
    c. by blade compression loads and thermal expansion.
    d. by torque loading and thermal expansion.

5. **The main contributory factors which cause creep in turbine blades are:**

    a. high temperature and tensile loading.
    b. high rpm and torque loading.
    c. high rpm and high gas speeds.
    d. high temperature and high gas speeds.

6. **A free power turbine:**

    a. has a clutch between the compressor and the power output shaft.
    b. has no mechanical connection with the other turbine or compressor shafts.
    c. has a direct drive with a free wheel unit.
    d. comes free with every 2000 gallons of AVTUR.

7. **The mixture of impulse and reaction blade shape in the average turbine blade is such that:**

    a. the inner half is impulse and the outer half is reaction.
    b. the inner half is reaction and the outer half is impulse.
    c. the leading edge is reaction and the trailing edge is impulse.
    d. the trailing edge is reaction and the leading edge is impulse.

8. **Blade creep is:**

a. movement of the turbine blades around the turbine disc.
b. temporary expansion due to temperature change.
c. temporary elongation due to centrifugal forces.
d. permanent elongation due to heat and centrifugal force.

9. **The net operating temperature of a gas turbine engine is limited by:**

a. the materials from which the combustion chamber is constructed.
b. the amount of fuel which can be fed into the combustion chamber.
c. the ability of the compressor to pass sufficient air rearwards.
d. the materials from which the nozzle guide vanes and the turbine blades are constructed.

10. **The impulse-reaction blade is twisted along its length so that:**

a. there is a greater angle at the base than at the tip.
b. the gas flow is accelerated through the turbine.
c. the gas does equal work along the whole of its length.
d. the gas flow is decelerated through the nozzle guide vanes.

Answers

1	2	3	4	5	6	7	8	9	10
c	c	b	a	a	b	a	d	d	c

Chapter

18

Gas Turbines - The Exhaust System

The Jet Pipe

The exhaust system is an often underrated part of the propulsion unit, its design exerts a considerable influence on the performance of the engine. The gases which discharge from the turbine must exit in the correct direction and at the optimum velocity to provide the thrust of the turbojet engine, while in the turboprop engine the turbine gas temperature and back pressure at the turbine are to a large extent dictated by the design of the outlet nozzle.

The temperature of the gases entering the exhaust system can be between 550°C and 850°C. This can rise to as high as 1500°C if afterburners (reheat) are used. The fuselage of the aircraft, if it has the exhaust system running through it, must be protected from these temperatures, this is done by both allowing a clearance between the jet pipe and the aircraft skin through which air is allowed to circulate, and insulating the jet pipe with some form of fibrous material sandwiched between thin layers of stainless steel.

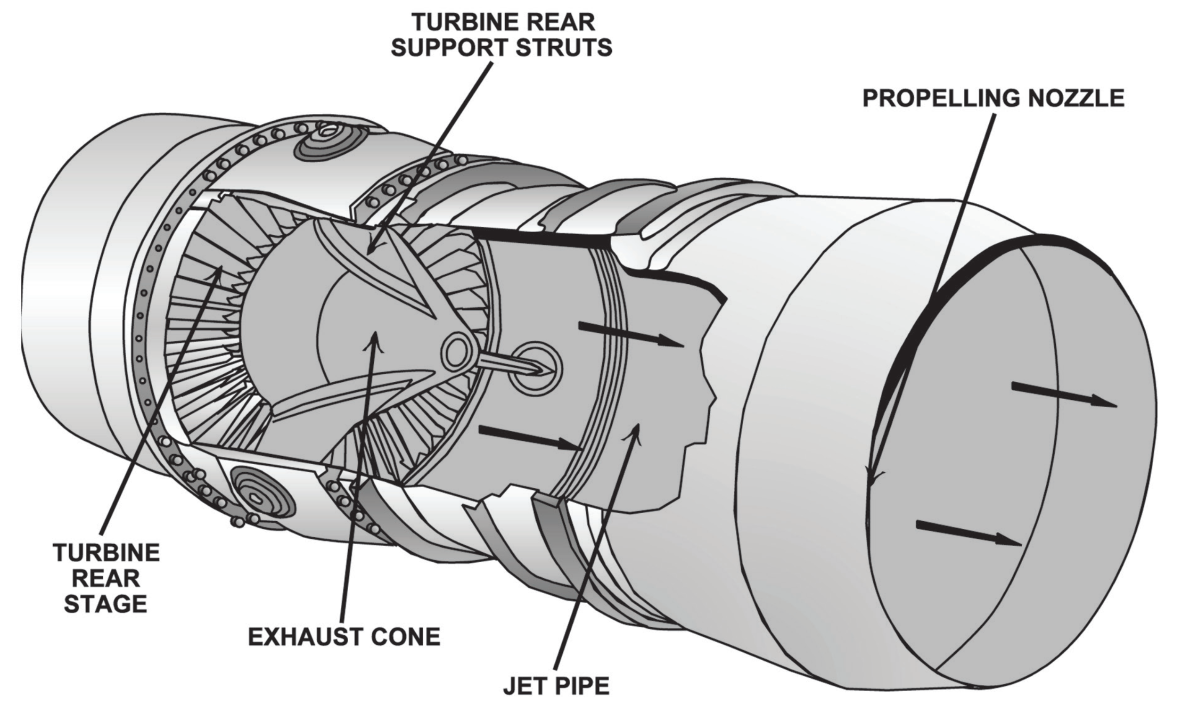


Figure 18.1 A basic jet pipe.

Jet Pipe Design

The gas velocity leaving the turbine can be between 750 - 1250 feet per second, this is somewhere around Mach 0.5. If this gas has to negotiate a long jet pipe before being ejected into the atmosphere to provide thrust, a great deal of turbulence will be caused within the pipe, this will lower the efficiency of the engine and reduce its thrust.

Figure 18.1 shows the basic layout for the jet pipe of an aircraft without afterburners. Although the shape of the outer casing appears to be convergent, at the point where the gas leaves the turbine, **the shape of the volume within the casing is in fact divergent.**

This is made possible by the insertion of the **exhaust cone**, a conical shaped device positioned close up to the turbine disc rear face. As well as helping to reduce the velocity of the gases leaving the turbine before they pass down the length of the jet pipe, so minimizing turbulence, the exhaust cone also prevents the hot gases flowing across the disc face, further reducing disturbance, and preventing overheating of the disc.

The rear turbine bearing is also supported inside the exhaust cone via **turbine rear support struts**, these are streamlined by fairings which also straighten out any residual whirl which may exist in the gas stream as it exits the turbine. This residual whirl can cause additional losses if it is allowed to pass into the jet pipe.

The exhaust gases travel down the jet pipe to atmosphere via the convergent **propelling nozzle**. This increases the gas velocity to speeds of Mach 1 (the speed of sound in relation to the temperature of the gases) in a turbojet engine at virtually all throttle openings above idle. At this velocity, sonic speed, the nozzle is said to be choked.

The term **'choked'** implies that no further increase in velocity can be obtained unless the gas stream temperature is increased, for instance with the assistance of 'reheat'.

Inlet and Exhaust Danger Areas

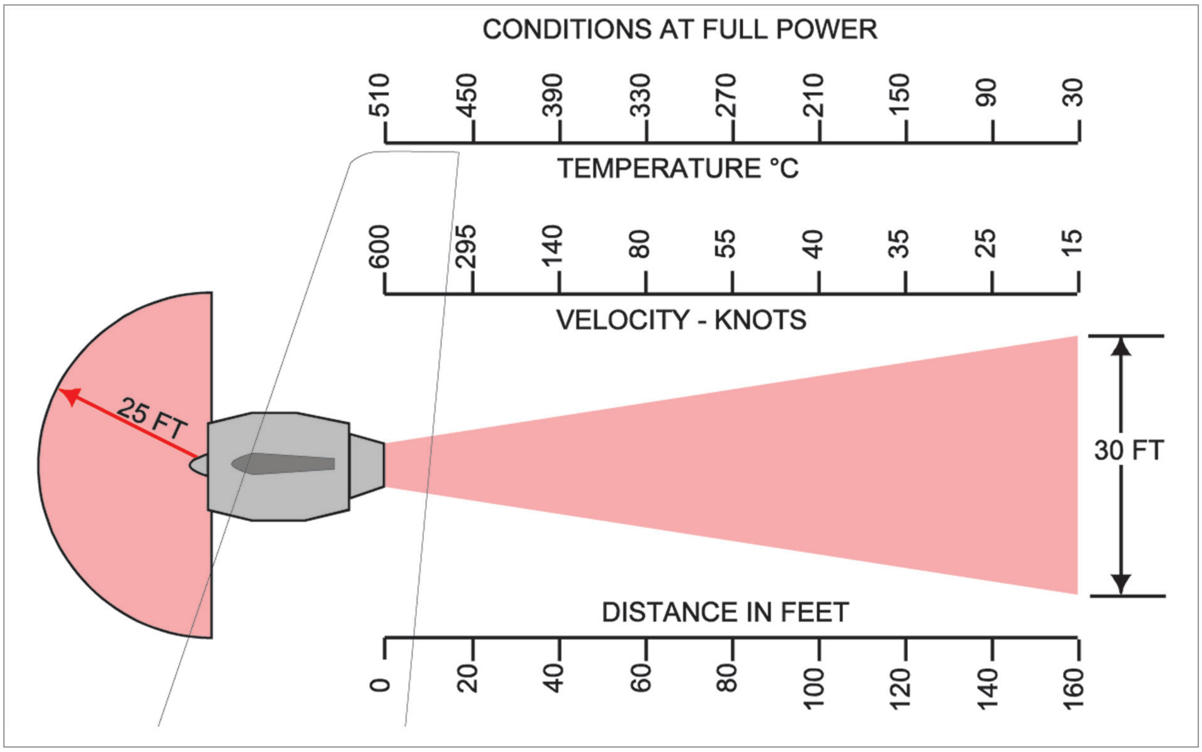


Figure 18.2 Inlet & exhaust danger areas.

Gas Parameter Changes and Exhaust Mach Numbers in both a Convergent and a Convergent-Divergent Nozzle

In the convergent exhaust duct, the shape of the duct accelerates the gas. In a turbojet, the gas flows at subsonic speed at low thrust levels only, at almost all levels above idle power the exhaust velocity reaches the speed of sound in relation to the exhaust gas temperature, at this point the nozzle is said to be 'choked'. This means that no further increase in velocity can be obtained unless the temperature is increased.

When the gas enters the convergent section of the convergent-divergent nozzle its velocity increases with a corresponding fall in static pressure. The gas velocity at this point now reaches the local speed of sound (Mach 1). As the gas flows into the divergent section it progressively accelerates towards the open exit, the reaction to this increase in momentum is a pressure force acting on the inside wall of the nozzle. A component of this force which acts parallel to the longitudinal axis of the nozzle produces the further increase in thrust.

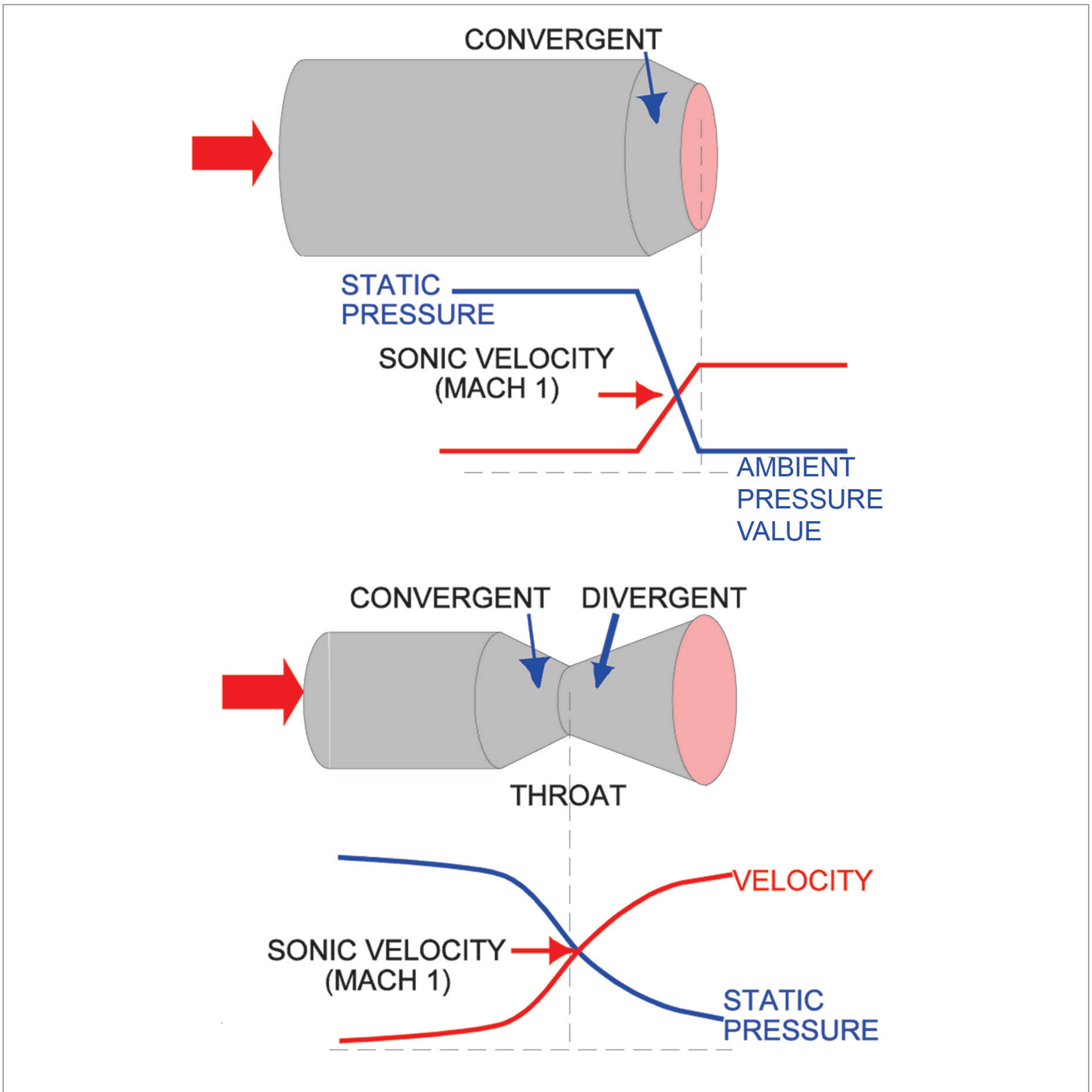


Figure 18.3 Gas parameter changes.

The Low Ratio Bypass Engine Exhaust System

Having two gas streams to pass to atmosphere makes the exhaust system of the bypass engine a slightly more complex affair. The low ratio bypass engine exhaust, see *Figure 18.4*, combines the bypass air and the hot exhaust gases in a mixer unit, this ensures thorough mixing of the two streams before they are ejected into the atmosphere.

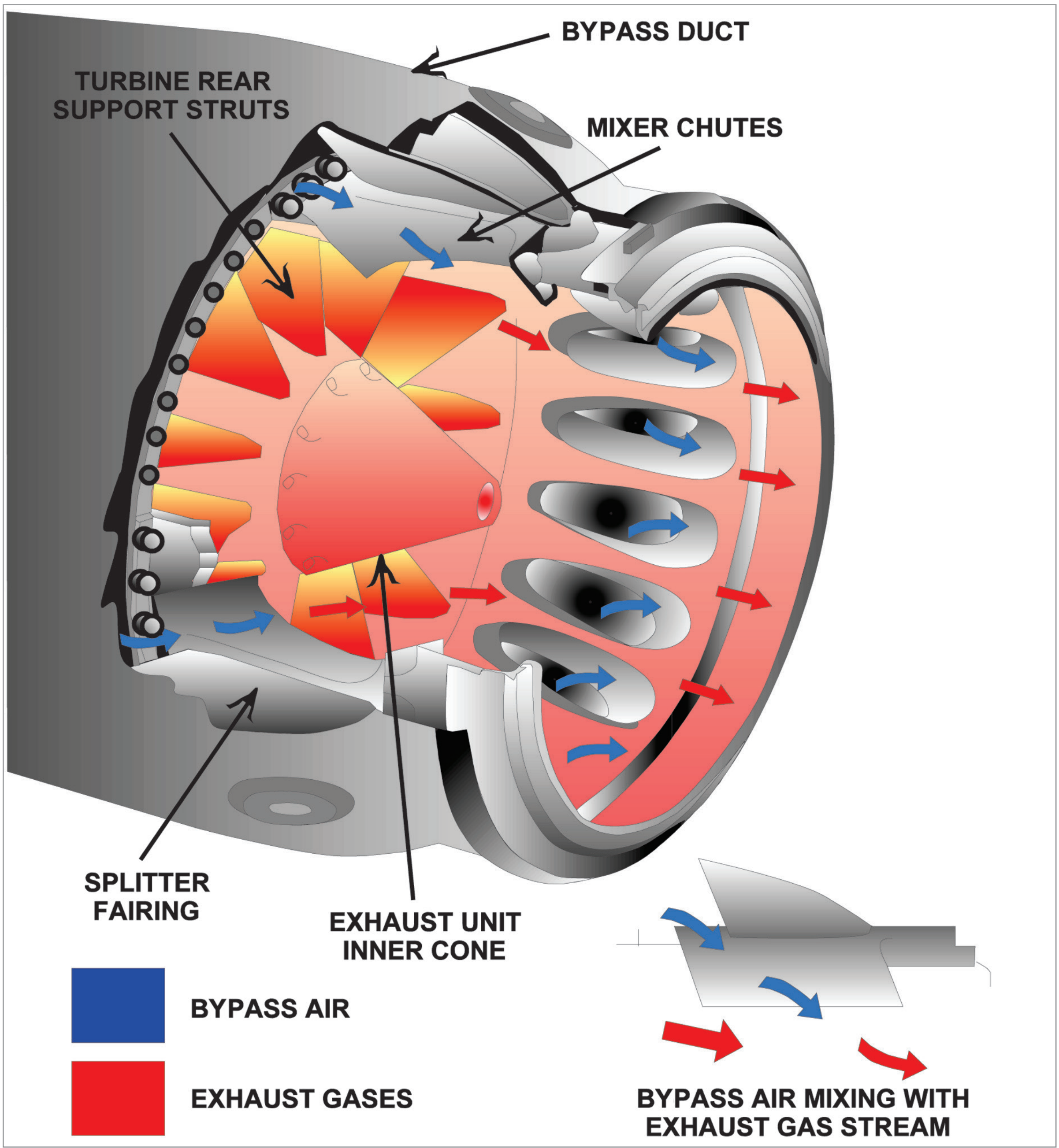


Figure 18.4 A low ratio bypass engine exhaust unit.

The High Ratio Bypass Engine Exhaust System

Figure 18.5 shows two methods used to exhaust the cold bypass air and the hot exhaust gases. The top illustration shows the standard method whereby the hot and cold nozzles are co-axial and the two streams mix externally.

Greater efficiency can however be obtained by fitting an integrated exhaust nozzle. Within this unit the two gas flows are partially mixed before ejection to atmosphere.

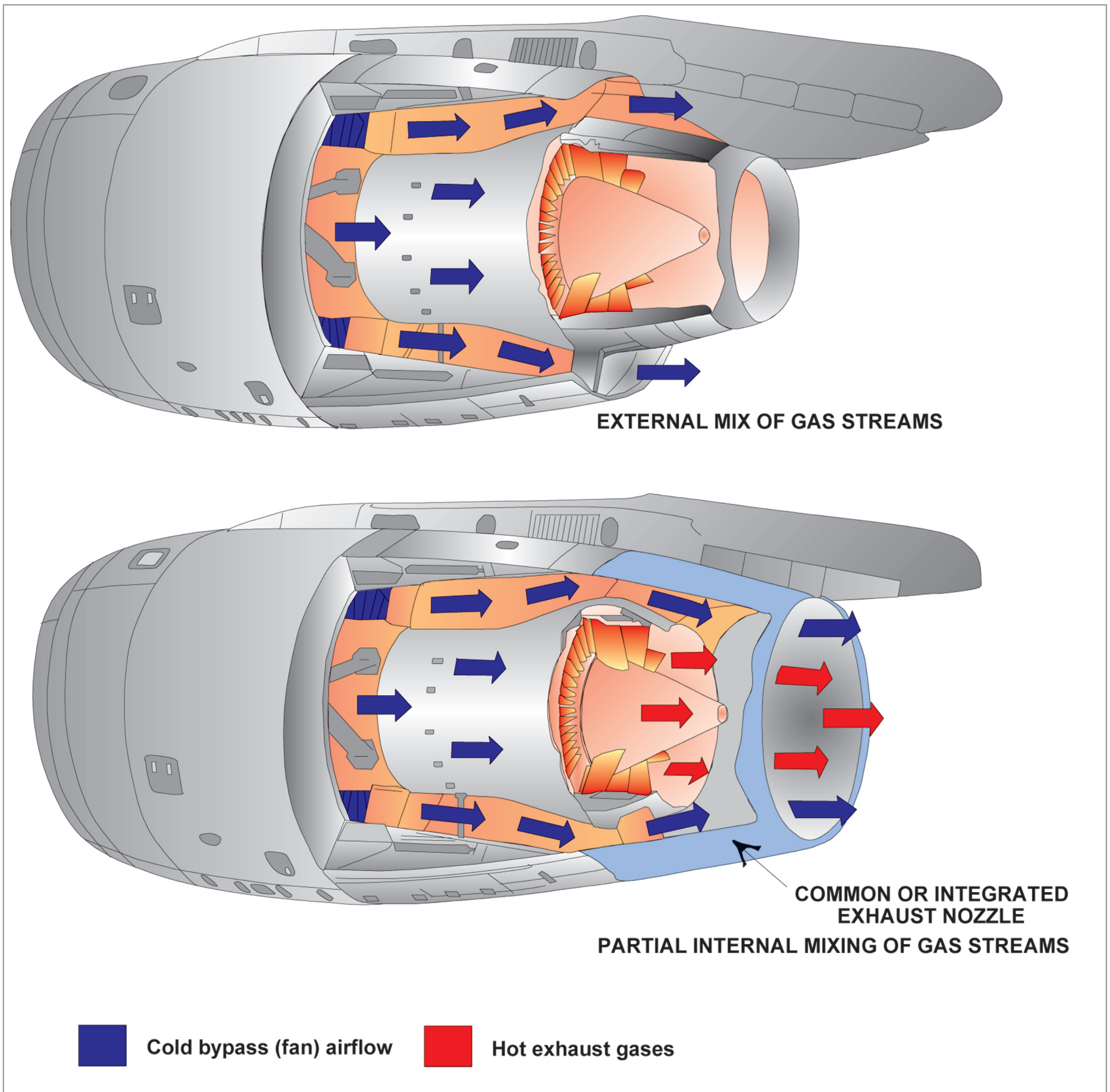


Figure 18.5 High ratio bypass engine exhaust systems.

Noise Suppression

Figure 18.6 shows relative sound levels from various sources, some of the highest among them being aircraft engines.

Although an aircraft's overall noise signature is the combination of sounds from many sources, the principal agent is the engine. Airport regulations and aircraft noise certifications governing the maximum noise level which aircraft are allowed to produce, have forced rigorous research into ways of reducing that noise.

The most significant sources of noise from the engine originate from the compressor (the fan in high ratio bypass engines), the turbine and the exhaust. Although the noises which spring from these various sources all obey slightly different laws and mechanisms of generation, they all increase with greater relative airflow velocity.

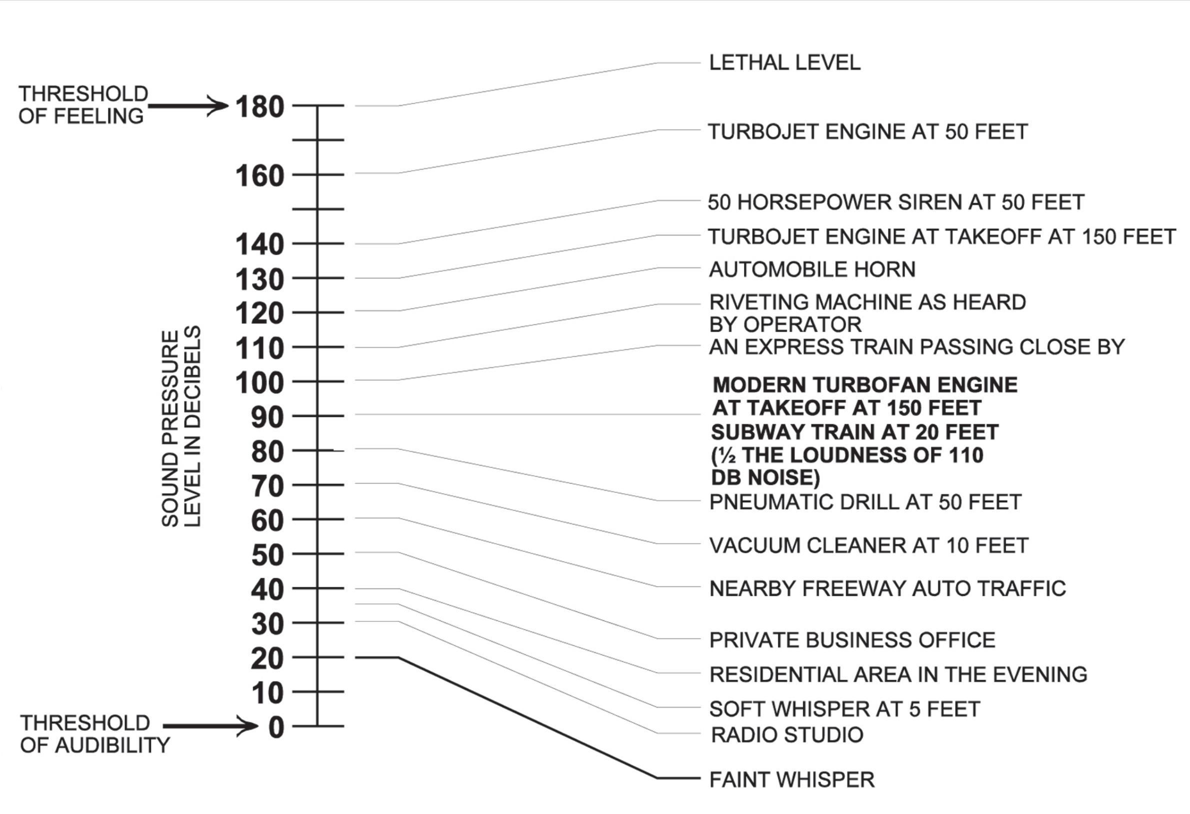


Figure 18.6 Sound levels from various sources.

Exhaust noise is affected to a larger degree than either compressor or turbine noise by a reduction in velocity, it is logical therefore to expect that a reduction in exhaust jet velocity would have a stronger influence in reducing noise levels than an equivalent reduction in either compressor or turbine speeds.

The relative speed difference between the exhaust jet and the atmosphere into which it is thrusting causes a shearing action which in turn creates a violent and extremely turbulent mixing. *Figure 18.7* shows the pattern formed and the zones where high and low frequency noise is generated.

With a pure jet engine, the noise of the exhaust is of such a high level that the noise of the compressor and the turbine is insignificant, except at very low thrust conditions.

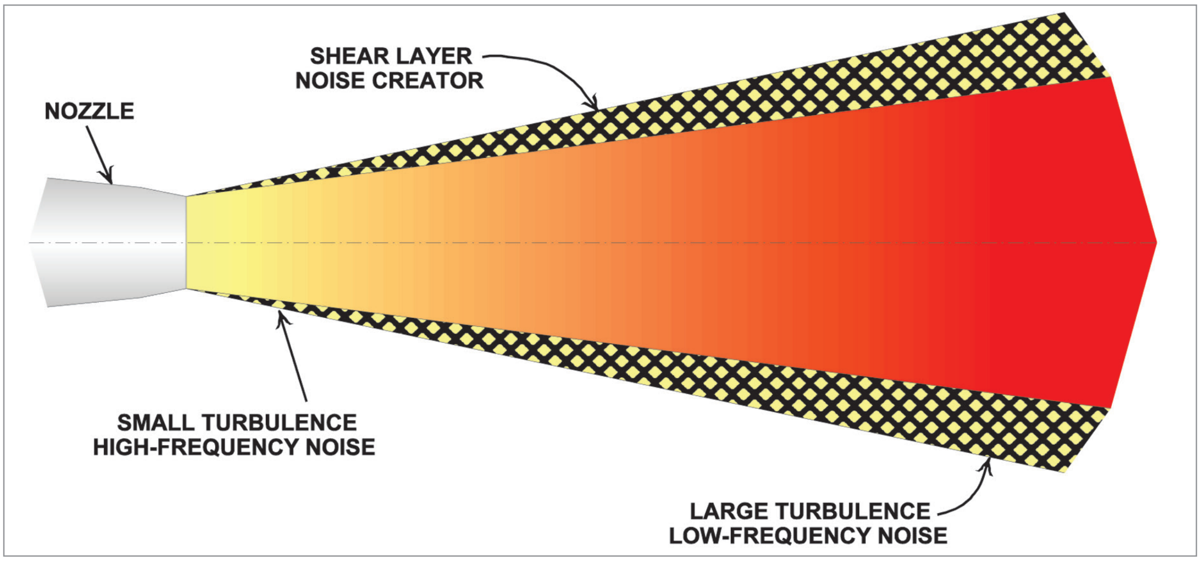


Figure 18.7 The pattern of noise created by jet exhaust.

The exhaust noise of a bypass engine drops because of the reduction in velocity, but because they are handling a much greater power, the turbines and the low pressure compressor generate a higher noise output.

In the case of a high ratio bypass engine (5 to 1), the noise from the jet exhaust has reduced to such a degree that the noise from the low pressure compressor (the fan) and the turbine become predominant.

Having reduced noise from the main source, it was logical to suppose that engine manufacturers would then concentrate on lowering the levels of noise from the rest of the engine, the fan and the turbine.

The use of noise absorbing material (acoustic-lining) in the bypass duct and the engine intake, see *Figure 18.8,* next page, was extremely efficient in reducing noise in that region, further down the engine, in the hotter zones, slightly different materials were used to great advantage in the same quest for noise reduction.

The disadvantages of these materials is that they add a small percentage in weight, and their skin friction is slightly higher, together they cause a slight increase in fuel consumption.

Whereas the modern engines could take advantage of the new methods of sound absorbing materials, aircraft fitted with older pure turbojets had to find some other system of reducing their noise output.

Aircraft can still be seen with ‘corrugated internal mixers’ and ‘lobe type nozzles’ fitted to the rear of their power units. The latter caused the gases to flow in separate exhaust jets that rapidly mix with slower moving air trapped by the lobes. The corrugated internal mixer was most efficient at reducing noise, but also induced performance penalties that limited its popularity with aircraft operators.

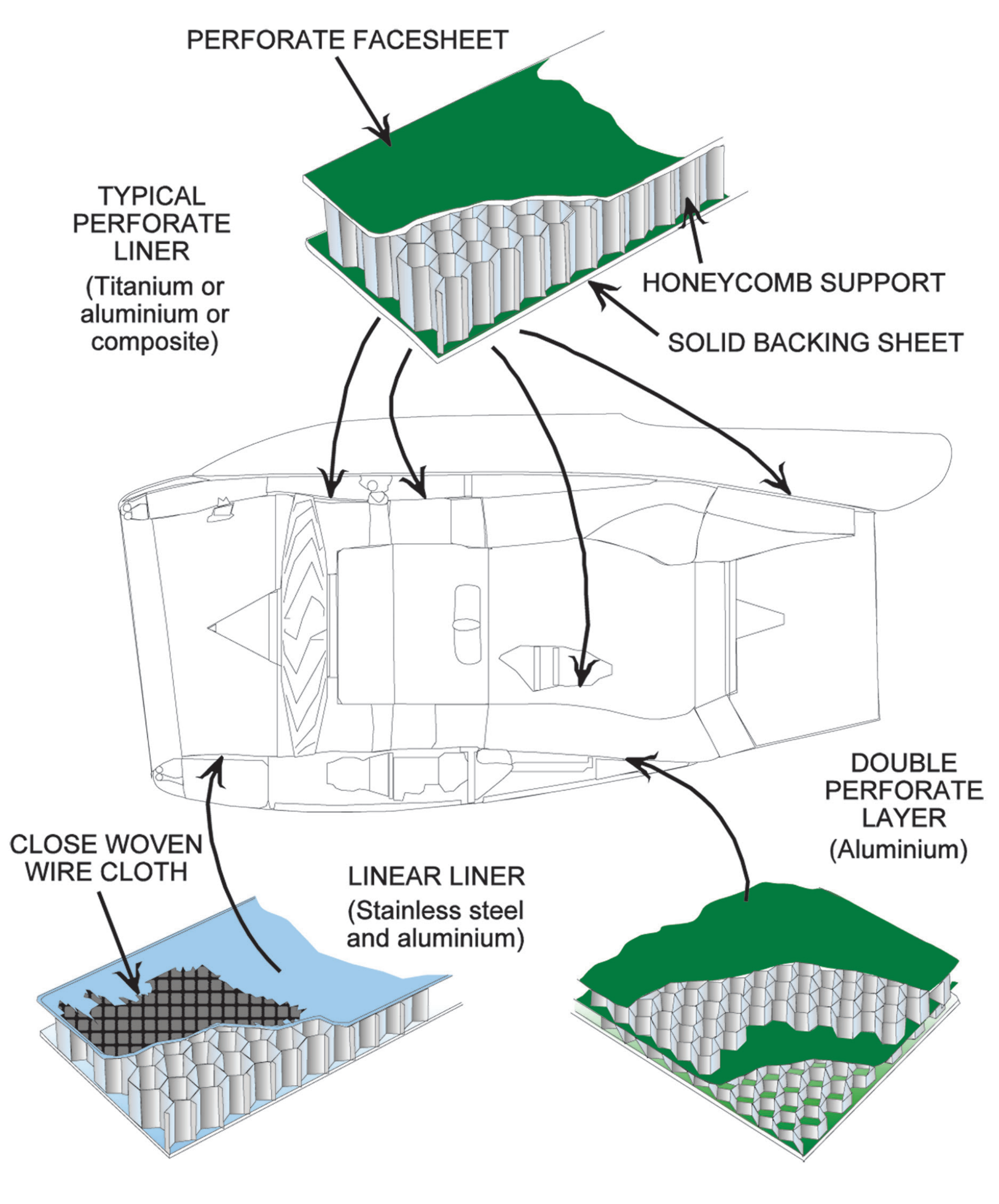


Figure 18.8 The types of materials used for noise suppression & their locations.

Questions

1. **The velocity of the gases in the exhaust unit is held to:**

   a. Mach 0.5 to minimize turbulence
   b. Mach 0.75 to optimize the pressure distribution
   c. Mach 0.85 to maximize thrust
   d. Mach 1 to maximize acceleration

2. **The exhaust cone:**

   a. straightens the gas flow before it goes into the turbine assembly
   b. prevents the hot gases flowing across the rear turbine face
   c. increases the velocity of the gases
   d. decreases the pressure of the gas

3. **The propelling nozzle is designed to:**

   a. increase the velocity and decrease the pressure of the gas stream
   b. decrease the velocity and increase the pressure of the gas stream
   c. to increase the velocity and the pressure of the gas stream
   d. to decrease the velocity and the pressure of the gas stream

4. **A nozzle is said to be "choked" when:**

   a. the gas flow through it is subsonic
   b. the gas flow through it reaches its sonic value
   c. the gas temperature rises
   d. the gas flow through it is supersonic

5. **A choked nozzle:**

   a. decreases thrust
   b. gives additional pressure without the addition of heat
   c. has no effect on thrust
   d. implies that no further increase in velocity can be obtained without the increase of heat

6. **The exhaust gases pass to atmosphere via the propelling nozzle which:**

   a. is a convergent duct, thus it increases the gas velocity
   b. converts kinetic energy into pressure energy
   c. is a divergent duct, thus it increases the gas velocity
   d. is a divergent nozzle, thus it increases the gas pressure

7. **The jet pipe is insulated from the airframe by:**

   a. heat insulation materials
   b. a cooling air jacket
   c. a combination of cooling air and insulating material
   d. semi-conducting geodetic structures

8. **The noise from a high ratio bypass engine:**

   a. is created mainly in the exhaust section
   b. is high in the exhaust section because of the high velocity gas flow
   c. is predominantly from the fan and the turbine
   d. is greater than that from a turbojet engine of comparable power output

9. **The shape of the volume within the jet pipe casing immediately to the rear of the turbine:**

   a. is convergent to accelerate the gases towards the propelling nozzle
   b. is divergent to accelerate the gases away from the turbine blades
   c. is convergent to increase the pressure of the gases in the jet pipes
   d. is divergent to reduce the velocity of the gases leaving the turbine

10. **The turbine rear support struts:**

   a. add swirl to the gases before they travel down the jet pipe
   b. prevent the hot gases flowing across the rear face of the rear turbine bearing
   c. allow entry of the bypass air into the exhaust system
   d. straighten out any residual whirl in the gas stream

11. **An exhaust nozzle is said to be choked when the velocity at the throat is:**

   a. Mach 0.5
   b. below Mach 1
   c. at Mach 1
   d. above Mach 1

Answers

1	2	3	4	5	6	7	8	9	10	11
a	b	a	b	d	a	c	c	d	d	c

Chapter 19

Gas Turbines - Lubrication

The Reasons for Lubrication

There are many reasons for having a lubricant within the engine besides that of reducing friction. However scrupulously clean the engine is maintained, there will always be a small amount of dirt or impurities that find their way inside. That dirt must be removed before it can cause damage to bearings or block small oil passageways.

The oil can be used to keep the engine clean by carrying dirt to the oil filter where it is strained out and where it remains until replacement of the filter.

The majority of the bearings within the engine are manufactured from steel, a metal which would soon oxidize itself if it were not prevented from doing so by a liberal coating of oil, thus the lubricant will also minimize corrosion inside the engine.

The engine bearings, particularly those around the hot end of the engine, must be cooled if they are to be able to withstand the constant stresses imposed upon them, the most likely medium for cooling is the lubricant which cleans, reduces friction and corrosion.

Not least among the tasks given to the lubricating oil is that of a hydraulic fluid, in many turbo-prop engines the control of the pitch of the propeller blades is achieved by passing some of the engine lubricating oil into the pitch change mechanism.

Lubricating Systems

Most gas turbine engines use a self-contained recirculatory lubrication system in which the oil is distributed around the engine and returned to the oil tank by pumps.

There are two basic re-circulatory systems, the pressure relief valve system, or the full flow system.

A schematic layout of the basic system is shown in *Figure 19.1* showing the relative location of the major components.

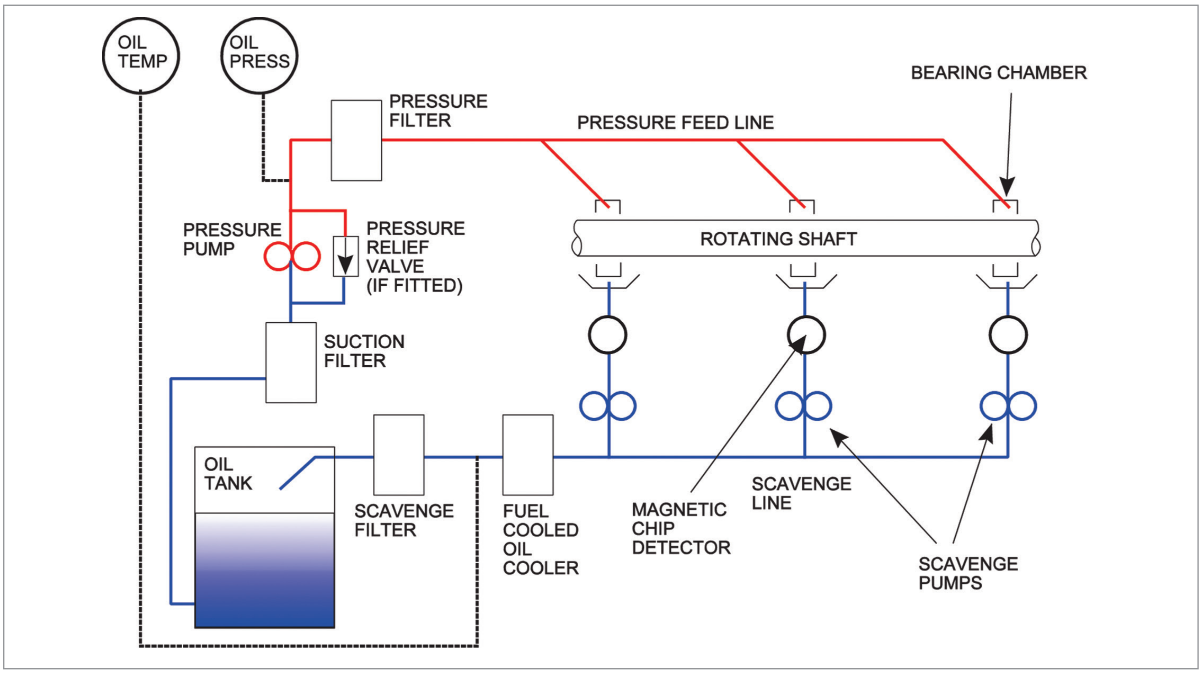


Figure 19.1 Schematic gas turbine oil system.

The oil used will be invariably **synthetic** because of the high temperatures involved. Oil level is checked immediately after engine shutdown. Unlike a piston engine the oil is not changed on a regular basis because gas turbine engines use more oil due to the nature of the air seals and the synthetic oil does not break down and oxidize like mineral oils do. The filters however are removed, washed out, and refitted at regular intervals to examine any debris collected and evaluate the wear rate of the engine.

The Pressure Relief Valve Lubrication System

In the pressure relief valve system a spring loaded valve limits the pressure in the feed line and so controls the flow of oil to the bearing chambers.

The pressure is restricted to a value which the engine designer considers correct for all conditions that the engine might encounter. The spring loaded valve opens at the pressure generated by the oil pressure pump at engine idling speed and consequently gives a constant feed pressure over the whole of the engine speed and oil temperature ranges.

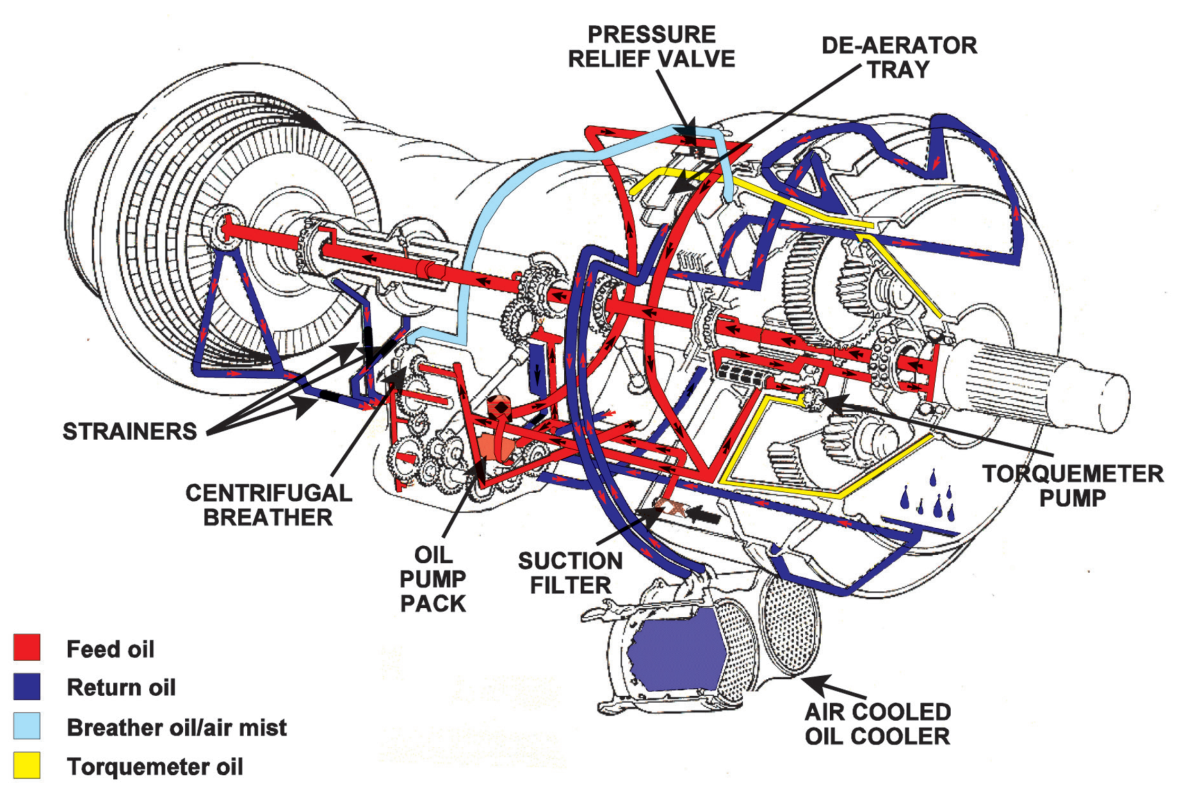


Figure 19.2 A pressure relief valve type oil system.

Figure 19.2 shows the pressure relief valve method and the basic components for a turboprop engine lubrication system. The oil is drawn through a suction filter to the oil pressure pump. The suction filter protects the pump from damage should any debris enter the tank. The oil is then passed through the pressure filter to the pressure relief valve which maintains the oil pressure to the feed jets in the bearing chambers constant.

The oil passes to the feed jets through internal drillings and external oil pipes, in this particular engine the hollow interior of the compressor/turbine shaft is used to transfer oil from the front of the engine, where it is used in the pitch control mechanism, all the way through to the rear, where it is used in the turbine bearings.

The torque meter pump shown in this diagram is used to boost engine oil pressure to a much greater figure, in some turboprop engines that figure can be as high as 600 pounds per square inch. This pressure is utilized to balance the axial thrust of the helically cut gears within the propeller reduction gear.

As has already been explained, measuring the torque meter oil pressure will give an accurate indication of the torque being transmitted to the propeller, reference figures which take account of the ambient temperature and pressure allow the pilot to find the minimum torque pressure which the engine should be capable of producing in any set of conditions.

When the oil has completed its tasks of lubricating, cooling, cleaning and acting as a hydraulic medium, it falls into collecting trays or compartments which communicate with the scavenge pumps.

The scavenge pumps are mounted in the same oil pump pack which contains the oil pressure pump. Although there is only one pressure pump, the oil pump pack may contain several scavenge pumps. This will ensure that the method of lubrication remains a dry sump system. The scavenge pumps push the oil through an air-cooled oil cooler in this particular engine, different engines may have different types of oil cooler fitted. Whatever the type of oil cooler, its job is to drop the temperature of the oil after its journey through the engine.

The next stage for the oil is the de-aerator tray, here any air bubbles which will have been collected in the oil are allowed to escape and the oil falls to the oil tank, in this case the tank is contained around the engine intake.

Any air pressure which has been built up within the engine lubrication system, through leakage from seals or from the de-aerator tray must be allowed to escape. If it was just vented to atmosphere then any oil mist contained within it will pass to atmosphere also, thus the oil contents would quickly diminish. To prevent this happening the oil mist is vented via a centrifugal breather which is positioned in the accessory gearbox.

The Full Flow Lubrication System

This system achieves the required oil flow to the engine throughout its entire speed range by allowing the oil pressure pump to directly supply the oil feed jets without the use of a pressure relief valve. Using this system allows the use of smaller pressure and scavenge pumps since the volume of oil passed is less than that in the pressure relief valve system. This happens because of the large amount of oil which is spilled back to the oil tank by the pressure relief valve at high engine speed.

In *Figure 19.3* the pressure pump picks up oil from the oil tank through a suction filter and passes it through a pressure filter to the distribution galleries. Across the pressure filter is an oil differential pressure switch. This can give warning of blockage of the filter. This warning is usually indicated at the ground crew servicing panel and is sometimes duplicated by a warning light on the flight deck.

One gallery takes the oil up to an oil pressure transmitter and low oil pressure warning switch. These are used primarily to give warning in the cockpit of malfunctions in the oil system. Other parameters indicated in the cockpit are those of oil quantity and oil temperature, the latter being measured as the oil leaves the oil cooler.

It is from this same gallery that oil is taken to lubricate all of the bearings in the accessory drive gearbox. The other gallery is used to transfer oil to the bearings which support all of the compressor spools.

The bearings are lubricated by oil jets which are positioned very close to the bearings so as to minimize the possibility of the oil being deflected from its target by local turbulence. Just prior to the oil jets are fitted thread type filters, these perform the function of a 'last chance' filter, removing any debris which may have managed to pass through the main pressure filter.

As in the pressure relief valve system, when the oil has completed its tasks it is collected and passed back through scavenge pumps. Prior to the oil reaching the scavenge pump it must pass over a chip detector and through a suction filter.

The scavenge pumps force the oil through to the oil cooling system, in the engine shown in *Figure 19.3* there are two types of oil cooler, a fuel-cooled oil cooler and an air-cooled oil cooler. Normally the fuel-cooled oil cooler is sufficient to cool the oil on its own, but in the event that it proves inadequate a valve opens automatically and brings the air-cooled oil cooler into operation as well.

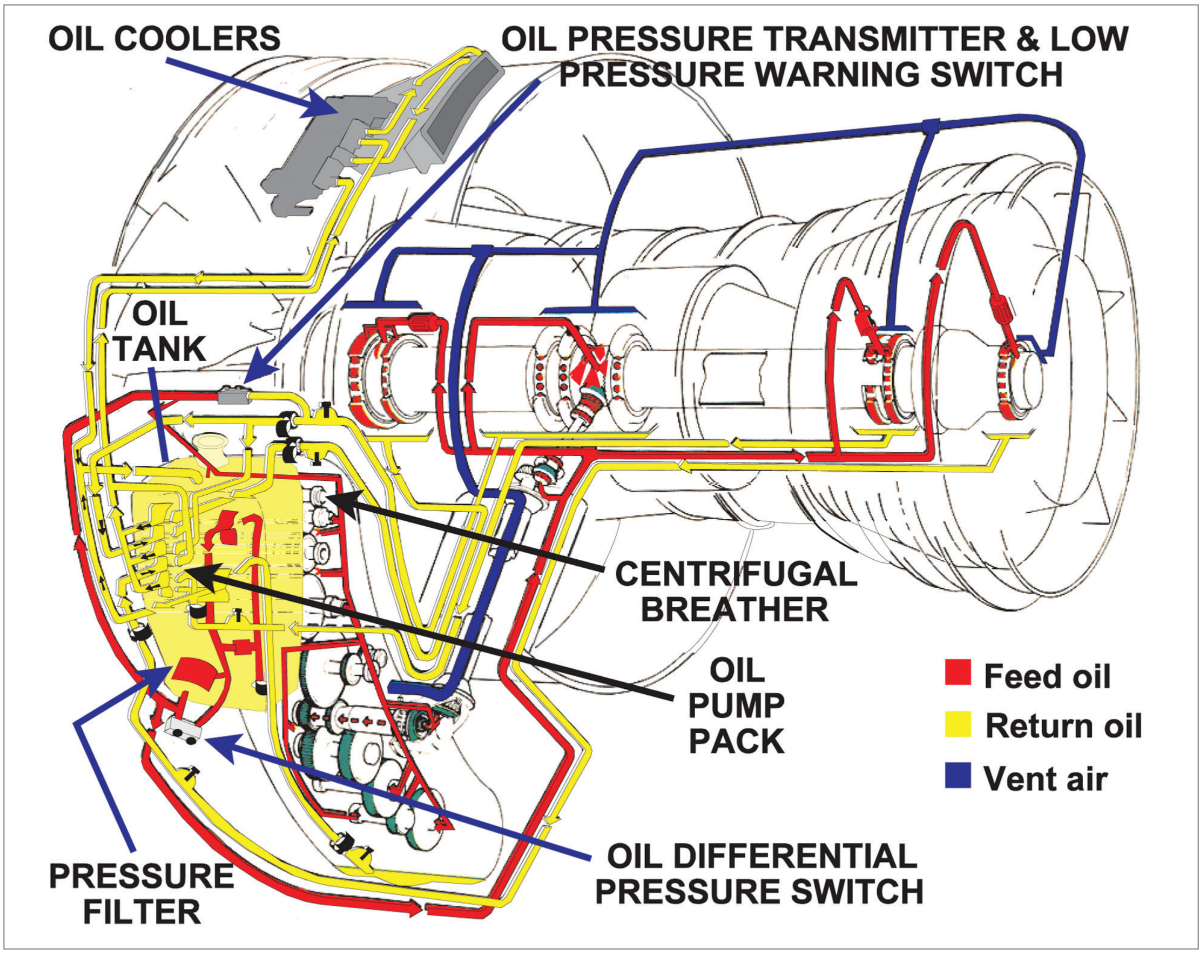


Figure 19.3 A full flow type lubricating system.

As has been seen previously, air pressure escaping from seals cannot be allowed to build up within the engine and it is vented through the hollow shaft between the intermediate gearbox and the external gearbox, leaving the latter via the centrifugal breather.

The Oil Tank

The oil tank is normally a separate unit mounted on the side of the engine, although it can be part of the engine intake, or even an integral part of the external gearbox. As a separate unit, *Figure 19.4*, it must incorporate provision for filling, both by gravity and, more normally, by pressure. There must also be some method of determining the contents of the tank, either by a sight glass or by a dipstick, sometimes by both. A de-aerator tray allows removal of air bubbles from the oil as it flows back into the tank.

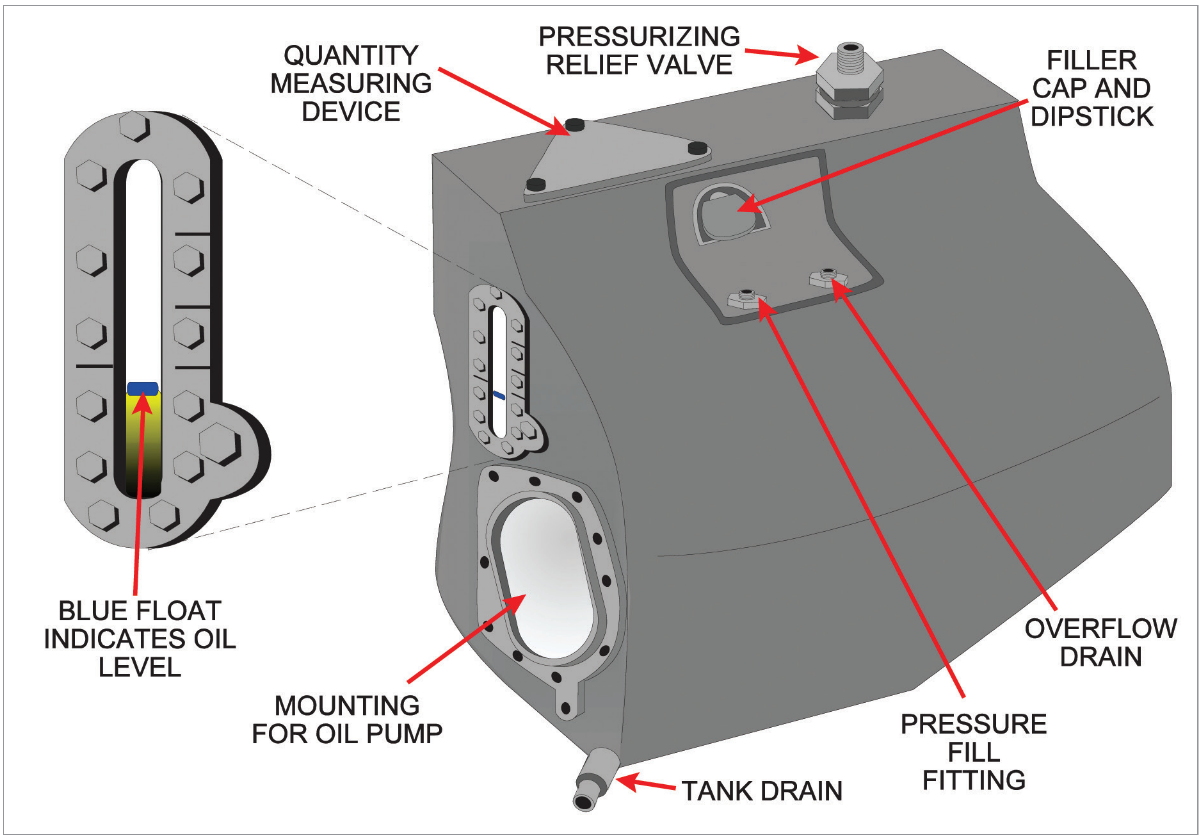


Figure 19.4 A typical oil tank.

Oil Pumps

Gear type pumps which consist of a pair of intermeshing steel gears located within a close fitting aluminium housing, are the normal method of delivering and retrieving oil in a re-circulatory system.

When the gears are rotated, oil is drawn into the pump, carried round by the teeth and delivered at the outlet. *Figure 19.5* shows a gear type oil pump.

The oil pumps, both pressure and scavenge, are fitted on the accessory housing.

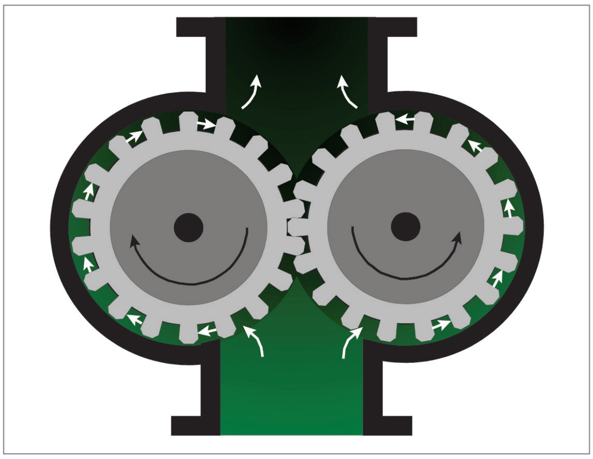


Figure 19.5 A gear type oil pump.

They are fitted within an oil pump pack which consists normally of one pressure pump and perhaps as many as six scavenge pumps.

The oil pumps are vital to the operation of the engine, if an oil pump fails the engine must be shut down immediately, for this reason the oil pump pack drive shaft is not fitted with a shear neck they must continue to supply oil for as long as possible, regardless of damage.

Oil Coolers

Oil coolers can be either air-cooled or fuel-cooled, some engines use both systems. If an engine does use both air and fuel to cool the oil, the oil temperature can be monitored electronically and the air cooler switched in only when necessary. This maintains the oil temperature at a figure which improves the thermal efficiency of the engine.

Whether it is fuel or air-cooled, the oil cooler is basically a radiator which exchanges heat from one medium to another. The cooler consists of a matrix assembly which is partitioned by baffle plates. The baffle plates ensure that the oil takes the longest path through the matrix and it thus gains maximum benefit from the cooling effect of the fuel flowing through the tubes within the matrix.

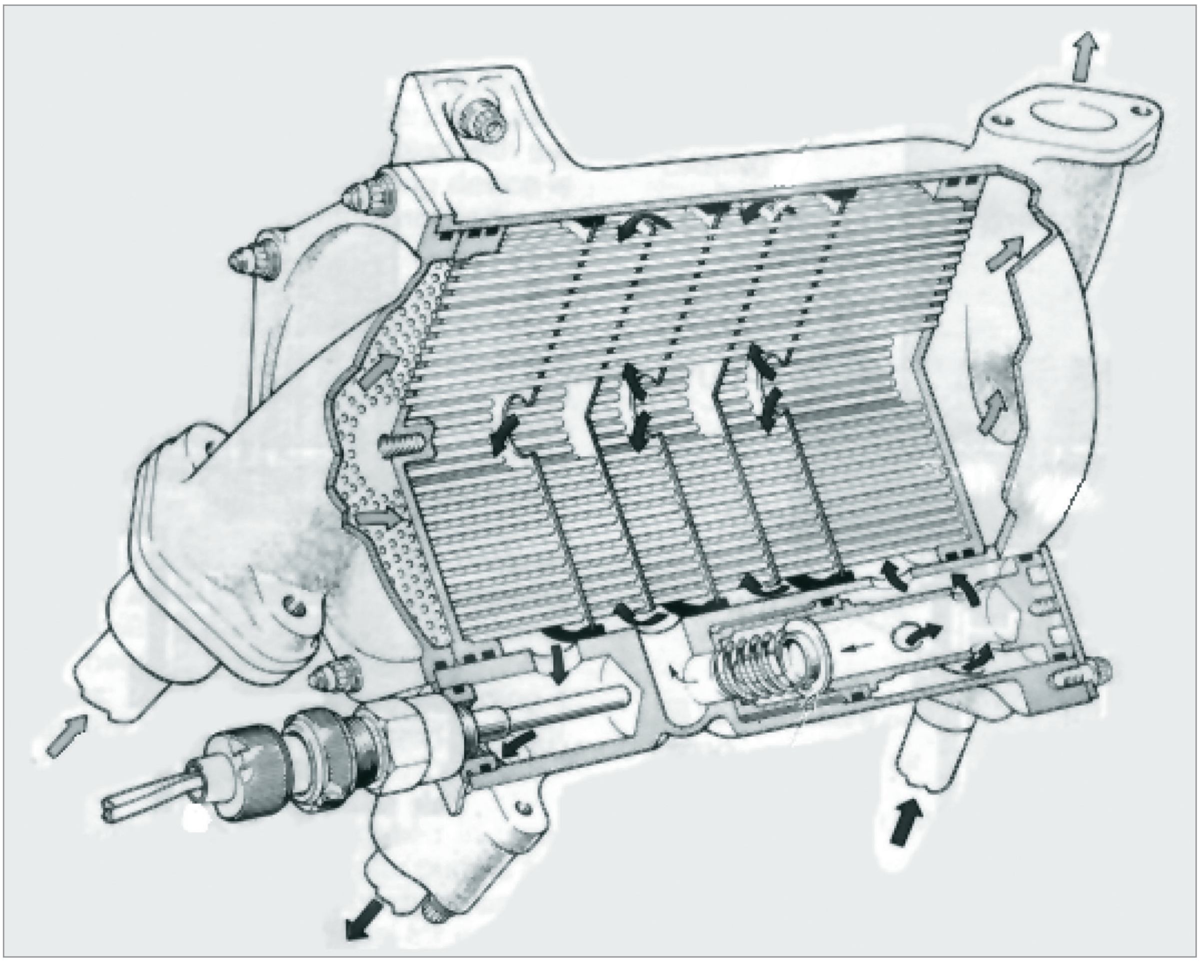


Figure 19.6 A fuel-cooled oil cooler

The fuel-cooled oil cooler has a double benefit, the fuel in the aircraft wing tanks is inevitably very cold and requires warming up before it gets to the fuel filter, the oil is hot and requires cooling, this device allows both requirements to be carried out within it, a rare chance of achieving two for the price of one. Incorporated in the fuel-cooled oil cooler is an oil bypass valve, this is fitted across the oil inlet and outlet.

At a predetermined pressure in the oil inlet zone, the valve will prevent oil passing through the cooler matrix and open a path direct to the oil outlet. This will prevent oil starvation should the cooler become blocked and also preclude the chance of any damage being done to the relatively fragile matrix assembly by very viscous oil.

In the event that damage to the matrix does occur, fuel is prevented from entering the oil system by a pressure maintaining valve which ensures that the oil pressure is always higher than the fuel pressure, thus the oil will leak into the fuel system rather than the other way round. A fuel-cooled oil cooler is illustrated in *Figure 19.6*.

Magnetic Chip Detectors

Chip detectors, which are magnetic plugs, are fitted into the scavenge lines to collect ferrous material from the oil as it returns to the scavenge pumps. The chip detector is retained in the pipeline by a bayonet fitting within a self-sealing valve housing. This means that the detector can be removed without any loss of oil.

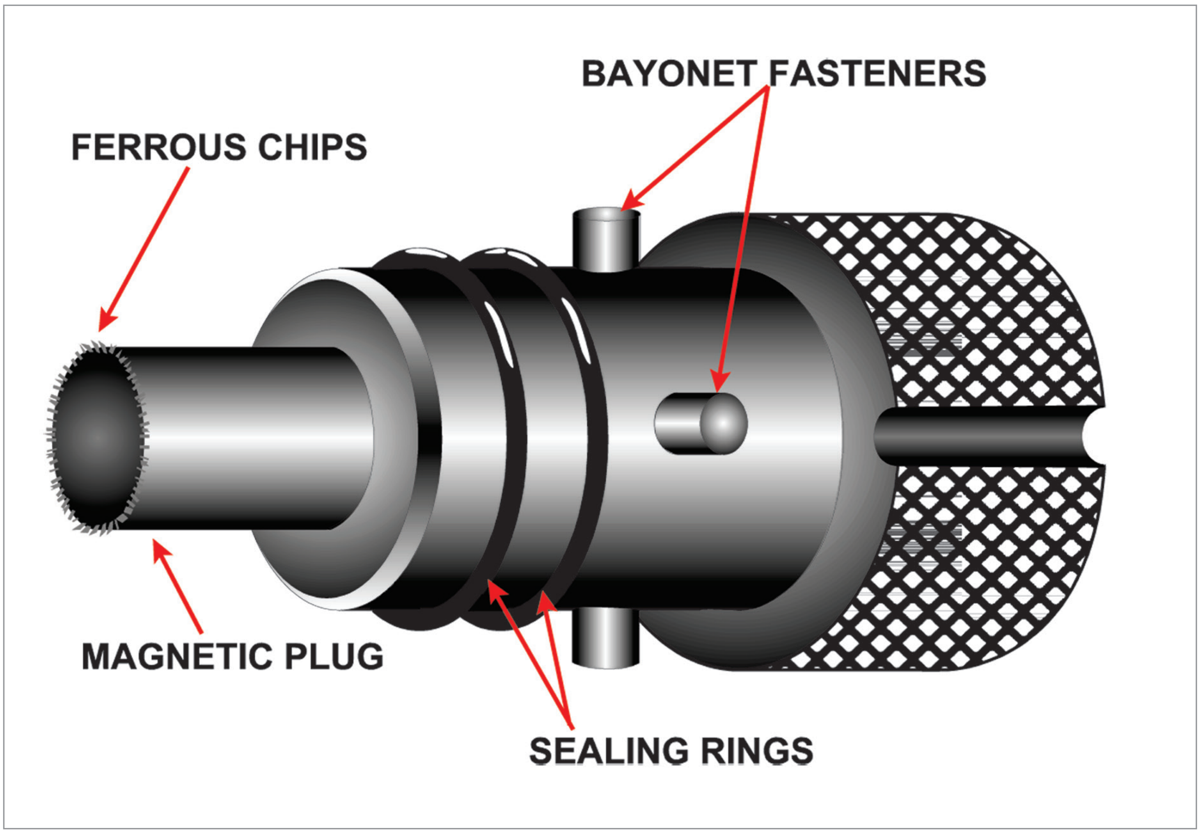


Figure 19.7 A magnetic chip detector.

Figure 19.7 illustrates the magnet contaminated by iron filings, evidence of impending failure in the bearing chamber monitored by that particular chip detector.

The Centrifugal Breather and Vent

To prevent excessive air pressure within the gearbox and the bearing chambers, the interior of the engine must be vented to atmosphere. Oil droplets in the air form an oil mist which, if it was allowed to escape unhindered, would deplete the engine oil contents rapidly. The oil mist is vented to the gearbox where it must pass through the centrifugal breather before reaching the atmosphere, see *Figure 19.8*.

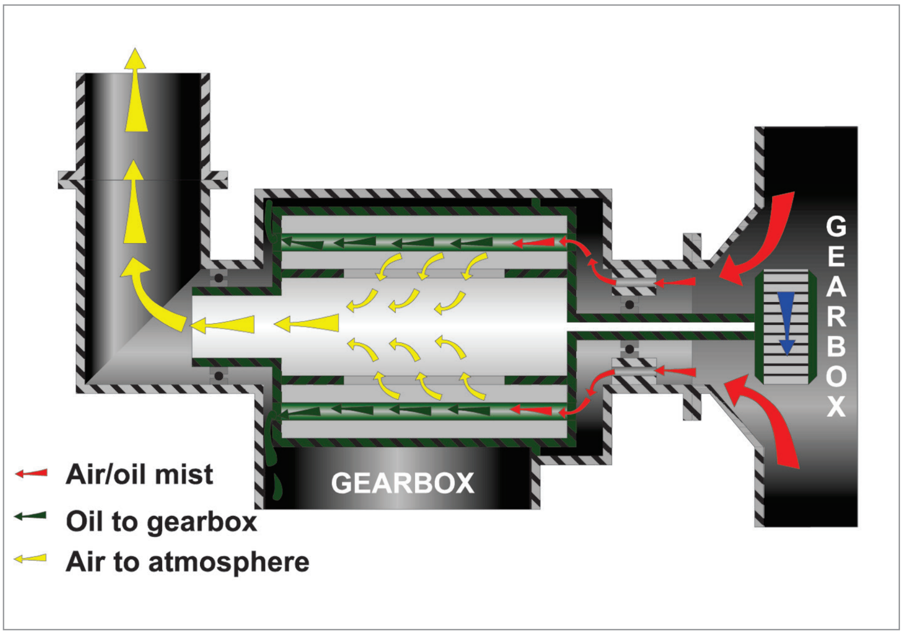


Figure 19.8 The centrifugal breather & vent.

The centrifugal breather is rotated at high speed and as the oil mist enters, it is thrown outwards by centrifugal force. Around the inside periphery are de-aerator segments, the oil is separated from the mist and is eventually flung back into the gearbox to be picked up by a scavenge pump. The air, having less inertia, makes its way out of the centre of the rotating portion of the breather to atmosphere having had all the oil removed. Thus the centrifugal breather minimizes oil loss in the gas turbine engine.

Filters

To facilitate the oil's task of cleaning, a number of filters and strainers are positioned within the lubrication system. This prevents debris and foreign matter from being continuously circulated around with the oil.

As described earlier the oil is drawn through a suction filter before it goes into the pressure pump, the suction filter takes the form of a coarse strainer which prevents debris being drawn into the pump and damaging it.

At the outlet of the pressure pump, a pressure filter is fitted, this is a very fine mesh filter which will retain any small particles which might block the oil feed jets. Mentioned earlier are thread type filters, performing the function of a 'last chance' filter immediately prior to the oil jets.

Each return oil line contains a scavenge filter, just downstream of the magnetic chip detector. These scavenge filters will collect any debris returning from the lubricated component.

Both pressure and scavenge filters are constructed in a tubular form from either a very finely woven wire cloth, or resin impregnated with fibres. Some filters may have a differential pressure switch fitted across them or alternatively they may be fitted with a 'pop up indicator', a small button which can be seen protruding from the filter casing to give a visual warning of a partially blocked filter.

Types of Lubricating Oils

Gas turbine engine oils must have a high enough viscosity for good load carrying ability, but they must also have a sufficiently low viscosity to ensure a good flow of oil at low temperatures, for instance starting after prolonged cold soaking.

Early gas turbine engines used the same oils as had been used in petrol engines for years, these oils were mineral based. It was found that under the higher temperatures and speeds at which gas turbine engines operated mineral oils burnt, scummed and oxidized.

To attain the properties mentioned at the start of this chapter synthetic oils had to be developed. These oils had the following qualities:

a) Low Volatility, to prevent evaporation at high altitudes.

b) High Flash Point, the temperature at which the oil vapours will ignite if near a flame.

c) High Film Strength, the ability of the oil molecules to stick together under compression loads and adhere to surfaces under centrifugal loads.

d) A Wide Temperature Range, most gas turbine lubricating oils have a temperature range of -45°C to +115°C.

e) A Low Viscosity, this increases the ability of the oil to flow under low temperature conditions.

f) A High Viscosity Index, this is an indication of how well the oil retains its viscosity when heated to its operating temperature.

The use of a low viscosity oil is enabled because of the absence of reciprocating parts and heavy duty gearing.

Questions

1. **A centrifugal breather is used on a gas turbine engine:**

a. to circulate the oil smoothly.
b. to minimize oil loss.
c. to emulsify the oil and air mixture for greater viscosity.
d. to allow oxidization of the oil.

2. **A high oil temperature would indicate that:**

a. the oil pressure was high.
b. the exhaust gas temperature (EGT) was high.
c. the oil filter was blocked.
d. the air intake of the oil cooler was blocked.

3. **Oil seals are pressurized:**

a. to ensure oil is forced into the bearings.
b. to ensure minimum oil loss.
c. to ensure that the oil is prevented from leaving the bearing housing.
d. to minimize heat loss in the bearing housing.

4. **In the event that damage occurs to the matrix of the fuel-cooled oil cooler:**

a. a pressure-maintaining valve ensures that the oil pressure is always higher than the fuel pressure.
b. the fuel pressure is always kept higher than the oil pressure to ensure that the fuel will leak into the oil system.
c. a differential pressure switch will illuminate a light in the cockpit.
d. the oil bypass valve will prevent a complete loss of oil pressure.

5. **The bearing chambers of a gas turbine engine are vented:**

a. via the auxiliary gearbox drive.
b. via the centrifugal breather.
c. via the air seals, into the gas stream.
d. to prevent oil loss.

6. **The main bearings in an axial flow gas turbine engine are normally pressurized by:**

a. compressor bypass air.
b. air at intake pressure.
c. air from an intermediate stage of the compressor.
d. gas from the second stage turbine section.

7. **Magnetic Chip Detectors are fitted in the engine:**

a. to facilitate early detection of cracks in the compressor blades.
b. to facilitate early warning of cracks in the turbine blades.
c. to provide a warning of impending failure in the engine bearings.
d. to prevent a build up of starch in the scavenge oil filter.

8. **An inter-stage air seal is used where:**

   a. engine sections are operating at different pressures.
   b. engine sections are subjected to pressures of the same value.
   c. it is more convenient.
   d. it is difficult to obtain access during routine servicing.

9. **An Internal Engine Overheat warning would necessitate:**

   a. the oil temperature to be closely monitored.
   b. the EGT to be closely monitored.
   c. the engine power to be reduced to idle.
   d. the engine to be shut down.

10. **If engine run down time is short, coupled with high oil consumption, the most probable cause is:**

    a. compressor blade rub.
    b. incorrect relief valve setting.
    c. excessive sealing air pressure.
    d. bearing chamber labryinth seal rubbing.

11. **Gas turbines use for lubrication:**

    a. mineral oil with additives (compound).
    b. mineral oil straight.
    c. multi-grade 20/50.
    d. synthetic oil.

12. **For a pressure relief lubricating system, select the correct statement:**

    a. the flow and pressure change with engine speed.
    b. the pressure relief valve is fitted in series with the pump.
    c. the pressure remains the same for all engine operating parameters.
    d. the relief valve opens when pressure has reached the required pressure. Any excess flow is returned by a dedicated line to the base of the engine for scavenging.

13. **If the engine oil pump ceases to function the engine:**

    a. will continue to operate at a lower rpm because the engine will be able to suck the oil from the reservoir and be sufficiently lubricated.
    b. should be shut down.
    c. will be unaffected because the scavenge pumps have a larger operating capacity than the pressure pumps and will ensure the engine is lubricated sufficiently.
    d. should be monitored for a period of time to record oil temperature.

14. **In a gas turbine engine oil temperature is measured:**

    a. as it leaves the fuel-cooled oil cooler (FCOC).
    b. before entering the engine.
    c. immediately after leaving the engine.
    d. in the engine.

15. **In a gas turbine engine oil pressure is measured:**

    a. in the engine.
    b. in the return line.
    c. after the pressure pump.
    d. in the FCOC to ensure oil pressure is always above fuel pressure.

16. **The magnetic chip detectors are fitted in:**

    a. the pressure line between the pressure pump and the engine.
    b. suction line between the reservoir and the pressure pump.
    c. return line between the engine and the scavenge pump.
    d. return line after the FCOC.

17. **Gas turbines use:**

    a. wet sump and mineral oil.
    b. dry sump and synthetic oil.
    c. wet sump and synthetic oil.
    d. dry sump and mineral oil.

Answers

1	2	3	4	5	6	7	8	9	10	11	12
b	d	b	a	b	c	c	a	d	d	d	c

13	14	15	16	17
b	a	c	c	b

Chapter

20

Gas Turbines - Thrust

Introduction

It was stated in Chapter 1 that thrust was derived as a reaction to accelerating a mass of air backwards thereby achieving forward thrust.

In accordance with Newton's third law, for every action there is an equal and opposite reaction. Or, by formula:

F = ma (Force = Mass × acceleration)

Thrust

A gas turbine engine is simply a device which manufactures potential pressure energy and then converts it into kinetic velocity energy.

Some of the energy performs work at the turbine and the remainder is used to create thrust. Simply, one unit of air has been increased in size by combustion with fuel and heat expansion so that it will have to accelerate greatly in order to leave the exhaust nozzle.

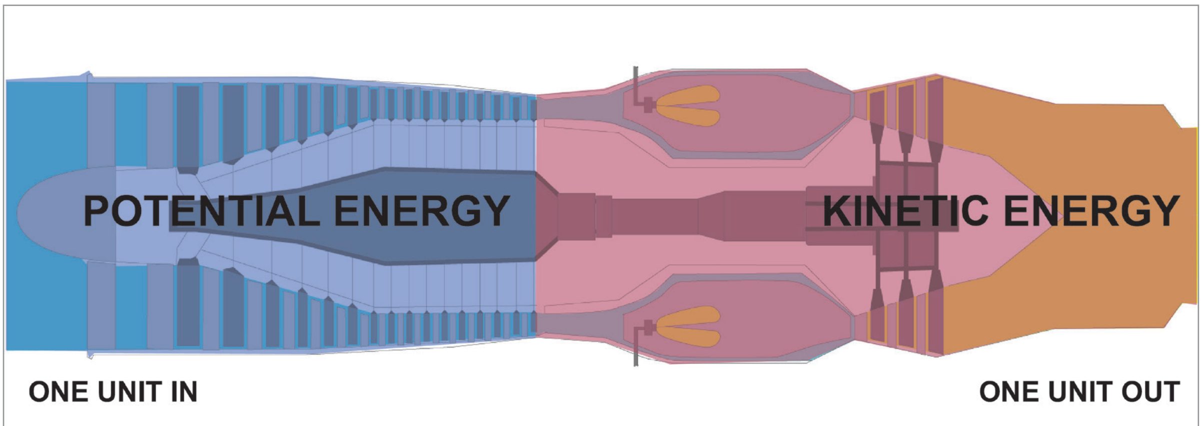


Figure 20.1

The Thrust Formula

There are two elements which make up the total thrust. These are momentum thrust and pressure thrust. Momentum thrust is always present when the engine is running, and is derived directly from the F = ma equation given above. An extra source of thrust, known as pressure thrust, occurs when the airflow through the engine reaches the speed of sound. Total thrust is given by the following formula:

Thrust = $W_a (V_o - V_i)$ + Pressure Thrust

where: W_a = Mass flow of air per second

V_o = exit velocity of air

V_i = inlet velocity of air

We will deal with the calculation of pressure thrust shortly.

Momentum Thrust

Because momentum thrust depends on the relationship between inlet and exit velocity of the air passing through the engine, it is dependent on the aircraft's speed through the air. It will be greatest when the aircraft is stationary on the ground before take-off and will reduce as the airspeed, and therefore the inlet speed, increases. It is considered to be maximum when the aircraft is stationary at sea level (high pressure) under conditions of low temperature (high density) and low humidity.

When the engine is stationary and developing its maximum thrust, this is known as gross thrust. When there is airflow passing through it, as when airborne, the thrust developed is known as net thrust.

Gross Thrust (Fg)

Gross thrust (Fg) is the thrust produced when the engine is not moving through the air. The acceleration given to the gas is the difference in velocity of the unit of air entering the intake (V_i), and the unit of air exiting the nozzle (V_o). Substituting into F = ma:

$$Fg = \frac{W_a(V_o - V_i)}{g}$$

where:

W_a = Weight of air per second

V_o = exit velocity of air in ft/sec

V_i = inlet velocity of air in ft/sec

g = gravitational force, 32.2 ft/sec^2

If the mass flow and velocities are given in Imperial units (i.e. lb/sec and ft/sec) it is necessary to convert from force to mass by dividing by g, as above. If they are given in SI units (kg/sec and metres/sec), the conversion is already factored into the units, and it is incorrect to divide by g.

Most gas turbine engine manufacturers express their engine outputs in lb wth a kN equivalent (in brackets) alongside.

Gross Thrust Calculation (Fg)

A small business jet is at rest before take-off, and is at take-off power. Mass airflow is 60lb/sec and the exhaust velocity (V_o) is 1600 ft/sec.

If the aircraft at rest, inlet velocity (V_i) is zero. We can now substitute into the momentum thrust equation:

$$Fg = \frac{W_a(V_o - V_i)}{g} = \frac{60\ (1600 - 0)}{32.2} = 2981\text{ lb } (13.26\text{ kN})$$

Carrying out the same calculation in SI units:

60 lb is 27.211 kg. 1600 ft is 487.68 metres.

$Fg = W\,(V_o - V_i) \quad = \quad 27.211\,(487.68 - 0) \quad = \quad 13.27\ kN$

(1 pound = 4.448 newtons)

Net Thrust Calculation (Fn)

Thrust reduces as aircraft speed increases, which results in a reduction in the acceleration of the mass flow through the engine. This is net thrust.

V_o remains constant and V_i increases, therefore the **a in F=ma** decreases.

Now assume that the same aircraft is flying at 300 knots TAS (506 ft/sec).

$$Fn = \frac{W_a(V_o - V_i)}{g} = \frac{60\ (1600 - 506)}{32.2} = 2038\ \text{lb}\ (9.07\ \text{kN})$$

Fan Engine Thrust

A fan engine produces both a core engine (or hot) stream at a high velocity and a fan (or cold) stream at a lower velocity. In this case, the hot and cold streams are dealt with separately and added together.

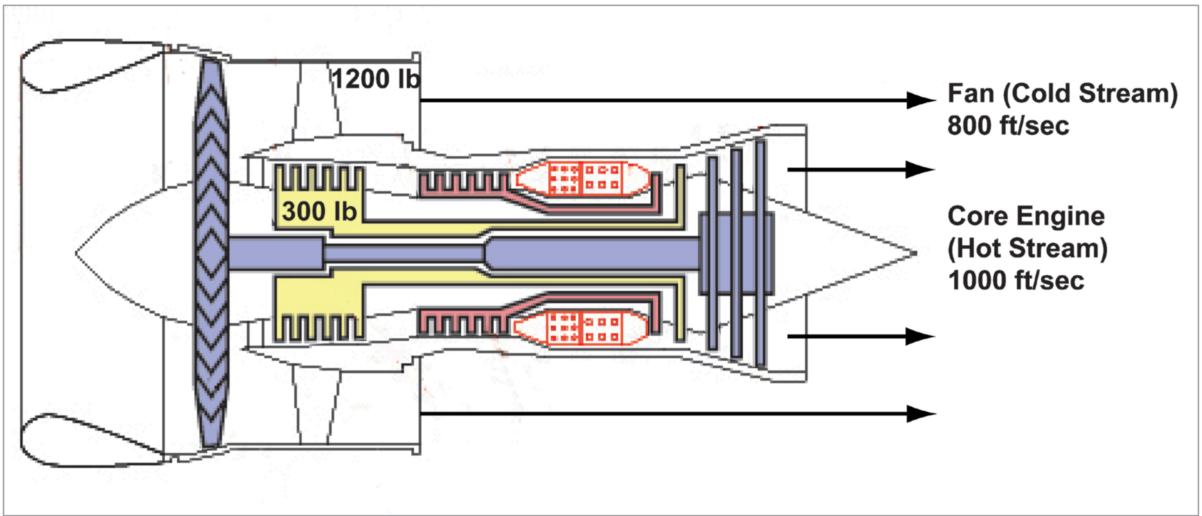


Figure 20.2

Example (Using Above Figures)

$$\text{Thrust (Fan)} \quad \frac{W_a(V_o - V_i)}{g} = \frac{1200 \times 800}{32.2} = 29\,814\ \text{lb}\ (132.6\ \text{kN})$$

$$\text{Thrust (Core Engine)} = \frac{W_a(V_o - V_i)}{g} = \frac{300 \times 1000}{32.2} = 9317\ \text{lb}\ (41.5\ \text{kN})$$

TOTAL = Fan + Core Engine = 29814 + 9317 = 39131 lb (175 kN)

Note: The fan accounts for 75% to 90% of the total thrust.

Pressure (Choked Nozzle) Thrust

Although the momentum change of the gas stream produces most of the thrust, additional thrust is produced when, under high thrust conditions, the gas velocity reaches the speed of sound and can not be accelerated any further. Under these conditions, the nozzle is choked and the pressure of the gases in the nozzle increases above atmospheric.

The pressure difference across the nozzle produces "pressure thrust" which is effective over the nozzle area, and is additional to "momentum thrust".

Most turbojet engines operate a choked nozzle during high power conditions. On these engines, pressure thrust is added to the calculated momentum thrust. Engines operating with a non-choked nozzle would use calculated momentum thrust only.

Choked Nozzle Thrust Example

The choked nozzle thrust is caused by the difference in the pressure at the nozzle, which is that of the atmosphere, and the pressure within the engine, which has increased because of supersonic airflow. For instance, at 32 000 feet, atmospheric pressure is about 4 lb/in^2 (psi). This is called ambient pressure, which we will label as Po. If the pressure inside the engine were 10 psi (which we will label as P), then the differential is 6 psi.

The general expression for force is:

FORCE = PRESSURE × AREA

This is expressed as: $P_f = (P - P_o) \times A$

Suppose that:

Area of nozzle (A) = 332 in^2

$P = 10$ psi

$P_o = 4$ psi

Pressure thrust = $P_f = (P - P_o) \times A$

$= (10 - 4) \times 332$

$= 1992$ lb (8.86 kN)

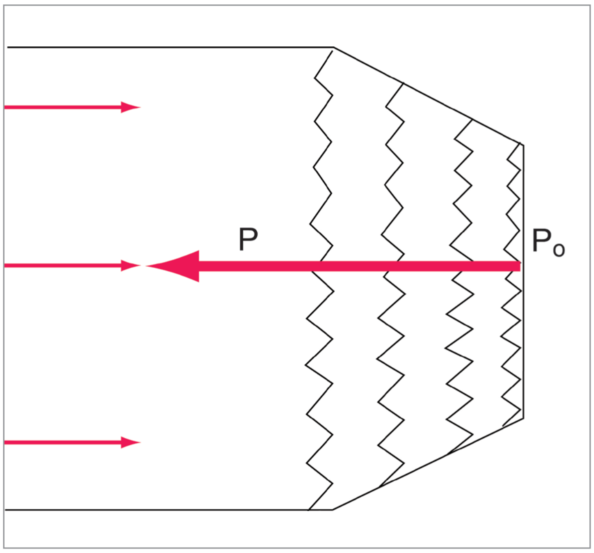


Figure 20.3

Thrust Indications

The power of a turbojet is measured in **thrust** and displayed by a P7 or EPR gauge which are thrust meters. A turbopropeller's output is measured in **shaft horsepower** (SHP) and displayed by a torque meter. In modern fan engines N1 and sometimes EPR are indications of thrust.

(N1, P7, EPR and Torque Meters are covered in Powerplant and Systems Monitoring Instruments).

Thrust Ratings

Take-off thrust	Maximum thrust from the engine which is normally time limited.
Go-around thrust	This can be take-off thrust but is normally a lower value of thrust.
Max continuous thrust	This thrust setting can be used continuously.
Max climb thrust	This thrust setting is equivalent to max continuous and gives best angle of climb speeds.
Max cruise thrust	This is a value below max continuous to prolong engine life.

Equivalent Shaft Horsepower (ESHP)

ESHP is the unit of power output for turboprop and some turboshaft engines.

ESHP = SHP + HP from jet thrust.

Under static conditions one shaft horsepower equals approximately 2.5 pounds of thrust.

The gas turbine engine can give a small mass of air a large acceleration (low bypass ratio turbo-jet) or a large mass of air a small acceleration (high bypass ratio turbo-fan, or turboprop). The merits of each relative to propulsive efficiency were discussed in chapter one.

The thrust or shaft horsepower developed must then be dependent on the mass of air entering the engine and the acceleration given to that mass as it passes through the engine, it will be affected by changes in altitude, temperature and airspeed which all have a bearing on the efficiency of the engine and therefore the gas energy available for conversion into thrust or SHP.

Specific Fuel Consumption (SFC)

To maintain an economical engine the ratio of fuel consumption to thrust or SHP must be as low as possible. This is the Specific Fuel Consumption (SFC) and is measured in pounds of fuel used per hour per pound of thrust or SHP. The thermal and propulsive efficiency determine the SFC.

Thrust to Weight Ratio

In a similar way to piston engines (which produce power), a gas turbine engine's thrust output can be compared to its weight. This is known as the Thrust to Weight Ratio and is used to compare one engine against another.

Example:

A gas turbine engine producing 53 000 lbf (static thrust) with a weight of 10 400 lb, would have a thrust/weight ratio of 53 000/10 400 = 5:1.

Variation of Thrust with rpm

The amount of thrust produced by a turbojet is proportional to its rpm. (Increased rpm increases the mass flow). The higher proportion of the thrust is produced at compressor speeds higher than 80-85% HP rpm.

At engine idle for a twin spool engine the HP rpm will be of the order of 50-60% and the LP rpm about 25%. These are the ground idle values. In flight these values will be higher because of the power take-offs from the engines.

In the high bypass ratio turbofan 25% N1 is approximately equivalent to 5% of the take-off thrust. Engine thrust is rated by the following terms:

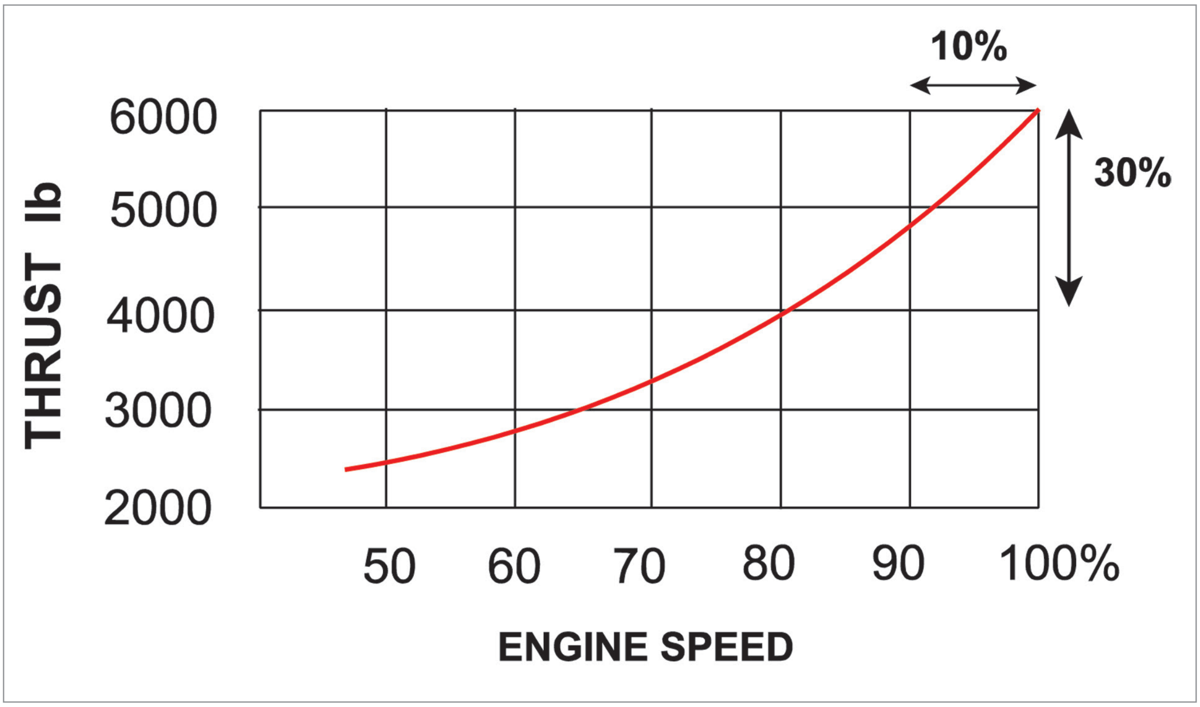


Figure 20.4

Variation of Thrust with Altitude

As aircraft altitude increases both temperature and pressure decrease. The fall of pressure causes a reduction in air density and therefore a loss of thrust as altitude increases. As the mass flow of air decreases the altitude sensing capsule of the fuel control unit adjusts the fuel flow to match the reduced airflow in order to maintain a constant engine speed for a fixed throttle position.

The fall of temperature increases the air density so that the mass flow of air into the engine increases and the thrust increases.

The combined effect of temperature and pressure reduction are that thrust will decrease but at a lower rate than if the pressure alone was reducing. Until of course the aircraft reaches the tropopause when any increase in altitude will cause the pressure to keep reducing but the temperature remains constant at -56°C. So the thrust will reduce at a greater rate. It will be seen that the SFC will remain essentially the same as the thrust decreases along with fuel burn as altitude increases.

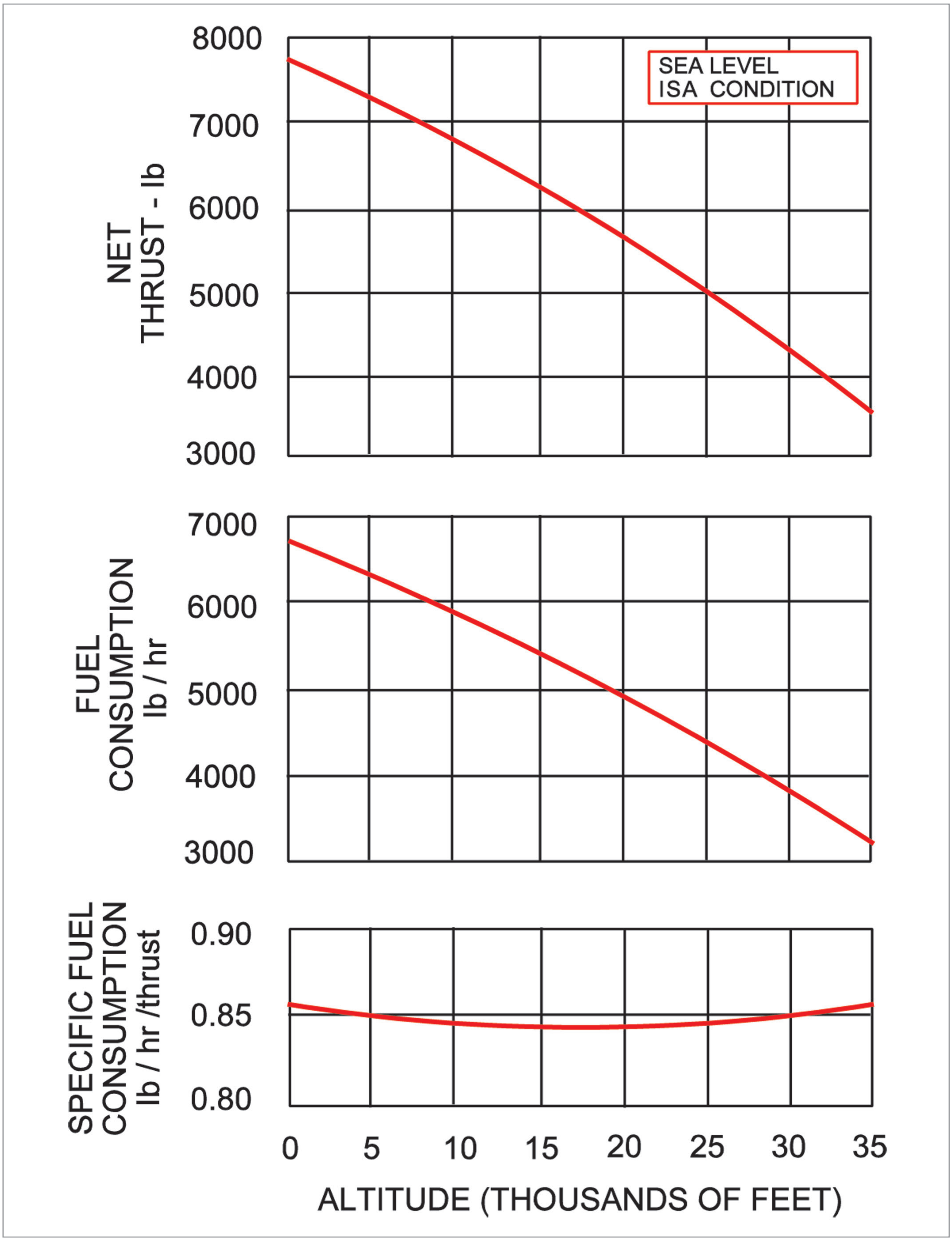

SEA LEVEL
ISA CONDITION
NET THRUST - lb
8000
7000
6000
5000
4000
3000
FUEL CONSUMPTION lb / hr
7000
6000
5000
4000
3000
SPECIFIC FUEL CONSUMPTION lb / hr /thrust
0.90
0.85
0.80
0
5
10
15
20
25
30
35
ALTITUDE (THOUSANDS OF FEET)

Figure 20.5

Variation of Thrust with Temperature

As temperature decreases air density increases and the mass of air for a given engine speed increases therefore thrust increases. To maintain the compressor speed however more fuel must be added or the compressor will slow down.

The opposite will happen in warmer air which is less dense, thrust will decrease because of the reduced mass flow and the compressor will speed up unless fuel flow is reduced.

In cold weather the denser air allows the engine to develop the required take-off thrust before the limiting temperature has been reached because of the maximum available pressure ratio across the compressor (power limiter). These are called **part throttle** or **flat rated** engines whereby the take-off rated thrust can be achieved at throttle settings below full throttle position.

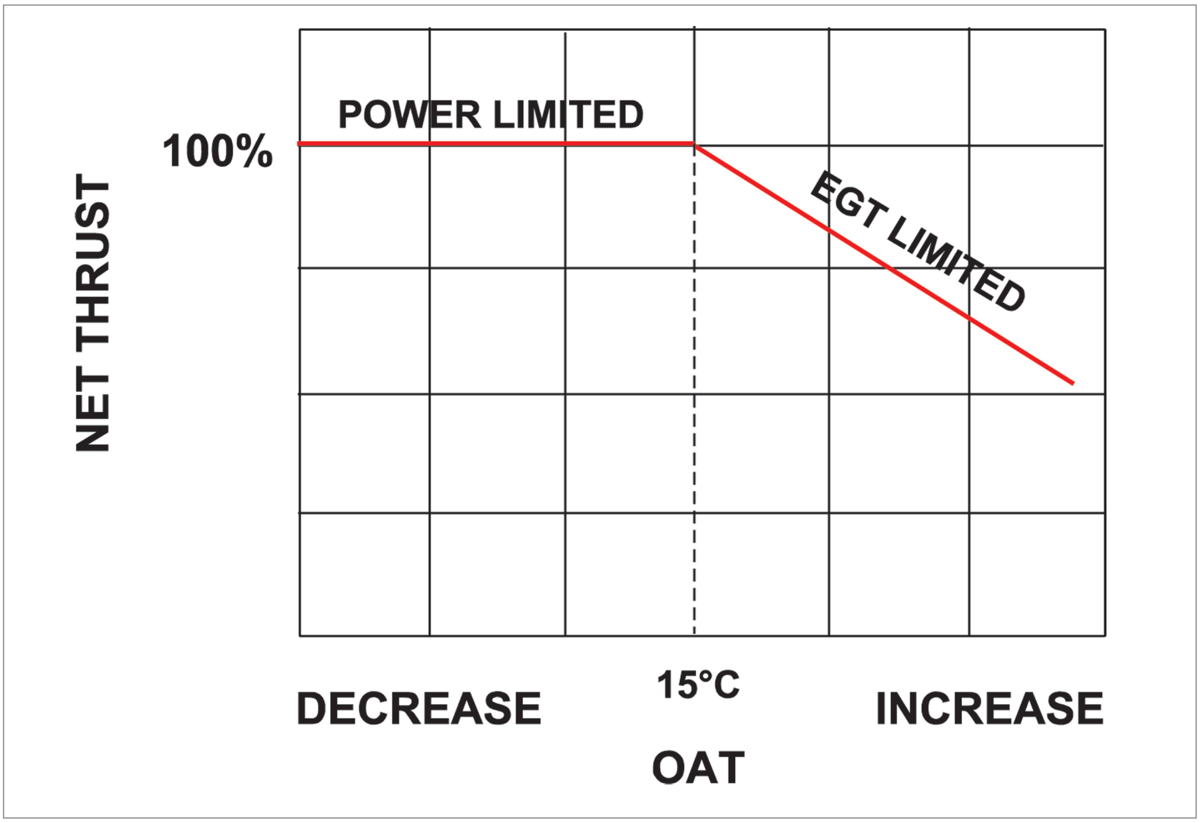


Figure 20.6

Variation of Thrust with Aircraft Speed

Theoretically as aircraft speed increases thrust decreases. If you look at the thrust equation then assuming that the exit velocity remains the same then if the inlet velocity increases then it follows that the thrust will decrease. In reality the forward speed generates extra pressure in the intake as described below.

The increase in Ram Ratio (*Figure 20.8*) increases the mass flow therefore fuel flow has to be increased causing an increase of SFC as the net thrust decreases.

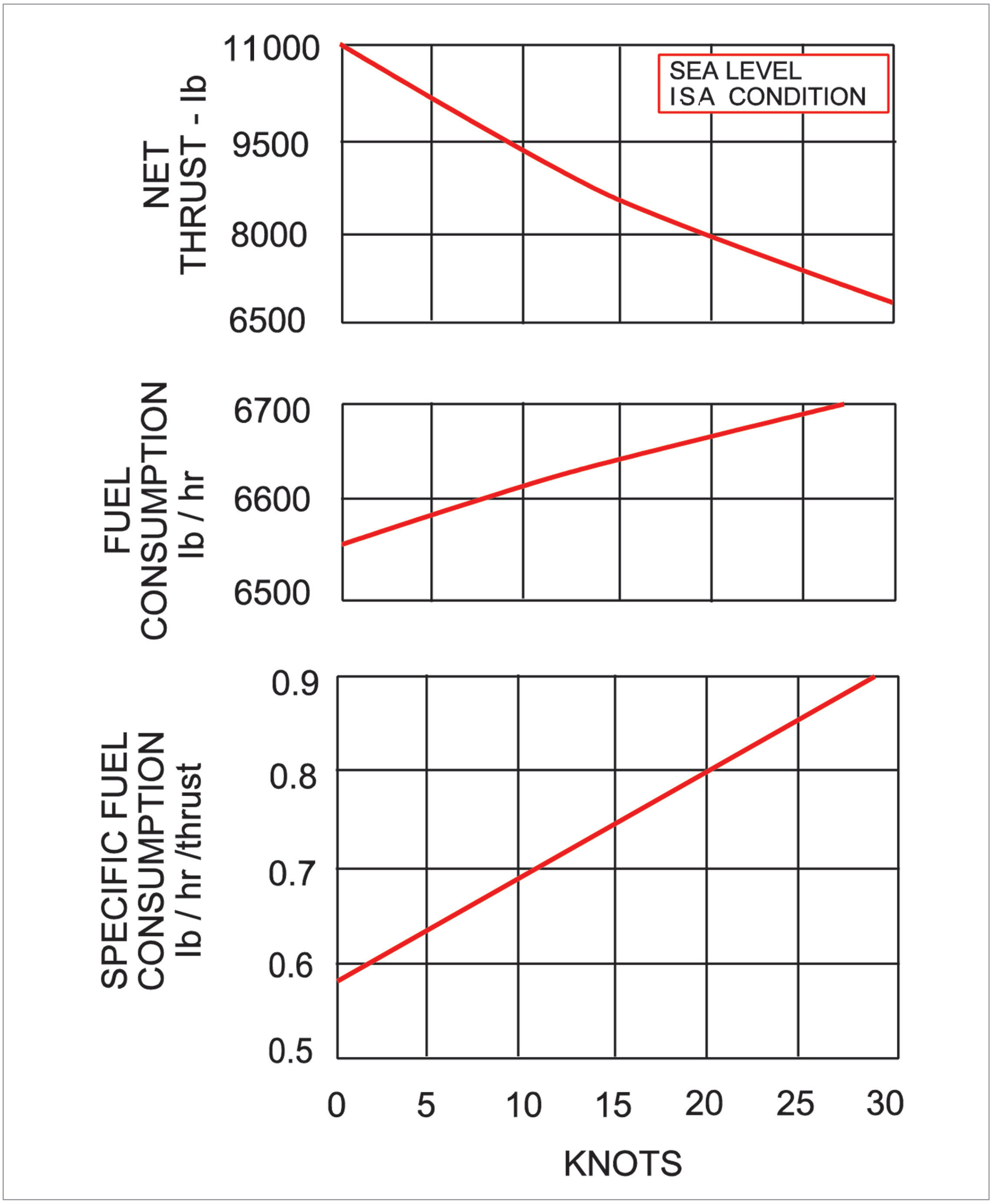


Figure 20.7

Ram Recovery

As the aircraft speed increases the inlet converts some of the extra velocity into pressure by the shape of the intake (Ram Recovery).

This increases the pressure at the face of the compressor therefore increasing the mass flow for a given compressor speed therefore restoring some of the otherwise lost thrust.

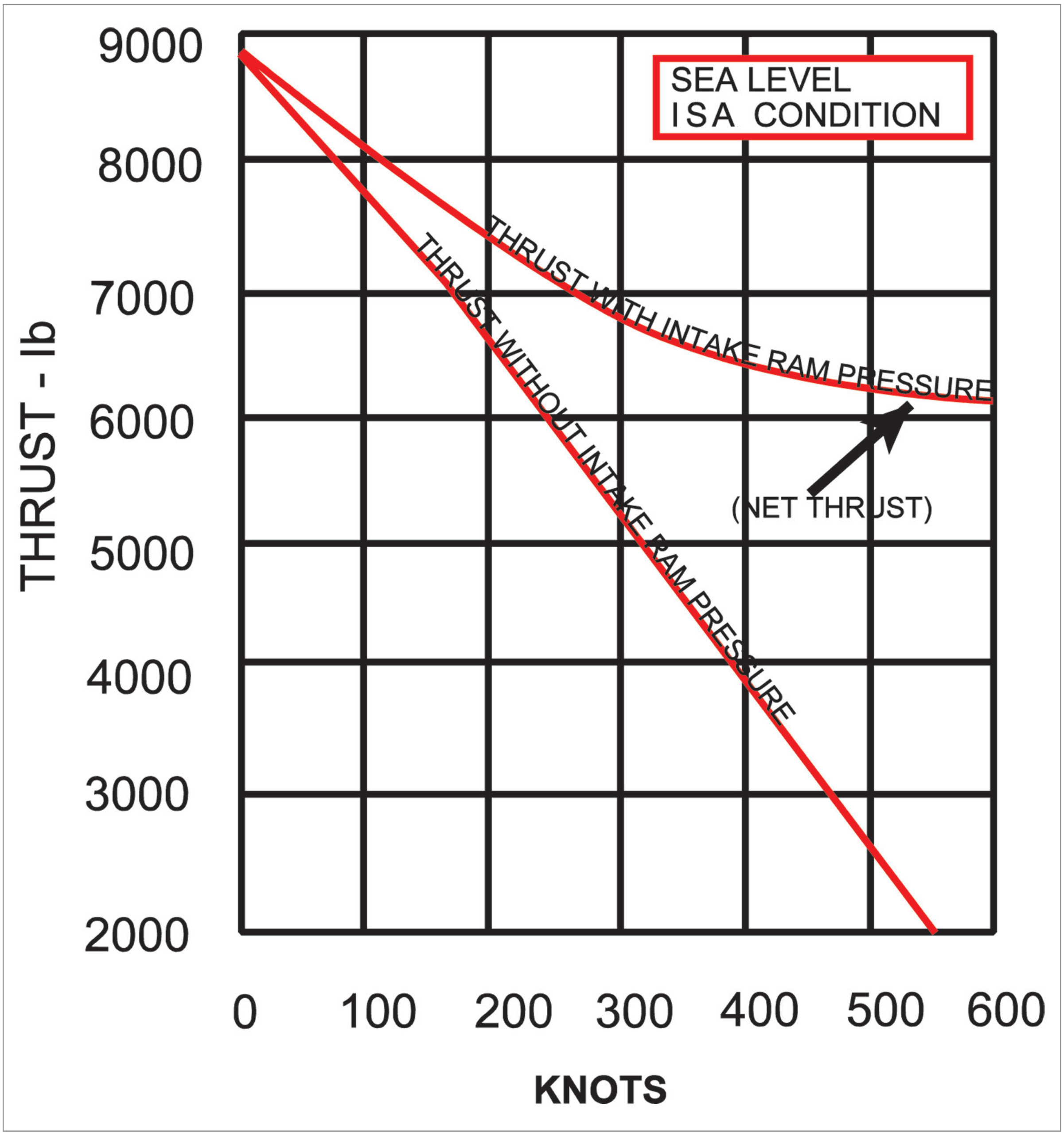


Figure 20.8

Effect of Altitude on SHP

As aircraft altitude increases a turboprop engine suffers a similar loss of power as density reduces.

Shaft horsepower and net jet thrust reduce (ESHP reduce).

As density reduces fuel flow reduces but the specific fuel consumption remains essentially the same.

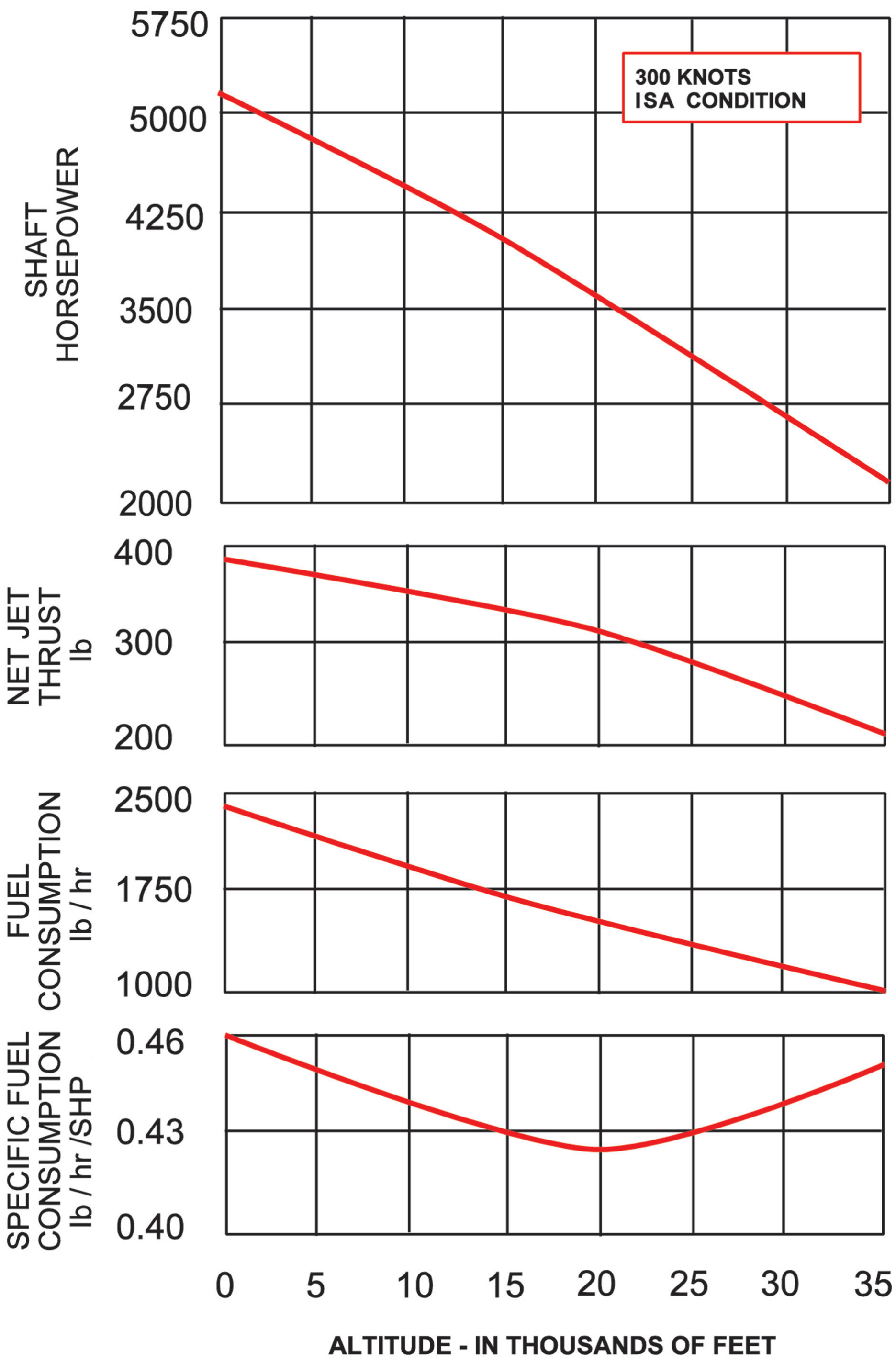


Figure 20.9

Effect of Aircraft Speed on SHP

As airspeed increases on a turboprop engine the ram effect into the intake causes the SHP to increase, as net jet thrust decreases.

Fuel burn increases in line with additional mass flow but sfc goes down.

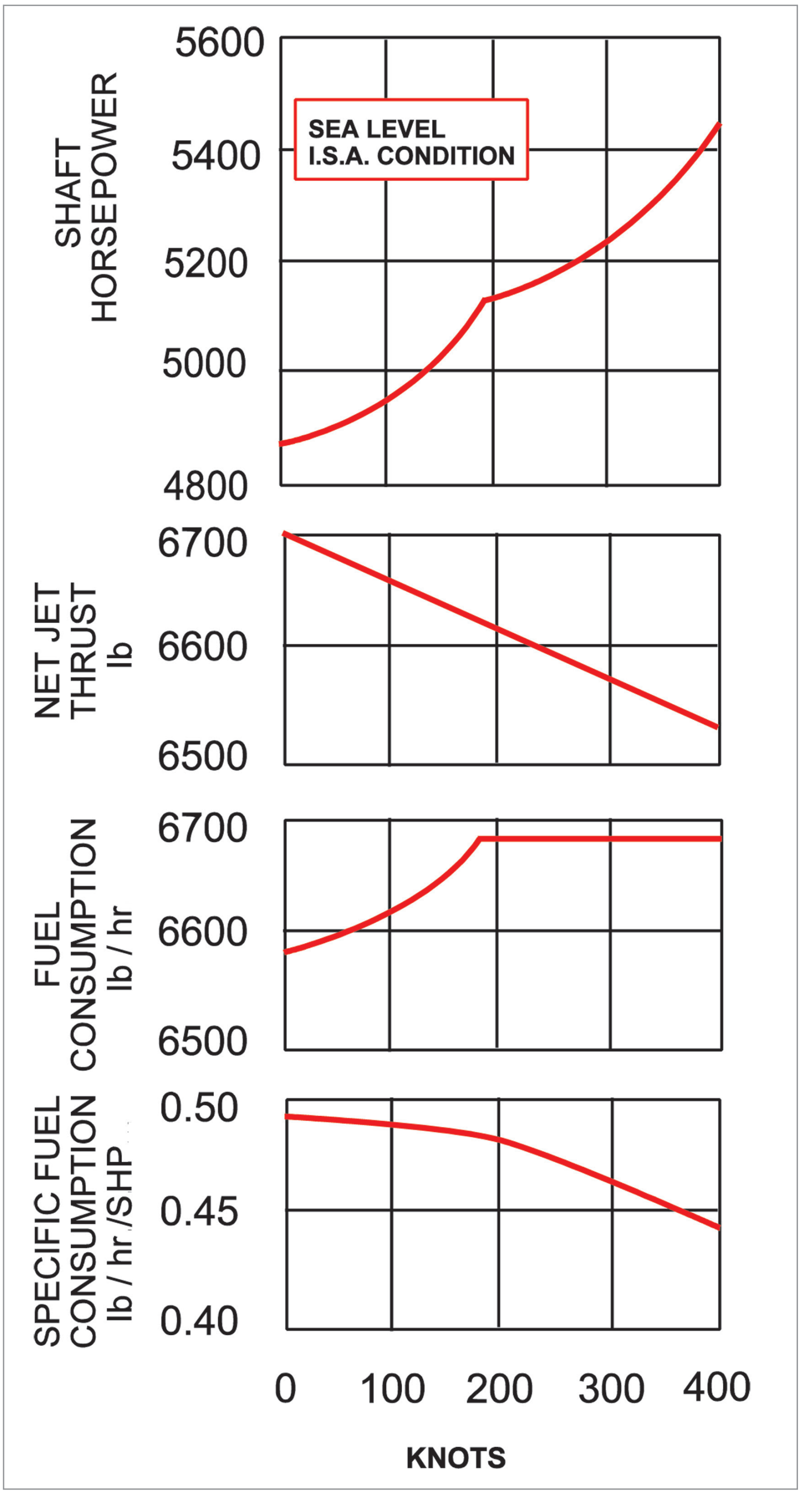


Figure 20.10

Questions

1. **In a gas turbine engine:**

   a. ram pressure is maximum at the start of the take-off run
   b. ram pressure is unaffected by airspeed
   c. thrust is unaffected by the aircraft's forward speed
   d. thrust is maximum and ram pressure at minimum at the start of the take-off run

2. **In a high bypass engine whose fan max rpm is 20 000 rpm, when turning at 5000 rpm will develop approx.**

   a. 25% take-off thrust
   b. 50% take-off thrust
   c. 5% take-off thrust
   d. 15% take-off thrust

3 **With an increase in altitude which of the following statements are correct for a jet aircraft with constant engine speed for a fixed throttle setting?**

   1. Temperature and pressure reduce with a resulting drop in thrust
   2. Fuel consumption will increase
   3. Fuel consumption will decrease
   4. Specific fuel consumption will increase
   5. Specific fuel consumption will decrease
   6. Specific fuel consumption stays relatively the same
   7. Temperature and pressure will reduce, resulting in an increase in thrust

   a. 1, 3, 6
   b. 2, 4, 1
   c. 7, 2, 4
   d. 1, 2, 5

4. **The maximum thrust that a jet engine can develop will be:**

   a. take-off thrust
   b. go around thrust
   c. max climb thrust
   d. max static thrust

5. **As temperature .... air density............. and the mass of air for given engine speed .... therefore thrust .... To maintain the compressor speed however .... fuel must be added or the compressor will ....**

a.	decreases	decreases	increases	increases	less	slow down
b.	increases	decreases	decreases	increases	more	slow down
c.	decreases	increases	increases	increases	more	slow down
d.	increases	decreases	increases	decreases	less	speed up

6. **From a standing start with an increase in forward speed jet thrust will:**

   a. increase
   b. stay the same
   c. decrease
   d. decrease then recover but will never achieve its initial setting

7. **On a turboprop aircraft with a 14 stage axial flow compressor while climbing it will experience:**

    a. increase shaft horsepower — increase jet thrust — increase fuel consumption
    b. decrease shaft horsepower — decrease jet thrust — decrease fuel consumption
    c. decrease shaft horsepower — increase jet thrust — decrease fuel consumption
    d. decrease shaft horsepower — decrease jet thrust — increase fuel consumption

8. **On a turboprop aircraft with a 14 stage axial flow compressor while increasing forward speed, it will experience:**

    a. increase shaft horsepower — increase jet thrust
    b. decrease shaft horsepower — decrease jet thrust
    c. decrease shaft horsepower — increase jet thrust
    d. increase shaft horsepower — decrease jet thrust

9. **On a part throttled engine, take-off thrust would be achieved:**

    a. later than normal due to pressure in the compressor being low
    b. later than normal due to the EPR being low
    c. at less than full throttle position
    d. later than normal due to the EPR being high

Answers

1	2	3	4	5	6	7	8	9
d	c	a	d	c	d	b	d	c

Chapter

21

Gas Turbines - Reverse Thrust

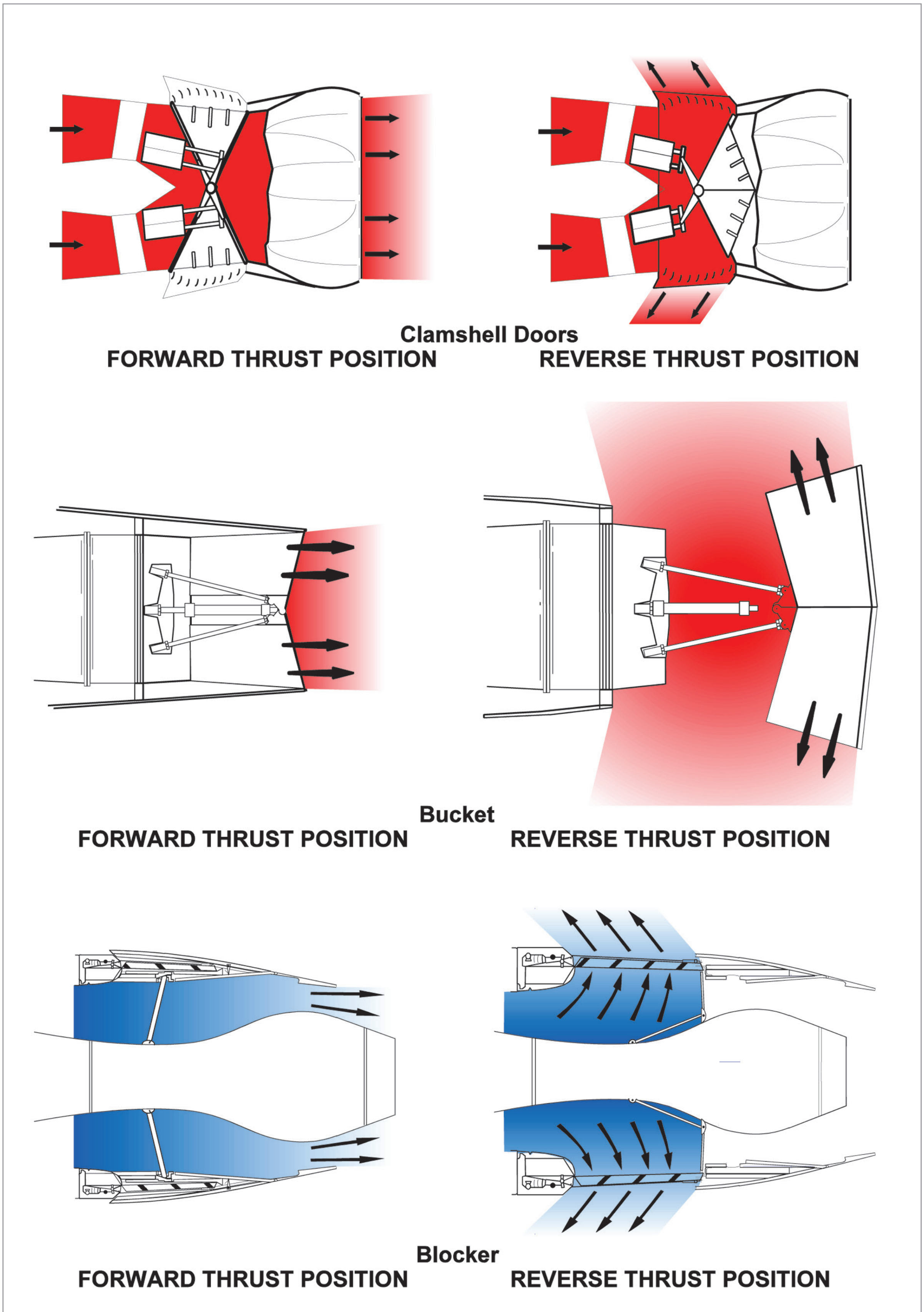


Figure 21.1 The types of reverse thrust systems.

Reverse Thrust

Modern aircraft braking systems, which incorporate anti-skid units and other sophisticated devices are extremely efficient, bad runway conditions however can reduce the ability of even the most refined braking systems to the point where they become a liability.

The addition of a Reverse Thrust capability has improved the situation so much that landing a modern aircraft on a wet and/or icy runway in crosswind conditions need now hold no terrors for the capable pilot.

The difference in stopping distance in an aircraft with and without reverse thrust are quite marked. Reverse thrust is selected immediately the weight of the aircraft is firmly on the mainwheels and coupled with ground spoilers can reduce the landing distance dramatically without producing friction at the wheels.

There are three basic Thrust Reversal Systems presently in use, they are:

a) Clamshell Doors.

b) Bucket Doors (External Doors).

c) Blocker Doors.

They are typically operated by hydraulic or pneumatic actuators or motors driving screwshafts and reverse the direction of the gas flow thereby reversing the thrust.

Clamshell Doors

The name "Clamshell" has been applied to this system of reverse thrust because of the shape of the reverse thrust doors, which resembles that of a clamshell.

The reverser doors are usually pneumatically operated and use high pressure compressor (P3) air as the power source. Pneumatic rams move the doors from their **stowed** (Forward Thrust) **position** to their **deployed** (Reverse Thrust) **position.**

In their **stowed** position, the clamshell doors cover **Cascade Vanes** which are revealed when the doors move to the **deployed** state.

Whilst deployed, the clamshell doors close the normal exhaust gas exit and it escapes through the Cascade Vanes in a forward direction so that the forward motion of the aircraft is opposed.

The lower cascade vanes, while directing the jet thrust forward, are angled so that the exhaust has an outboard angular component as well. This minimizes the chances of debris and hot gases being reingested into the engine intake during the use of reverse thrust.

External Door (Bucket) Reversers

The Bucket Reverser system is normally hydraulically operated. The rear of the exhaust pipe is shaped like two halves of a bottomless bucket which are hinged to enable them to swing backwards when selected to deflect the exhaust gas forward.

Cold Stream (Blocker) Reverser

This system is only used on **High Bypass Ratio FanJet Engines.** The essential difference between this system and the Clamshell Door and Bucket systems is that while the latter use the hot exhaust as the means of reverse thrust, the 'Blocker' system, as its name suggests, blocks and diverts the **Cold Bypass Airstream only.**

Operation of the system is initiated, as are the other two systems, by movement of **reverse thrust levers** in the cockpit, each engine with a reverse thrust capability has a reverse thrust lever.

In the case of the blocker system, the speed and direction of an **Air Motor** is determined by operation of the **reverse thrust lever.** The output of the air motor drives through flexible shafts to open or close the Blocker Doors, which, by their movement, expose or cover Cascade Vanes to direct the By-Pass air where it is required.

Indication and Safety Systems

In order that the pilot may have information regarding the position of the reverse thrust doors, **REVERSE THRUST WARNING LIGHTS** are fitted. These are usually **AMBER** lights positioned somewhere on the forward instrument array within full view of the crew.

The light will illuminate whenever the reverser doors are unlocked and away from their STOWED (Forward Thrust) POSITION.

Like a great number of things which purport to be beneficial, the Reverse Thrust system can, if wrongly serviced or mishandled, become more of a curse than a blessing. Safeguards have to be built into the system which will protect the aircraft in case of a malfunction or incorrect handling.

Other indications may be provided - reverser deployed, reverser operating etc dependent upon the aircraft type.

Figure 21.2 illustrates the **throttle lever** and **reverse thrust lever** of an engine fitted with reverse thrust.

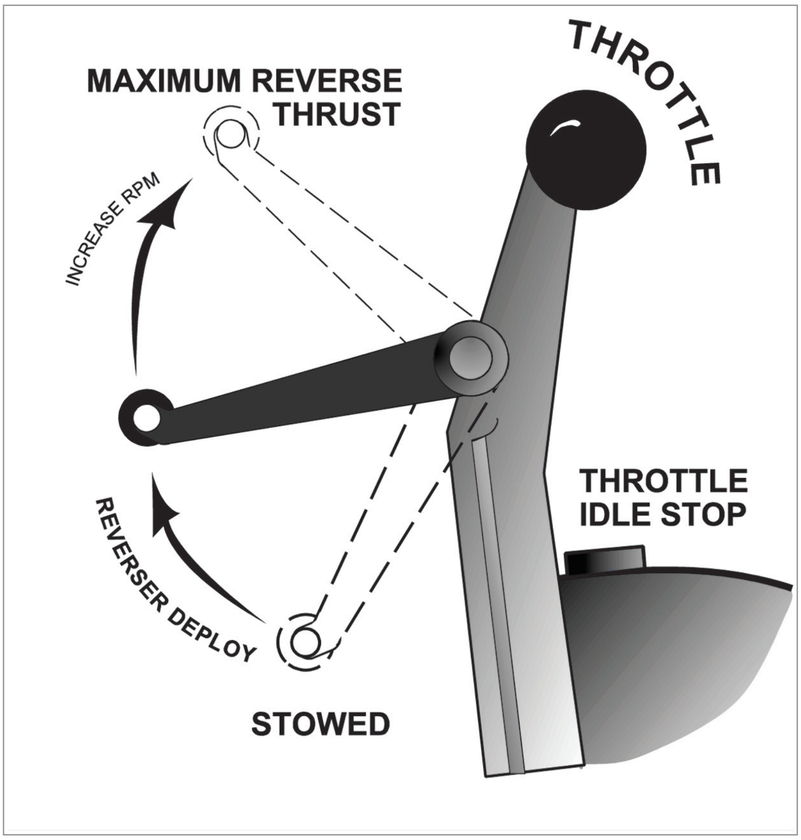


Figure 21.2 Throttle & reverse thrust lever.

There are five safeguards built into the selection of Reverse Thrust, they are:

a) Reverse thrust **cannot be selected until** the **throttle lever** is at **idle.**

b) Reverse thrust **cannot be activated until** the aircraft has the weight on the mainwheels (air/ground logic interlock).

c) **rpm** in Reverse **cannot be increased above idle until** the reverse thrust doors are in the **deployed** (Reverse Thrust) **position.**

d) If, **while Forward Thrust is selected,** the reverser doors inadvertently move to the **deployed** (Reverse Thrust) **position**, the **throttle** may automatically **close to idle.**

e) If, while Reverse Thrust is selected, the reverser doors inadvertently move to the **stowed** (Forward Thrust) **position**, the **reverse thrust lever** will automatically go to the **reverser deploy position** *(See Figure 21.2).*

Restrictions of Use

While there is normally no restriction on the upper speed at which Reverse Thrust can be selected, there are aircraft with systems fitted which place a restricted minimum speed of operation on the Reverse Thrust system.

Earlier it was described how the lower cascade vanes of the clamshell door system were angled forwards and **outwards**, this was to minimize the chances of debris and hot gases being re-ingested into the engine.

There is nevertheless a clear danger that, despite the angle of the cascade vanes, if the aircraft is only moving forwards slowly, or is stationary, the depression in the engine air intake will overcome the deflection applied to the exhaust gas stream (and any associated debris), and suck it into the compressor with potentially catastrophic consequences for the engine.

To prevent the likelihood of this happening, Standard Operating Procedure (SOP) on some aircraft is to reduce the position of the **reverse thrust lever** to the **reverse idle position** at typically 60 - 80 knots. Subsequently, at a speed where it is considered there is no further benefit to be gained from maintaining that Idle Reverse position, i.e. when it is judged that there is no further requirement for a **sudden** selection of full **reverse power**, usually at about 50 knots, the **reverse thrust lever** is returned to the **stowed** position.

Ground Manoeuvring Reverse Thrust is not Normally Used

When in use engine indications must be closely monitored, in particular for excessive EGT. Care must be exercised when increasing reverse rpm that the engines respond symmetrically as adverse yaw can be induced.

There may also be a performance limitation imposed if one engine thrust reverse system is inoperative as the total reverse capability will be reduced and on a two wing pylon mounted engined aircraft, may mean that the good reverser may not be operated either because of the asymmetric effect.

Questions

1. Use of reverse thrust below the recommended speed may cause:

a. over stressing of the gear oleos.
b. ingestion of the exhaust gases and foreign objects.
c. more fuel to be provided to the burners.
d. the TGT limit to be exceeded, in which case the reverse thrust lever will return to the forward thrust position.

2. A big fan engine gets reverse thrust by:

a. reversing the direction of rotation of the compressor.
b. deflecting the exhaust gases.
c. blocking the bypass air.
d. reversing the hot stream gases.

3. Before reverse thrust can be selected, the forward thrust lever must be:

a. pulled back to idle power.
b. positioned to reverse minimum power.
c. put back to the reverser deploy position.
d. positioned to reverse maximum power.

4. An aircraft uses clamshell doors for thrust reversal to:

a. direct the gas flow rearwards.
b. block the flow of exhaust gas.
c. absorb any change in thrust.
d. change the direction of the exhaust gas.

5. A reverse thrust warning light illuminates:

a. only when the reverser doors are fully deployed in the reverse thrust position.
b. when the reverser doors are stowed in the forward thrust position.
c. when the reverser doors are not stowed in the forward thrust position.
d. whenever reverse thrust is selected.

6. Once the blocker doors are fully deployed, with an increase in rpm, which of the following statements would be incorrect?

a. Forward thrust from the hot gases would increase.
b. Forward thrust from the hot gases would decrease.
c. Reverse thrust from the blocked air would increase.
d. TGT will increase.

Answers

1	2	3	4	5	6
b	c	a	d	c	b

Chapter

22

Gas Turbines - Gearboxes and Accessory Drives

Auxiliary Gearbox

The auxiliary gearbox (accessory drive) provides the power for hydraulic, pneumatic and electrical mechanisms for use on the engine and in the aircraft, and is also used to drive fuel pumps, oil pumps and tacho-generators and various other devices necessary for efficient engine operation.

The drive for the accessory unit is taken usually from the high pressure compressor shaft, via an internal gearbox, to an external gearbox which provides the mountings for the accessories and also, in the majority of cases, the starter motor.

In the case of modern turbofan engines there is much less of a problem concerning where to conceal the accessory drive unit. The engine itself is so massive that even the largest accessories can be fitted into the cowling that forms the air intake faring. Much more of a problem in this particular case is that of how to get the drive shaft through the engine from the high pressure compressor shaft. If the drive were taken from the hot end of the engine the losses incurred would be very high, also the type of material used for the shafts would have to be fairly exotic.

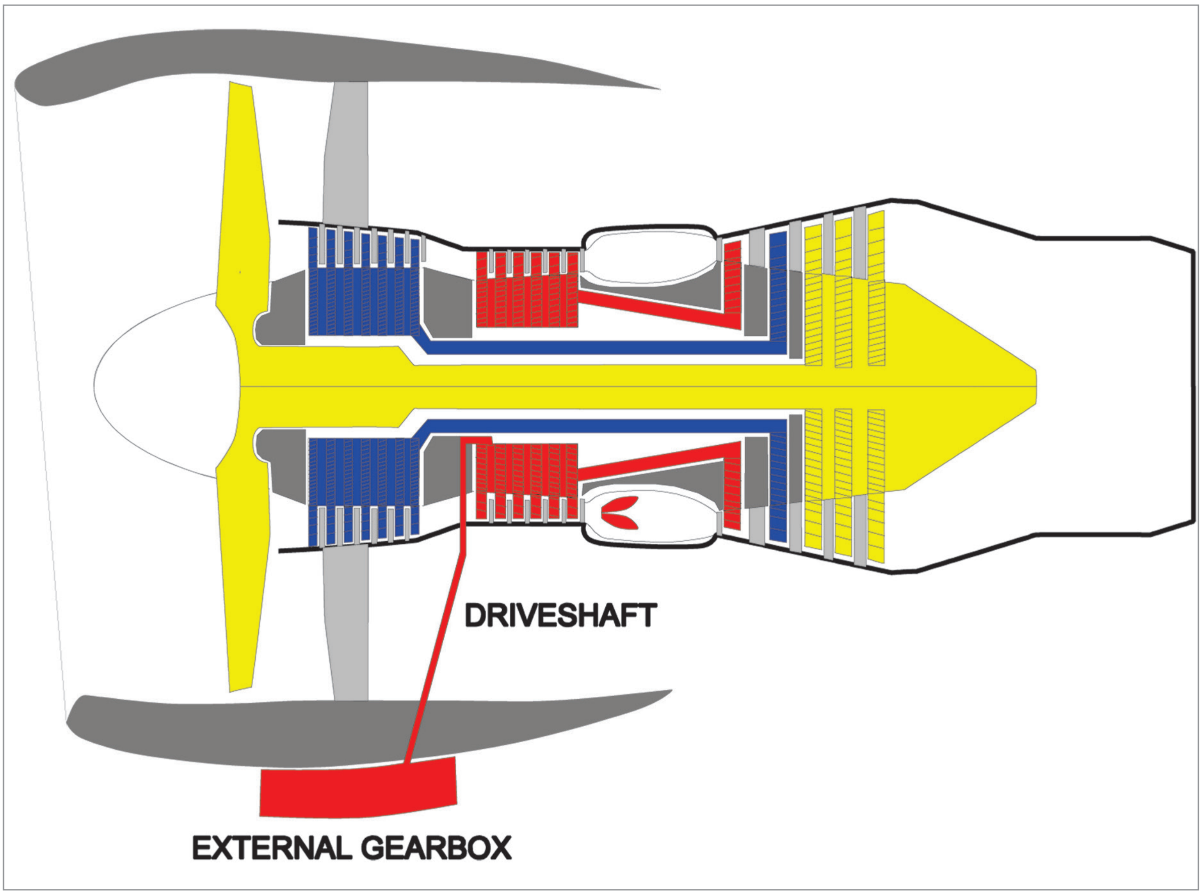


Figure 22.1

Allowing for Expansion of the Compressor Shaft

Axial movement of the compressor shaft would cause the teeth of the bevel gears to move apart and the drive would be interrupted. Momentary interruption of a drive transferring 400 - 500 horsepower would impart massive damage to the teeth of the bevel gears and probably destroy them.

This state of affairs obviously cannot be allowed to exist, however, axial movement of the compressor shaft must occur due to expansion and contraction during the working cycle.

Some method of arranging the gears so that they do not disconnect themselves with axial movement of the shaft has to be found before a reliable drive unit can be manufactured. *Figure 22.2* shows two of the methods currently in use on modern engines.

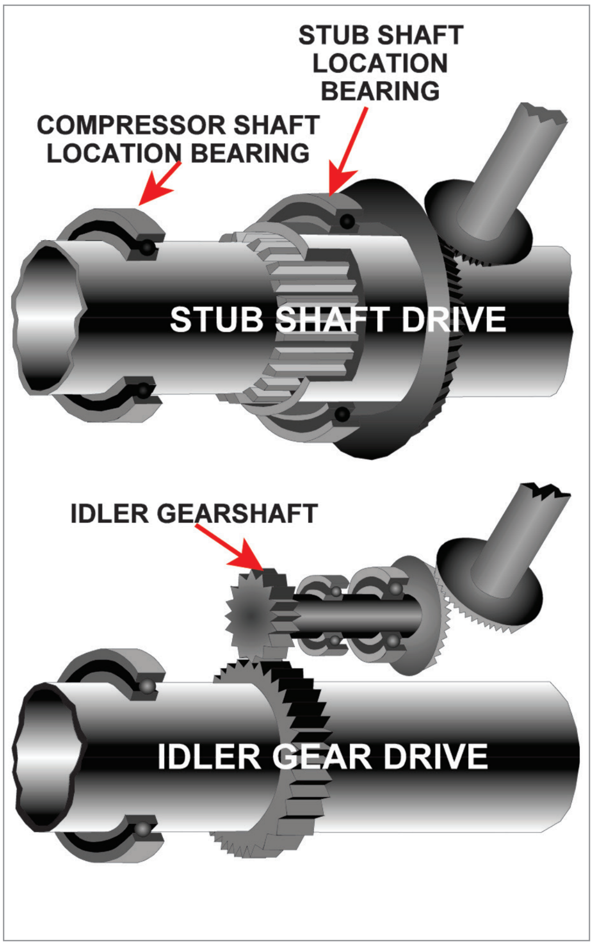


Figure 22.2 Two methods of gear drive from the compressor shaft.

Stub Shaft Drive

If the compressor shaft is splined, that is it has grooves cut in it parallel to its axis, then a stub shaft, which has teeth cut internally that conform to the pattern of the grooves in the compressor shaft, can be fitted around the compressor shaft.

This means that the shaft can move axially while the stub shaft is held firmly in the correct position by the location bearing.

Idler Gear Drive

An alternative system uses an idler gear shaft which is held firmly in position by location bearings. One end of the idler gear shaft terminates in a wide toothed spur gear which can accommodate axial movement of the compressor shaft and the spur gear carried on it, and the other end has fitted a bevel gear which meshes with the radial drive shaft.

Spreading the Load

In an effort to spread the load of driving accessories, some engines take a second radial shaft from the low pressure compressor shaft, which is rotating at a slower speed, and use it to drive a second external gearbox.

This system has a second advantage of allowing the accessories to be divided into two smaller groups, thus overcoming the difficulties of limited space around the engine. This is illustrated in *Figure 22.3*.

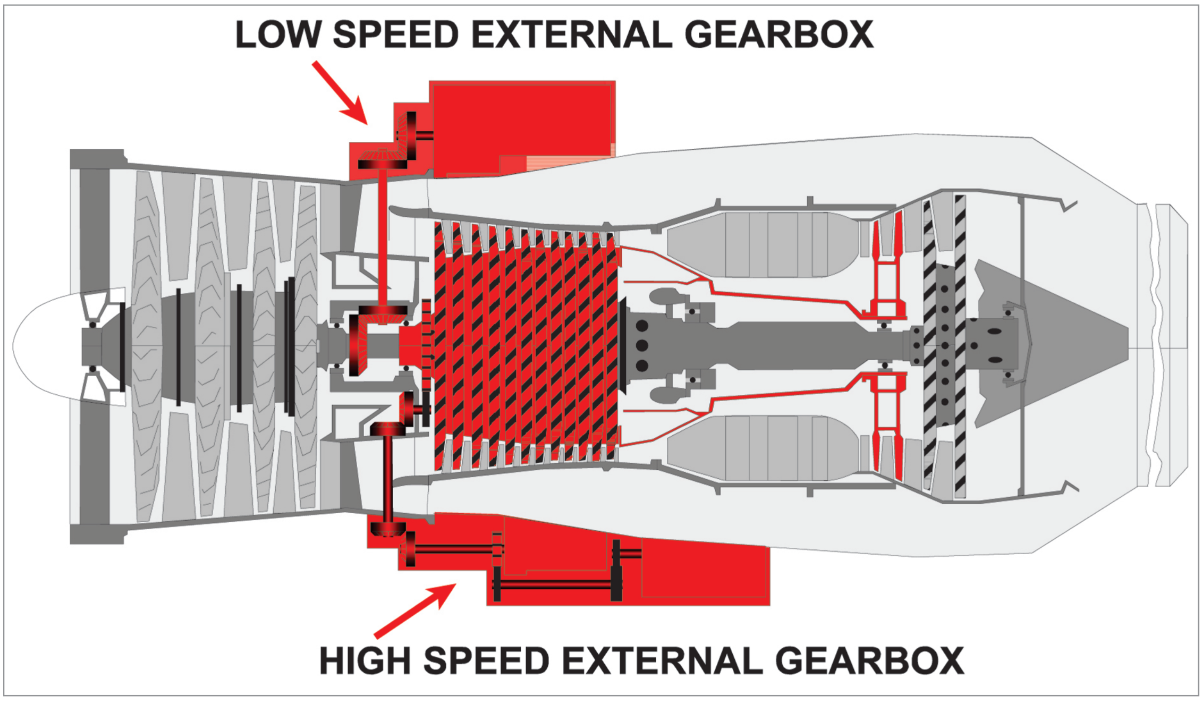


Figure 22.3 Spreading the load of accessories between two gearboxes.

Because on start-up the starter motor causes the HP compressor shaft to rotate first, accessories specific to the engine, such as the oil pumps and the fuel pumps, are grouped on the gearbox driven by that shaft.

This is classified as the high speed external gearbox, because it is being driven by the shaft which is rotating at the highest speed of all. Logically we can expect that the other gearbox will be called the low speed external gearbox.

Having to fit it around the engine means that the gearbox must be shaped like a banana, and to ease servicing it is usually located on the underside of the engine. *Figure 22.4* shows an external gearbox and some of the associated accessories, amongst them the engine hand turn access, a device intended to assist the inspection of the interior of the engine. Also worthy of interest are the oil pumps, notice they are contained in an oil pump pack, a unit which contains one pressure pump but in some engines as many as six scavenge pumps.

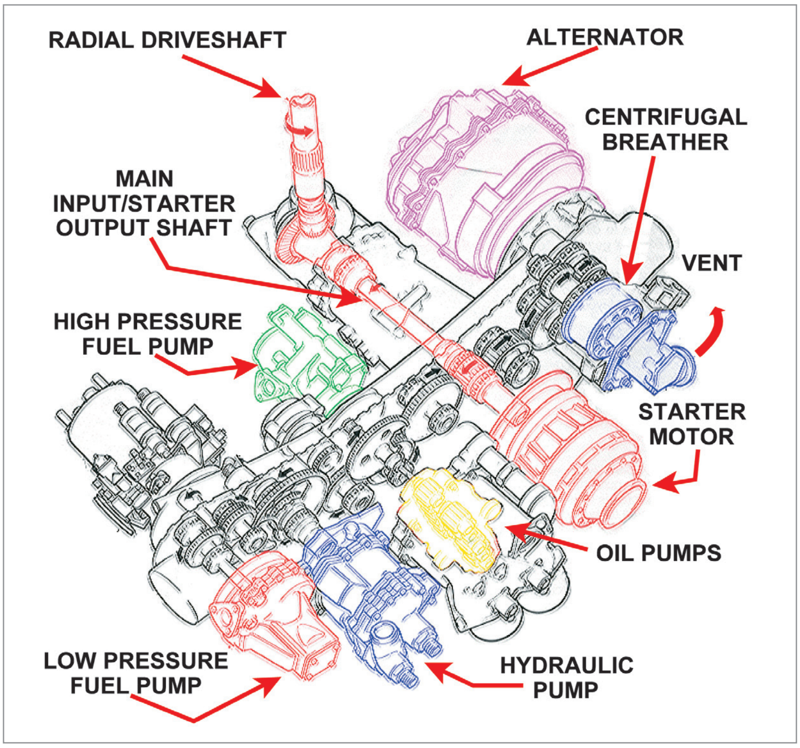


Figure 22.4 An external gearbox showing various accessories.

The width of the gear teeth indicates that the greatest load from driving the accessories is taken on the right side of the gearbox, while the thinner teeth on the left side gear wheels show that their load is much smaller. This grouping of small and large gears enables an efficient distribution of the drives for the minimum weight.

The Shear Neck

Mechanical failure of an accessory could cause the failure of the whole gearbox with the associated loss of the engine.

To prevent this happening the mechanical equivalent of an electrical fuse is fitted to some of the accessory drives.

A weak section is machined into the drive shaft, this is known as a shear neck. It is designed to fail at a load perhaps 25% in excess of the normal maximum for the particular component being driven by that shaft.

In circumstances of excessive overload, the shear neck will break, allowing failure of the individual component while the rest of the gearbox and accessories continue as normal. This feature is not utilized in the drives of primary engine accessory units, such as the oil pumps or HP fuel pumps, because any failure of these components would necessitate the immediate shutdown of the engine.

Questions

1. **The effect of modifying a gas turbine engine to include one further hydraulic pump will result in:**

   a. increase in specific fuel consumption
   b. decrease in specific fuel consumption
   c. decrease in rpm
   d. increase in EGT

2. **The drive for fuel, oil and hydraulic pumps is normally taken from the:**

   a. LP fan
   b. intermediate compressor
   c. HP spool
   d. HP turbine

Answers

1	2
a	c

Chapter 23

Gas Turbines - Ignition Systems

General

All gas turbine engines have a dual ignition system fitted and they all use high energy (HE) igniter units for engine starting. HE ignition systems have an output of approximately twelve joules (one watt equals one joule per second).

It may sometimes be necessary to have the igniters selected in circumstances other than engine starting, for instance during take-off from contaminated runways or flight through heavy precipitation to help prevent engine 'flame out'. The use of the high energy ignition system on these occasions would cause the igniter plug to be eroded so quickly that it would shorten its working life dramatically. To minimize this, some aircraft engines are fitted with a combination ignition system which includes a low energy (three to six joules) continuous selection as well as the high energy (six to twelve joules) starting selection.

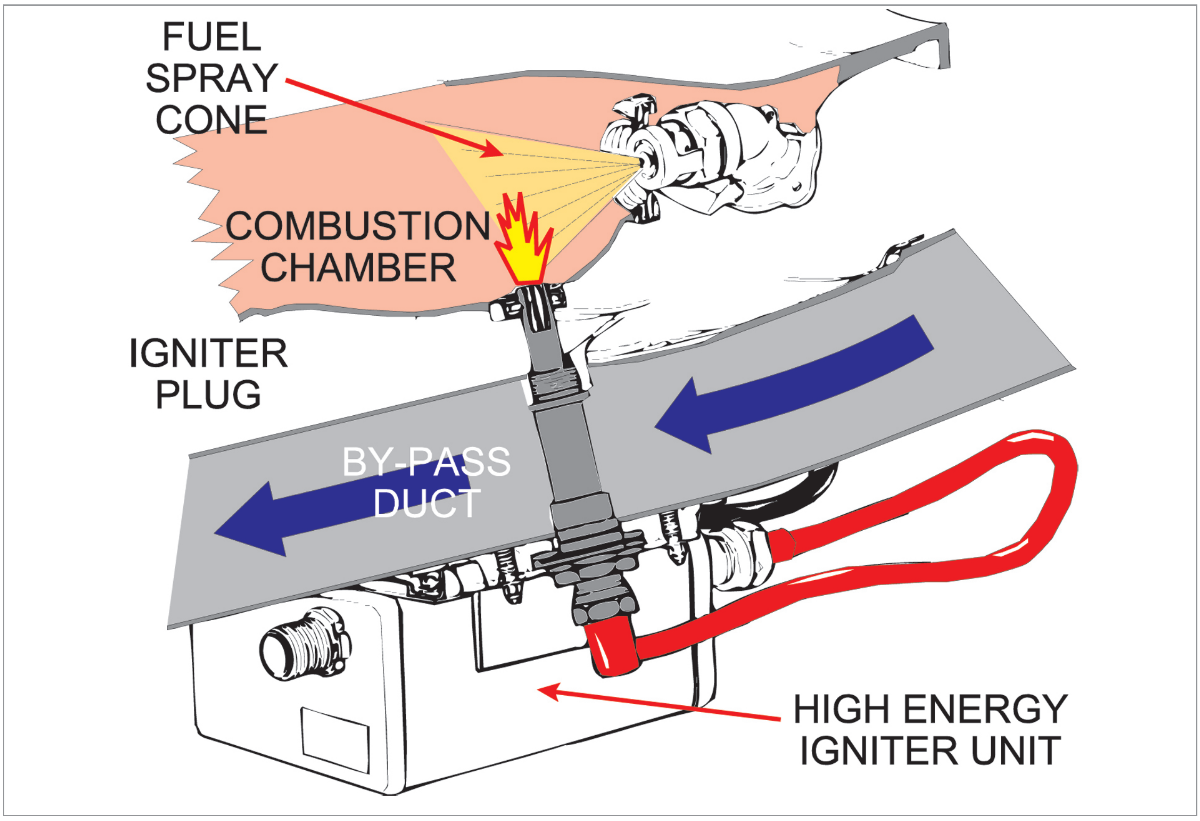


Figure 23.1

The starting ignition system is activated when the engine start sequence is initiated either automatically or by the operation of the HP cock, start lever or fuel and ignition switch. The igniters are automatically deactivated at some point after self-sustaining speed typically by a speed switch in the HP rpm indicator.

Continuous ignition is activated by selection on the engine start panel and activates the low energy mode of the igniters.

Automatic ignition is a feature of some aircraft and is typically activated by the aircraft stall warning system to automatically select continuous ignition during a detected aircraft stall.

The High Energy Ignition Unit

The high energy ignition unit works on the principle of charging up a very large capacitor and then discharging it across the face of an igniter plug.

The actual size of the capacitor makes it potentially a lethal device, and several safety factors have to be built into the high energy ignition unit (HEIU) to make it conform to safety regulations. The circuit shown here illustrates all of the components within a HEIU supplied by 28 volts DC.

With the supply connected, the primary coil and the trembler mechanism are fed with 28 volts DC. The trembler mechanism works in a manner similar to an electric bell, and by doing so causes the primary coil input to become a sawtooth waveform. This is a very crude form of AC and by transformer action the voltage is passed to the secondary coil where its voltage is boosted to 25 000 volts.

The 25 000 volts AC is changed back to DC in the rectifiers and commences charging the reservoir capacitor.

As the value of the charge in the capacitor builds up, it eventually reaches a level that allows a spark to jump the discharge gap. The energy in that spark has then to flow through the choke, this acts as a normal inductance and slows down the flow to make the duration of the spark longer. The energy then passes to the igniter in the combustion chamber.

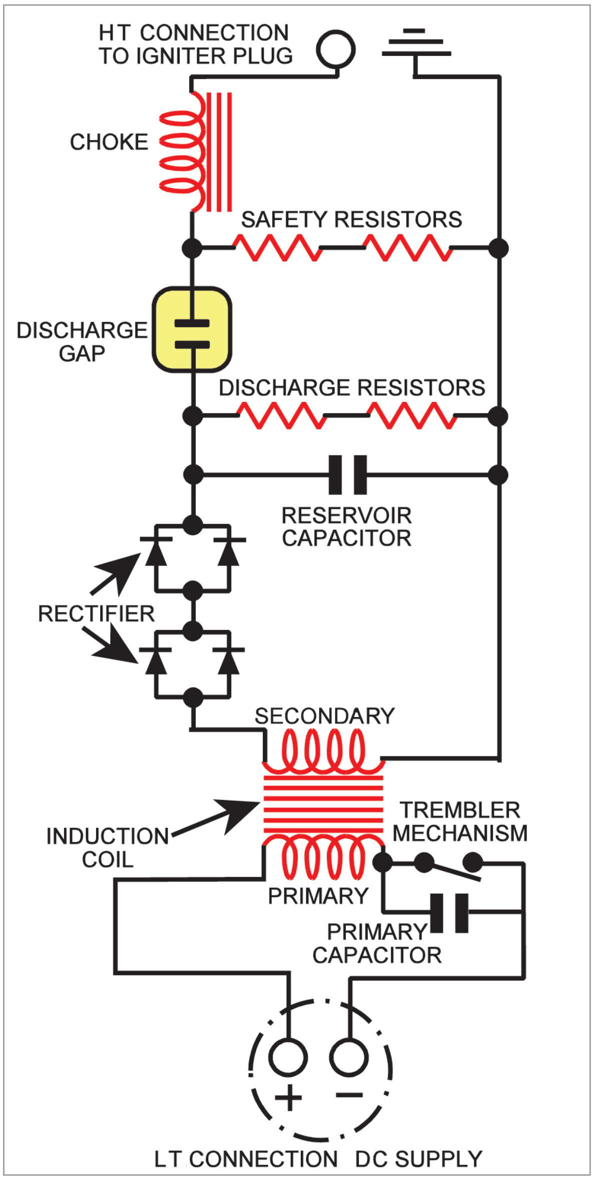


Figure 23.2

The discharge resistors act as a safety device should the unit have to be removed for servicing, the charge which may remain in the capacitor could be lethal to anyone touching the casing of the HEIU, so it is allowed to leak through the resistors to zero the charge once the supply has been removed.

The safety resistors act as a kind of safety valve if the igniter plug becomes disconnected. If this did happen, there would be a continued build-up of energy in the capacitor which eventually would cause it to explode, to prevent this the safety resistors allow energy in excess of the normal level to flow through them in an attempt to balance the charge on the plates of the capacitor.

The normal rate of sparking of the HEIU is between 60 - 100 per minute, this is completely random, and anyone listening at the jet pipe before engine start, if relight is selected, should hear an unsynchronized beat if both units on the engine are working correctly.

As well as this type of unit there are transistorized devices, and for aircraft which have AC electrical system there are units which will work on that type of supply.

Igniter Plugs

There are two types of igniter plug. The older of these two types works in a similar manner to that of the piston engine spark plug, but with a much bigger spark gap. The potential required to jump this gap is approximately 25 000 volts and this creates the need for very good insulation within the unit and in the cabling.

A more modern version of this system is that of the surface discharge igniter plug shown in *Figure 23.3*. This second type of igniter plug has the end of the insulator formed from a semi-conductor material.

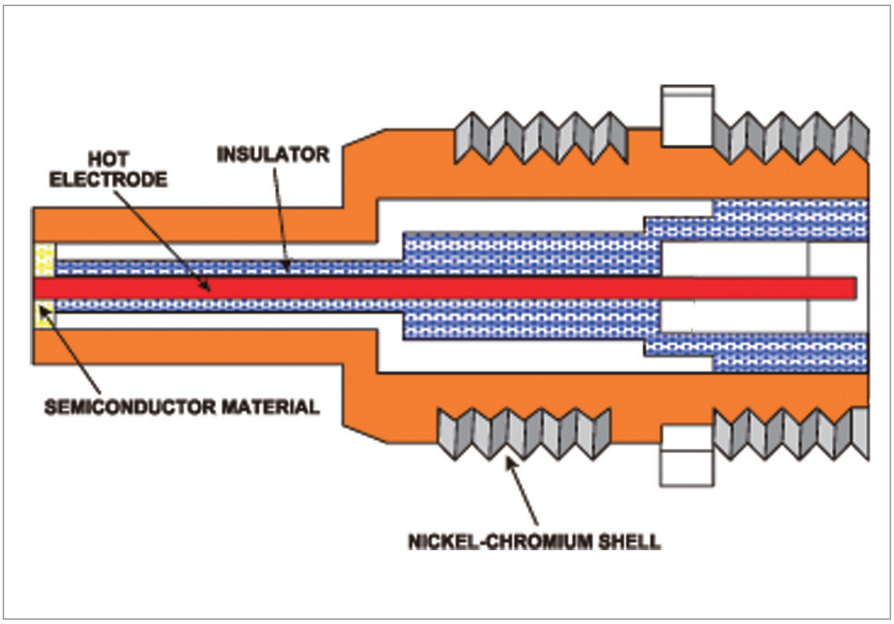


Figure 23.3

This allows an electrical leakage from the hot electrode to the body of the igniter. This ionizes the surface of the semi-conductor material to provide a relatively low resistance path for the energy stored in the capacitor. The discharge takes the form of a high intensity flashover from the hot electrode to the body of the igniter which only requires approximately 2000 volts.

Figure 23.1 shows the HEIU mounted on the side of an engine and the position of the igniter within the combustion chamber.

Questions

1. The low energy ignition system would be used:

a. only for starting the engine on the ground.
b. during take-off from wet runways.
c. for relight at high altitude.
d. during a blow out (motoring over) cycle.

2. Precautionary use of igniters may be necessary during:

a. flight through heavy tropical rainstorm.
b. ground running.
c. flight through sandy conditions.
d. flight through very dry air.

3. A high energy ignition system works on the principle of:

a. obtaining power from a step up transformer from the aircraft's AC power system.
b. magneto static induction.
c. Fleming's Right Hand Rule.
d. obtaining energy from the discharge of a capacitor.

4. A gas turbine engine which has both high and low energy ignition systems uses the high energy system for (i), and the low energy system for (ii):

	(i)	(ii)
a.	engine starting	high altitude relighting
b.	high altitude relighting	take-off from contaminated runways
c.	take-off from snowy runways	engine start
d.	take-off from flooded runways	take-off from snowy runways

5. In a High Energy Igniter Unit, the discharge resistors:

a. allow sufficient energy to be stored in the capacitor to provide relight facilities up to 55 000 ft.
b. protects the unit from excessive voltages.
c. allow the capacitor to discharge when the unit is switched off.
d. prolong the discharge.

6. In a High Energy Igniter Unit, the choke:

a. protects the unit from excessive voltages.
b. prolongs the discharge to the plug.
c. prolongs the life of the igniter
d. protects the unit from excessive current.

7. The rate of discharge of a High Energy Ignition Unit is:

a. 60 - 100 times per minute.
b. 4 discharges per revolution.
c. 60 - 100 per second.
d. governed by the resistance of the igniter plug.

8. The power supply for the spark in the combustion chamber is:

a.	low volts	high current
b.	low volts	low current
c.	high volts	low current
d.	high volts	high current

Answers

1	2	3	4	5	6	7	8
b	a	d	b	c	b	a	d

Chapter

24

Gas Turbines - Auxiliary Power Units and Engine Starting

The Auxiliary Power Unit (APU)

As aircraft became more complex a need was created for a power source to operate the aircraft systems on the ground without the necessity for operating the aircraft's main engines. This became the task of the **Auxiliary Power Unit (APU).** The use of an APU on an aircraft also meant that the aircraft was not dependent on ground support equipment at an airfield. It can provide the necessary power for operation of the aircraft's **Electrical, Hydraulic and Pneumatic systems.** It should come as no surprise that the power unit selected to do this task is a **Gas Turbine Engine.**

The gas turbine produces very high power for a light weight, making it ideal for the task. The APU can use the same fuel system as the man engines so reducing the need for additional systems. The type of engine layout normally used is that of the **Free Turbine, Turboshaft Engine.** A turboshaft engine is both small and lightweight yet produces around 600 hp. The free turbine arrangement makes the engine very flexible, as the compressor is not affected by changes of load on the free turbine which drives the accessories via a gearbox. The free turbine is usually designed to run at constant speed, this ensures that a generator run by the APU maintains a constant frequency without the need for an additional constant speed drive unit.

Some aircraft use air bled from the compressor of the APU to power aircraft's pneumatic system, but it is more common for the free turbine to drive a separate **Load Compressor** to supply these services. A typical layout for an APU is shown in *Figure 24.1.*

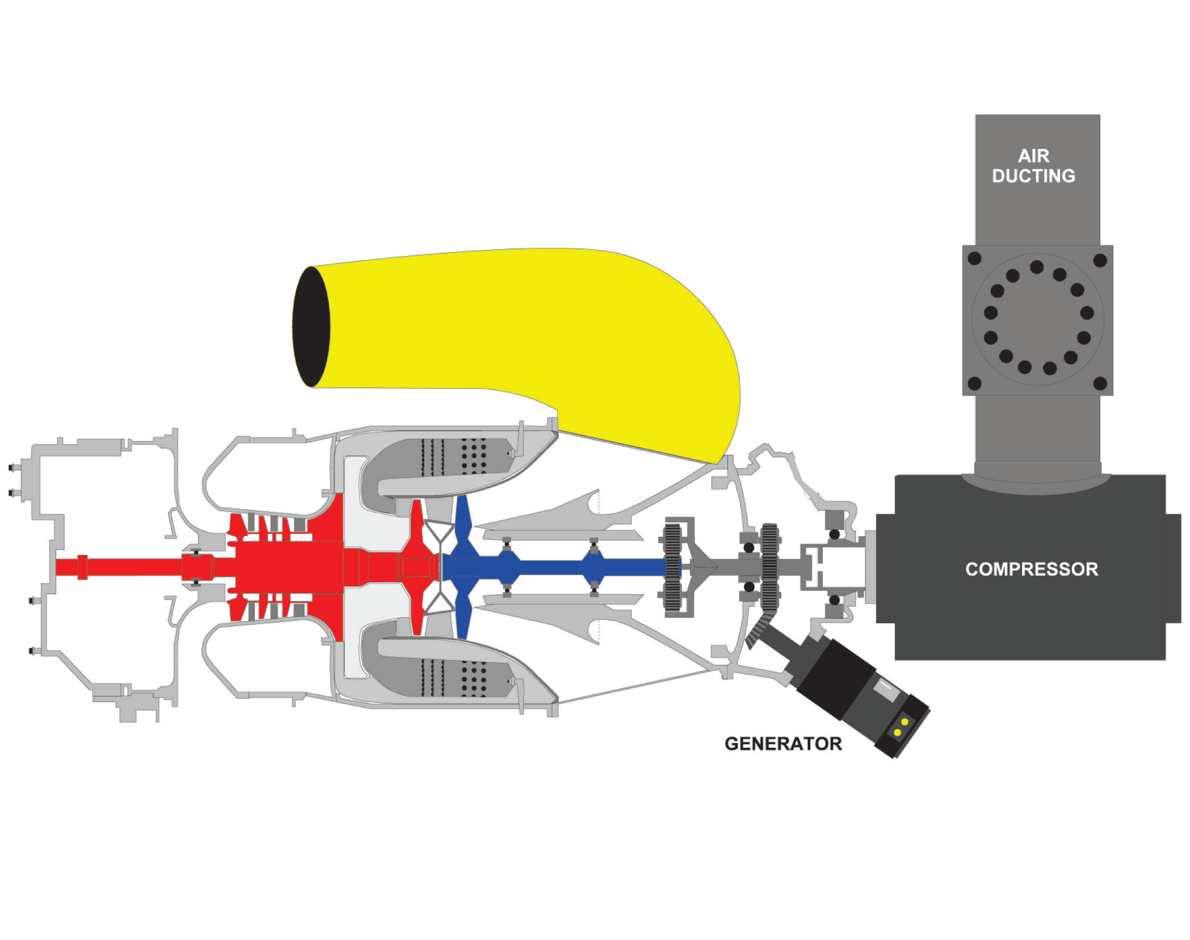


Figure 24.1 Free turbine turboshaft APU

APU Operations in Flight

The APU was further developed so that it could also be operated in the air, providing a back-up source of power to the systems in the event of an engine failure. This requirement has become more important with the introduction of twin engine aircraft now flying long haul routes under Extended Twin Operations' (ETOPS) regulations.

The design philosophy behind the APU is to keep it simple, rugged and reliable. It must however be able to be started in flight at high altitudes, and continue to operate under load at even higher altitudes. For example the L1011 (Tri-Star) can start its APU up to 25 000 ft and it will deliver power up to 31 000 ft.

APU Control and Operation

The pilot has very little in the way of indication when starting and running the APU compared to the aircraft's main engines *(see Figure 24.2)*. Indications of turbine temperature, compressor speed and system fault indicating lights may be displayed. Extensive use is made of **Automatic Sensors** which will **shut the APU down** in the event of an **APU fire, system malfunctions** or **operating limits being exceeded.** The APU inlet may be of single or double-entry design and will typically have a motorized door which opens when the APU master switch is selected and will close automatically after a cooling period on shutdown. Like all engines using air as its working fluid, power output is reduced at higher altitudes where air density is reduced. The **Automatic Shutdown** acts as a governor device protecting the APU against overloading.

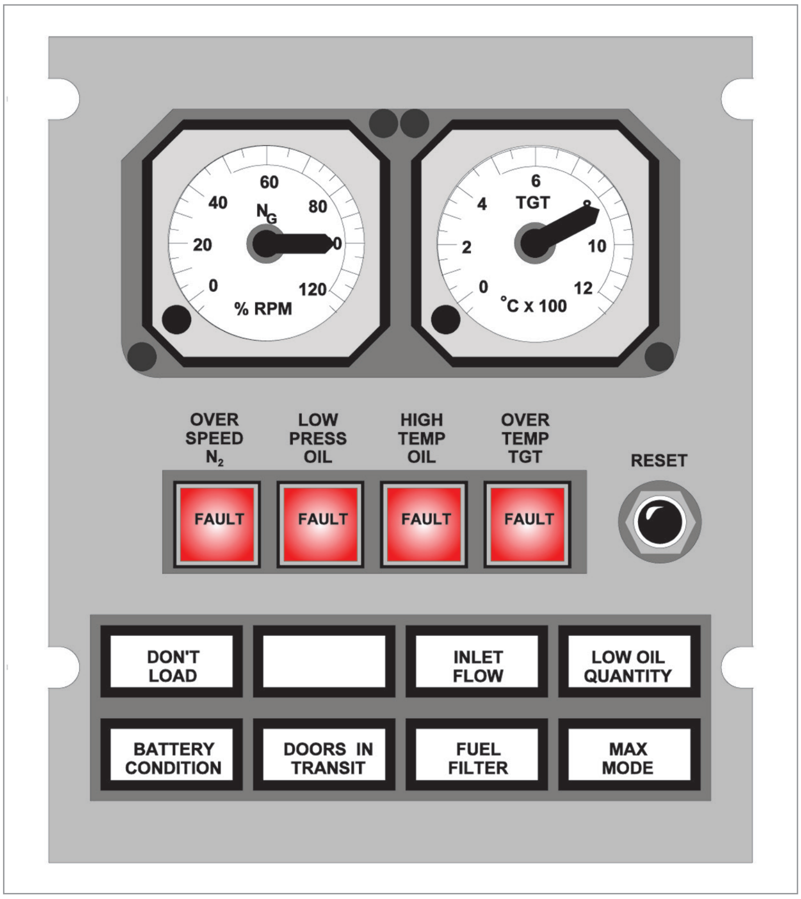


Figure 24.2 Pilots APU Indications

With modern technology the pilot's flight deck controls for the APU are very few. They usually consist of:

a) A power on start switch. (PWR ON)

b) A normal stop switch.

c) A manual emergency shut down and fire suppression control.

There is an external APU control panel to facilitate the shutting down of the APU from somewhere other than the flight deck. An example of an external APU control panel is shown in *Figure 24.3*.

The APU is normally positioned in part of the airframe where its operation will not cause harm to personnel working around the aircraft whilst it is on the ground. This is normally the tail of the aircraft.

The APU's turboshaft engine can easily be started by an electric starter motor powered from the aircraft's battery. When started the APU is usually allowed to stabilize in rpm and temperature before it is used to power the aircraft's systems. The APU may not be able to power all the aircraft's systems, but it will provide sufficient services that the aircraft can be operated safely.

The APU is in operation normally on the ground during start and taxi of the aircraft and operated in the air as previously stated in the event of failure of a main engine. It is also normally selected prior to landing.

Figure 24.3 External APU control panel

Ram Air Turbines

In addition to an APU some aircraft may be fitted with a Ram Air Turbine (RAT) to provide power to aircraft systems in **emergency** situations.

The RAT consists of a turbine wheel which is driven by airflow due to the aircraft's forward speed (Ram Air). The turbine can be internally mounted in the aircraft, and the ram air directed onto it via a control valve. Alternatively, the turbine can be extended into the airflow. The design is normally fail safe. If power is lost on the aircraft, the RAT will automatically be selected to run.

The turbine drives a gearbox to which can be fitted a **Generator** or a **Hydraulic Pump.** These will power essential electrical supplies or flying controls in an emergency.

The Requirements of a Starting System

In order to start a gas turbine engine there are three basic requirements:

a) The compressor/turbine assembly must be rotated to get air into the combustion chambers.

b) Fuel must be provided in the combustion chambers.

c) Ignition must also be provided in the combustion chambers to start the air/fuel mixture burning.

Extra to these basic requirements are two others:

a) The necessity to motor over the engine with no igniters operating. This is sometimes called a' blow out' or 'motoring over cycle'. The necessity to motor over the engine will usually only occur when there has been a failure to start, sometimes called a "wet start" where the engine is dried out by motoring it over, or after a "hot-start" where the engine is cooled down by motoring it over.

b) The need for the igniters to be operated independent of the start cycle.

Starter Motor

There are several methods of obtaining engine rotation upon engine start. The most common methods of rotating the HP compressor on modern civil aircraft are:

a) The Air Starter Motor.

b) The Electric Starter Motor.

Any starter system will have a **'duty cycle'** the time limit that the starter is allowed to be 'energized' and may have to be followed by a cooling down period before re-energizing.

The Air Starter Motor

The air starter motor *(Figure 24.4)* is possibly the most popular starting system presently in use. It is light, simple to use and very economical utilizing low pressure air. The air starter motor fastened to the accessory gearbox of the engine. The sources of air available for engine start, in order of preference they are:

a) The Aircraft APU.

b) The Ground Power Unit.

c) A Cross-bleed Start, where air from an already started engine is used.

Air from one of these sources is fed through an electrically controlled start valve to the air inlet to rotate the turbine rotor and is then exhausted. The turbine turns the reduction gear to rotate the engine drive shaft through the **sprag clutch ratchet**.

Ignition may be automatically selected at the same time as engine start, or in conjunction with the introduction of the fuel. Some moments after the engine starts rotating, the fuel HP cock is opened and moments after that the engine should 'light up'. This is indicated by an increase in EGT and a more rapid acceleration of the engine.

At a predetermined engine speed, greater than self-sustaining, the start valve is closed. The sprag clutch automatically disengages as the engine accelerates up to idling speed and the starter motor ceases to rotate. The **sprag clutch ratchet** is designed to prevent the starter motor being driven by the engine after engine start. The danger, should this happen, is that the starter motor will rotate at a speed sufficient to cause it to break up due to centrifugal force.

Also included may be a **flyweight cutout switch**, this is used to shut off the starting air supply by removing the electricity energizing the starter air valve. This device will automatically terminate the engine start cycle when the engine has reached a speed slightly in excess of self-sustaining speed.

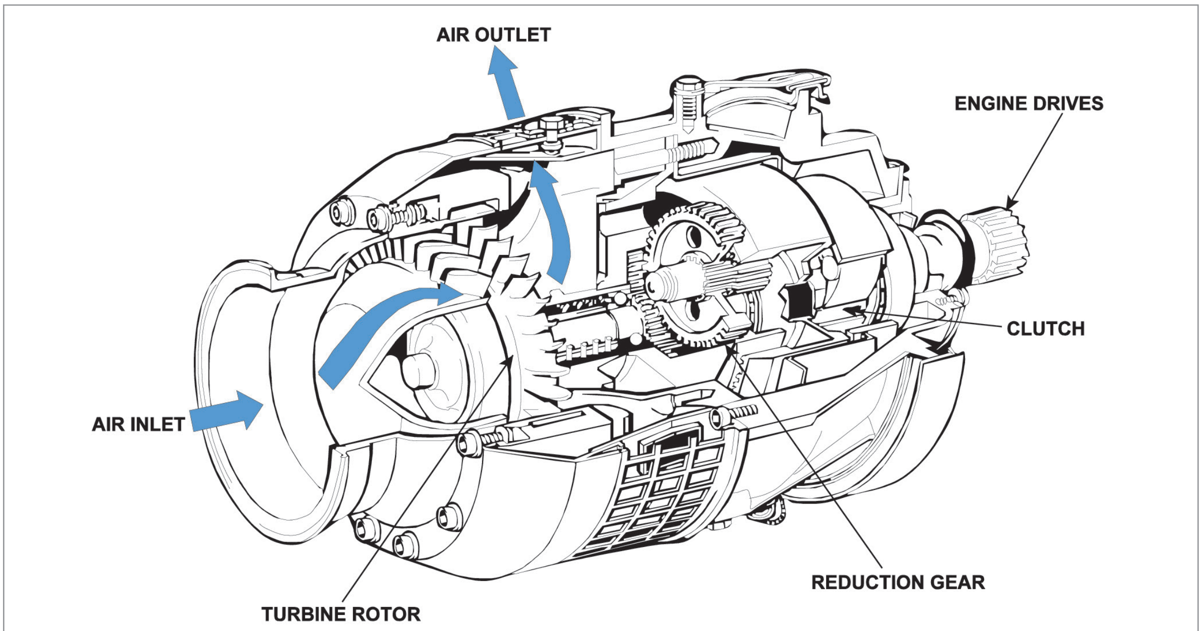


Figure 24.4 An air starter motor

The Electric Starter Motor

The electric starter motor was the original means of starting a gas turbine engine and is still used in smaller executive jets and helicopters, however it has fallen out of favour in modern larger engines because of its weight.

Rapidly becoming more popular on smaller engines is the starter/generator combination which because of its dual purpose has a greater usefulness / weight ratio.

As with the majority of the other starting systems, the starter motor is attached to the engine accessory gearbox and drives the compressor when it rotates. Most electric starter motors incorporate an automatic release clutch device to disengage the starter drive from the engine drive.

This consists of a pawl and ratchet type mechanism, very similar to that employed in the air starter motor, which actually performs three functions, firstly it prevents excessive starting torque being applied to the engine, secondly it acts as an overrunning clutch when the engine accelerates up to idle speed, and thirdly it performs the previously mentioned task of disengaging the starter from the engine.

A problem associated with the sprag clutch ratchet is known as the ‘crash re-engagement’ which occurs when the starter motor is re-energized before the driven spool has slowed sufficiently for the clutch mechanism to engage itself.

The starter/generator connection to the accessory gearbox is different from that of the straightforward starter motor.

It must remain permanently engaged to the gearbox if it is to perform its function as a generator and of course its control circuitry is much more complicated.

Normal Start Cycle

A typical starting sequence for a two spool turbofan engine is described here (refer to *Figure 24.5*). The system shows each engine has an air turbine starter motor which is supplied with low pressure high volume air from the APU, Ground Cart or other engine. The normal bleed air ducting is utilized and the flow of air reversed to the starter motor. The air supply will not reverse into the engine compressor because of a non-return valve at the LP outlet and a non-return valve facility in the HP Shut Off Valve.

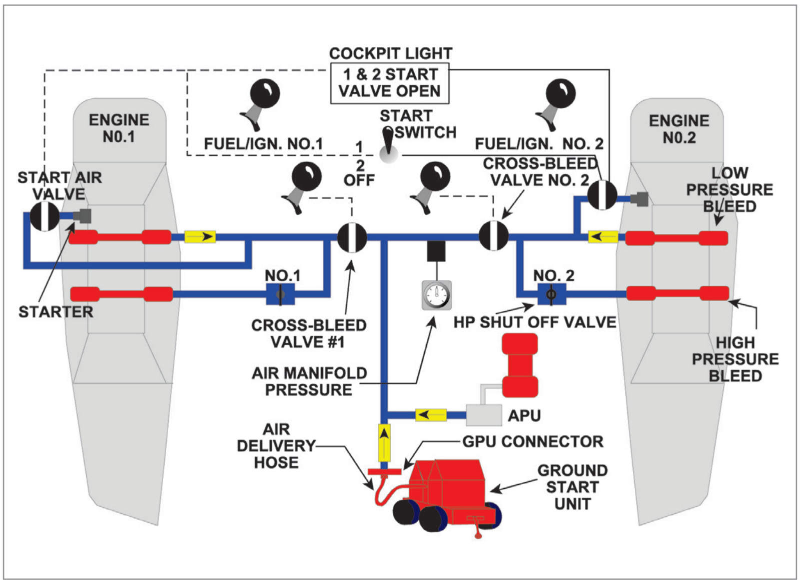


Figure 24.5 Two engine air starter layout

During the engine start sequence the instruments which require the most attention are the EGT (exhaust gas temperature) gauge, and the HP compressor rotational speed gauge (N2), These two parameters must be monitored closely to ascertain whether or not the start cycle is proceeding safely. Other instruments that require to be monitored are fuel flow, LP rotation N1, duct pressure and start valve warning light, if applicable.

Figure 24.6 illustrates in graphic form the way that the EG. and HP rpm should react during a normal start.

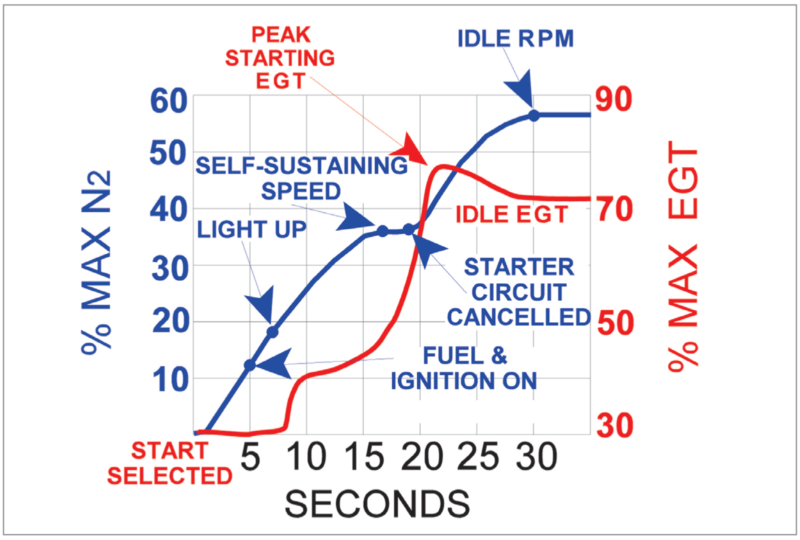


Figure 24.6 RPM/EGT starting relationship

Upon start selection, the starter motor is powered. Initially fuel and ignition is not supplied, the compressor begins to accelerate under the influence of the starter motor and starts to force air through the combustion chambers.

When the compressor has achieved the rpm stated for that engine the fuel and ignition is activated by selection of the switch, the switch is then held until the start is successful.

Light up is indicated by an increase in EGT and must occur within a specified time (20 secs typically). The initial increase is quite sharp, there being an excess of fuel in the combustion chamber, once this is burnt off however, the rise steadies. The gas which is being produced in the combustion chambers now adds impetus to the turbine blades which eases the task of the starter motor, the engine continues to accelerate.

The Fuel Control Unit (FCU) progressively increases the fuel flow as the compressor accelerates towards idle. This means that the air/fuel ratio becomes biased towards being very rich, the evidence of this is the second steep rise in the EGT.

Continued acceleration of the engine brings the compressor to self-sustaining speed, the speed at which the engine can accelerate without the help of the starter motor. However, the starter motor is not de-selected at this point, it is kept supplying power until the engine has accelerated a little more. This gives the engine a better chance of smoothly reaching idle rpm. Self-sustaining speed is approximately 30% N2 (High Pressure Compressor).

The starter motor and igniters may be cancelled automatically by a speed switch in the N2 gauge. As it continues towards this point, the EGT peaks, this is caused by the airflow reaching the value appropriate to the idle fuel flow, when that happens the temperature drops from its highest value to that of idle EGT.

When the engine has stabilized at ground idle the fuel and ignition switch can be released and the after start checks carried out. Idle rpm is approximately 60% N2 and 25% N1.

The indications referred to in the preceding paragraph will be observed during a normal start, regardless of the type of starter motor which is used.

Operation of the Blowout Cycle

A blowout or motoring over cycle may be required if fuel had been put into an engine during an unsuccessful attempt to start. To prevent "torching", the fuel has to be allowed to drain away or evaporate (blown out) before another attempt can be made to start the engine.

To do this, the starting circuit has the facility whereby the starter motor can be activated without the use of fuel or ignition.

In most modern turbofan engines the air turbine starter motor will have a 'duty cycle' of 3-5 minutes! If the engine fails to light up within the specified time limit then the fuel and ignition switch may be selected off but the starter motor will continue to turn the compressor and 'blow out' the unburnt fuel until a second attempt to start is carried out. This of course must be within the 'duty cycle' of the starter.

In-flight Starting

In the event of an engine flaming out, it may be required to activate the fuel and ignition without operating the starter motor to achieve an airborne windmill air start. Evidence that an attempt to relight has been successful will be obtained from the EGT and rpm gauges, a rise in the value of either of these shows that a light up has occurred.

Starting Malfunctions

As has already been stated the two instruments which require the most attention during engine start are the EGT gauge and the (HP) compressor rotational speed gauge.

It is worth remembering also that it is prudent to keep one's hand on the engine fuel and ignition switch during the start cycle until the parameters indicate that they have stabilized.

The Hot Start

It is really only possible to determine that a hot start is happening by comparing its indications to those of a normal start. The EGT can initially rise as normal, the rapid acceleration towards the EGT limit only becoming apparent a few seconds into the start.

In many cases the only chance of stopping the temperature limit being exceeded lies in having the ability to switch off that engine's fuel and ignition switch as quickly as possible. Waiting for instructions or discussing the indications will almost certainly cost you or your company the price of a new engine (hence keeping your finger on the fuel and ignition switch). If the EGT does exceed the limit by only one degree the engine is to be considered unserviceable.

The reasons for a hot start lie almost entirely in having too much fuel and not enough air to cool the gases through the turbine.

This can be caused by a variety of reasons, such as the throttles either not being set to idle during the preflight check or being knocked away from the idle position, or alternatively the engine not rotating fast enough or partial seizure because of ice. This is a very common fault and is most likely to be caused by a tailwind during the second start of the day. The residual heat in the engine adding to the problem.

The Wet Start

The failure to start, more commonly known as the wet start, is indicated by the EGT not rising and the engine rpm stabilizing at the maximum that the starter motor can achieve.

It may be some time before it is realized that the problem is a wet start, starting malfunctions on gas turbine engines are rare and always come as a surprise, except in the simulator, where they will become the norm. This long period, during which fuel is being pumped into the engine, means that the engine is becoming saturated with it. This is confirmed by the fuel flowmeter indication. The danger exists that this fuel, if ignited, will cause a very large jet of flame to issue from the exhaust system, the phenomenon called 'torching'.

To prevent this happening, before attempting a second start a "motoring over" or "blow out" cycle must be carried out. In preparation for the "blow out"cycle, do not terminate the start cycle when the 'wet start' is diagnosed, just close the HP fuel and ignition switch and allow the starter to continue to turn the compressor for a specified time before attempting a restart.

The Hung Start

The indications of a 'hung start' are the EGT being higher than would be expected for the rpm at which the engine has stabilized, which is lower than self-sustaining speed.

This high EGT is not greater than the limit, however, maintaining the engine in this state will do it no good at all, and could do it a great deal of harm.

The HP cock must be closed and the problem investigated, the usual answer being the fact that there is not sufficient airflow through the engine to support efficient combustion (e.g. contaminated compressor).

This of course means that the gases from the combustion chambers will not have sufficient power to assist the starter motor in accelerating the engine beyond self-sustaining speed, once the starter motor cycle has finished, the engine rpm remains stable below the figure that will enable it to accelerate away to idle speed.

Engine Rundown Time

Engine Rundown Time or Spooldown Time is the time taken for the engine to stop after the HP fuel cock is closed. Mental note should be taken of the Rundown Time of each engine and comparison made, thereby giving advance warning of engine malfunction.

Questions

1. Which of the following statements would be more correct with regard to an APU?

a. APUs provide emergency hydraulics power for the brakes only
b. APUs provide electrical, pneumatic and hydraulic power for ground use only
c. APUs provide electrical, pneumatic and hydraulic power for air use only and can provide an amount of thrust
d. APUs provide electrical, pneumatic and hydraulic power for ground and air use and can provide an amount of thrust

2. In the event of an APU fire on the ground it:

a. will need to be shut down immediately
b. will shut down immediately
c. will auto shutdown and fire bottle automatically operate
d. will need to be shut down immediately and the fire bottles will be required to be fired immediately

3. Which of the following would result in an automatic shutdown of an APU?

1. Overspeed of compressor
2. Over-temp of lubrication system
3. Turbine over-temp
4. Combustion chamber over-temp
5. Compressor outlet pressure exceeded
6. Low pressure of lubrication system

a. 1, 2, 3 and 6
b. 1, 2, 4 and 6
c. 2, 3, 5 and 6
d. 2, 3, 4 and 6

4. A Ram Air Turbine is used to provide:

a. emergency hydraulic power for the flaps and slats only
b. emergency hydraulic power for the undercarriage
c. emergency hydraulic power for the elevator, rudder and ailerons along with possible emergency electrical power
d. emergency hydraulic power for the brakes along with possible emergency electrical power

5. The power to start an APU comes from:

a. ground power unit
b. aircraft main DC battery
c. aircraft main engine generator
d. aircraft main AC battery

6. A typical APU can provide:

a. air for air conditioning on the ground
b. air for engine starting
c. electrical power for ground or in-flight use
d. all of the above

7. **The advantage of an air starter system is that:**

a. it is safer in operation than other systems, and no fire risk
b. it is light, simple and economical
c. it provides a more rapid start
d. it is totally self-contained and needs no external source of power

8. **A "Hung Start" is indicated by:**

a.	high EGT	-	high fuel flow	-	low rpm
b.	low EGT	-	idle fuel flow	-	low rpm
c.	low EGT	-	high fuel flow	-	high rpm
d.	high EGT	-	idle fuel flow	-	low rpm

9. **If a gas turbine engine fails to light up within the specified time:**

a. it must be motored over with the HP fuel cock shut
b. the fuel system must be drained
c. no further attempt to start may be made until the fuel has evaporated
d. it must be motored over with the HP fuel cock shut and no igniters selected

10. **A Relight is:**

a. the action of restarting a flamed out engine, usually while airborne
b. what occurs when the engine drain valve is stuck open
c. the initiation of the after-burning system
d. what must be prevented after a "wet start"

11. **A "Hung Start" occurs when:**

a. the engine accelerates but does not light up
b. the engine stabilizes above self-sustaining speed
c. the engine lights up but does not accelerate to self-sustaining speed
d. there is a double igniter failure

12. **After engine start, the engine igniters are normally deactivated by:**

a. an electric interlock system
b. a speed switch
c. the time switch
d. centrifugal force

13. **Failure of the engine to light up is shown by:**

a. the failure of the engine to turn and no TGT
b. low rpm fuel flow indication, and no TGT
c. TGT increasing but no rpm
d. no rpm and no TGT

14. **The term "self sustaining speed" means that:**

a. the aircraft can roll forward with no further opening of the throttles
b. the speed from which the engine can accelerate to full power within 5 seconds
c. the engine will run independently of external help
d. the speed from which the engine can accelerate to idle without the help of the starter motor

15. **Before opening the high-pressure fuel shut off valve during the engine start:**

a. the compressor must be turning at the correct rpm in the right direction
b. the Low Pressure compressor must be stationary
c. the Low Pressure fuel cock must be shut
d. the Low Pressure compressor must be rotating faster than the High Pressure

16. **The air supply to operate an air starter usually comes from:**

a. an external installation
b. storage bottles carried in the aircraft
c. the auxiliary power unit
d. a cross-bleed start

17. **The air supply for an air start system is:**

a. at a relatively low pressure, but high volume
b. filtered to prevent damage to the starter motor
c. preheated to avoid icing in the starter nozzle guide vanes
d. at a high pressure but low volume

18. **The starter motor is disengaged from the engine start system:**

a. as soon as the engine lights up
b. just above self-sustaining speed
c. at 26% HP rpm
d. just below self-sustaining speed

19. **In a twin spool engine self-sustaining speed is normally reached at:**

a. 60% N2
b. 60% N1
c. 30% N2
d. 30% N1

20. **In a twin spool engine the typical idle speeds are:**

a.	60% N2	25% N1
b.	25% N2	60% N1
c.	40% N2	30% N1
d.	80% N2	45% N1

Answers

1	2	3	4	5	6	7	8	9	10	11	12
d	c	a	c	b	d	b	d	d	a	c	b

13	14	15	16	17	18	19	20
b	d	a	c	a	b	c	a

Chapter

25

Gas Turbines - Fuels

Introduction

The specification of an ideal fuel for either a gas turbine engine or a piston engine would include the following main requirements:

a) Ease of flow under all operating conditions.

b) Complete combustion under all conditions.

c) High calorific value.

d) Non-corrosive.

e) No damage to the engine from combustion by-products.

f) Low fire hazard.

g) Ease of engine starting.

h) Lubricity.

These requirements can be met and the methods of doing so are discussed later. In practice the cost of satisfying all of them is prohibitive and therefore compromises have to be made.

Gas Turbine Fuels

Gas turbine engined aircraft use kerosene fuels. The two main types of gas turbine fuel in common use in civilian aircraft are shown below, together with their characteristic properties:

JET A1 (AVTUR)

(Aviation turbine fuel). This is a kerosene type fuel with a nominal SG of 0.8 at 15°C. It has a medium flash point 38.7°C and waxing point -50°C.

JET A

This is a similar type of fuel, but it has a waxing point of -40°C. This fuel is normally only available in the USA.

JET B (AVTAG)(Aviation turbine gasoline)

This is a wide-cut gasoline/kerosene mix type fuel with a nominal SG of 0.77 at 15°C. It has a low flash point -20°C, a wider boiling range than JET A1, and a waxing point of -60°C.

This fuel can be used as an alternative to JET A1 but as can be seen, with its low flash point is a very flammable fuel and for reasons of safety is not generally used in civilian aircraft.

Fuel Colour

Turbine fuels are not dyed, they retain their natural colour which can range between a straw yellow to completely colourless.

Cloudy Fuel

If a fuel sample appears cloudy or hazy then there could be a number of reasons. If the cloudiness appears to rise quite rapidly towards the top of the sample then air is present, if the cloud falls quite slowly towards the bottom of the sample then water is present in the fuel. A cloudy appearance usually indicates the presence of water.

Jet Fuel Additives

FSII (Fuel System Icing Inhibitor).

A certain amount of water is present in all fuel. The water, which is normally dissolved within the fuel, gives rise to the following fuel system problems:

Icing

As an aircraft climbs to altitude the fuel is cooled and the amount of dissolved water it can hold is reduced. Water droplets form and as the temperature is further reduced they turn to ice crystals which can block fuel system components.

Fungal Growth and Corrosion

A microbiological fungus called Cladasporium Resinae is present in all turbine fuels. This fungus grows rapidly in the presence of water to form long green filaments which can block fuel system components. The waste products of the fungus are corrosive, especially to fuel tank sealing substances. The inclusion of FSII in the fuel will help to overcome these problems.

HITEC *(Lubricity Agent).*

A lubricity agent is added to the fuel to reduce wear in the fuel system components.

Static dissipater additives partially eliminate the hazards of static electricity generated by the movement of fuel through modern high flow rate fuel transfer systems.

Corrosion inhibitors protect ferrous metals in fuel handling systems, such as pipelines and storage tanks, from corrosion. Certain of these corrosion inhibitors appear to improve the lubricating qualities (lubricity) of some gas turbine fuels.

Metal deactivators suppress the catalytic effect which some metals, particularly copper, have on fuel oxidation.

Water in the Fuel

Water is always present in fuel, the amount will vary according to the efficiency of the manufacturer's quality control and the preventive measures taken during storage and transfer. Further measures can be taken to minimize water accretion once the fuel has been transferred to the aircraft tanks:

Water Drains

If the fuel can be allowed to settle after replenishment then the water droplets, being heavier than the fuel, will fall to the bottom of the tank and can then be drained off through the water drain valve.

Fuel Heater
The fuel can be heated by one or other means before it is passed through the engine fuel system.

In gas turbine engine systems the fuel is passed through a heat exchanger powered by compressor delivery air, to remove any ice crystals which may have formed while the fuel was exposed to the very low temperatures experienced at high altitudes. Some systems also utilize a fuel-cooled oil cooler, this has an added attraction in that we appear, just for once, to get something for nothing. After all, the oil has to be cooled and the fuel benefits by being warmed, bingo, two jobs for the price of one.

Atmosphere Exclusion
Once the fuel is in the aircraft fuel tanks, the main source of water contamination is the atmosphere that remains within the tank. If the tanks are topped up to full then the atmosphere is excluded together with the moisture it contains, thus minimizing the likelihood that the fuel will be contaminated. Caution is required here, filling up the tanks may prove an embarrassment the next day if the ambient temperature rises. The volume of the fuel in the tank will increase and there is the danger that it may spill out of the vent system.

Waxing

Waxing is the depositing of heavy hydrocarbons from the fuel at low temperatures. The deposits take the form of paraffin wax crystals which can clog the fuel filter and interfere with the operation of the fuel control unit. The effects of waxing can be minimized by:

a) The refinery keeping the levels of heavy hydrocarbons low.

b) The inclusion of a fuel heater in the engine fuel system.

Boiling

The temperature at which a fuel boils will vary with the pressure on its surface. As an aircraft climbs, the pressure on the surface of the fuel reduces and with that reduction comes an increased likelihood that the fuel will boil and form vapour. The vapour locks that this effect cause will effectively cut off the fuel supply to the engine with the inevitable result that the engine will stop.

Fuel booster pumps fitted inside the tanks can overcome this problem by pushing fuel towards the engine rather than engine driven pumps sucking fuel from the tanks.

The Effects of SG

The specific gravity of a liquid varies inversely with its temperature. The heat release from the fuel is directly related to its specific gravity and so changes in fuel density can change the power output of an engine. On modern aircraft this usually makes little difference as modern fuel control units will automatically compensate for the change in density of the fuel. It should be appreciated that a change in specific gravity will also change the weight of the aircraft. Specific gravity is also known as **relative density.**

Questions

1. **Water in the fuel tanks is:**

   a. added with FSII when refuelling
   b. is a consequence of atmospheric air entering the tanks through the engine
   c. is a consequence of atmospheric air entering the tanks through the vent system
   d. is a consequence of atmospheric air entering the tanks through the feeder box

2. **Water in the fuel tank is removed:**

   a. via a drain valve at the lowest point in the tank
   b. via a drain tank at the base of the engine
   c. via a scoop at the top of the tank
   d. every major servicing only

3. **The flash point of AVTUR is:**

   a. -38.7°C
   b. 38.7°C
   c. -40°C
   d. -20°C

Answers

1	2	3
c	a	b

Chapter

26

Gas Turbines - Fuel Systems

Introduction

The engine fuel system consists of a number of components which filter and monitor the fuel flow and supply the fuel to the fuel spray nozzles at the correct rate in proportion with the throttle position. The components are described below.

System Components

The booster pumps in the tank pass the fuel to the engine from the 'airframe fuel system' through non-return valves to an engine fuel shut off valve (pylon shut off valve) which is used to shut off the supply of fuel to the engine in the event of component removal. It can also be closed by the fire handle in the event of an engine fire warning to isolate the fuel from the engine.

It can be used in an emergency to stop the engine, but the engine will take longer to run down.

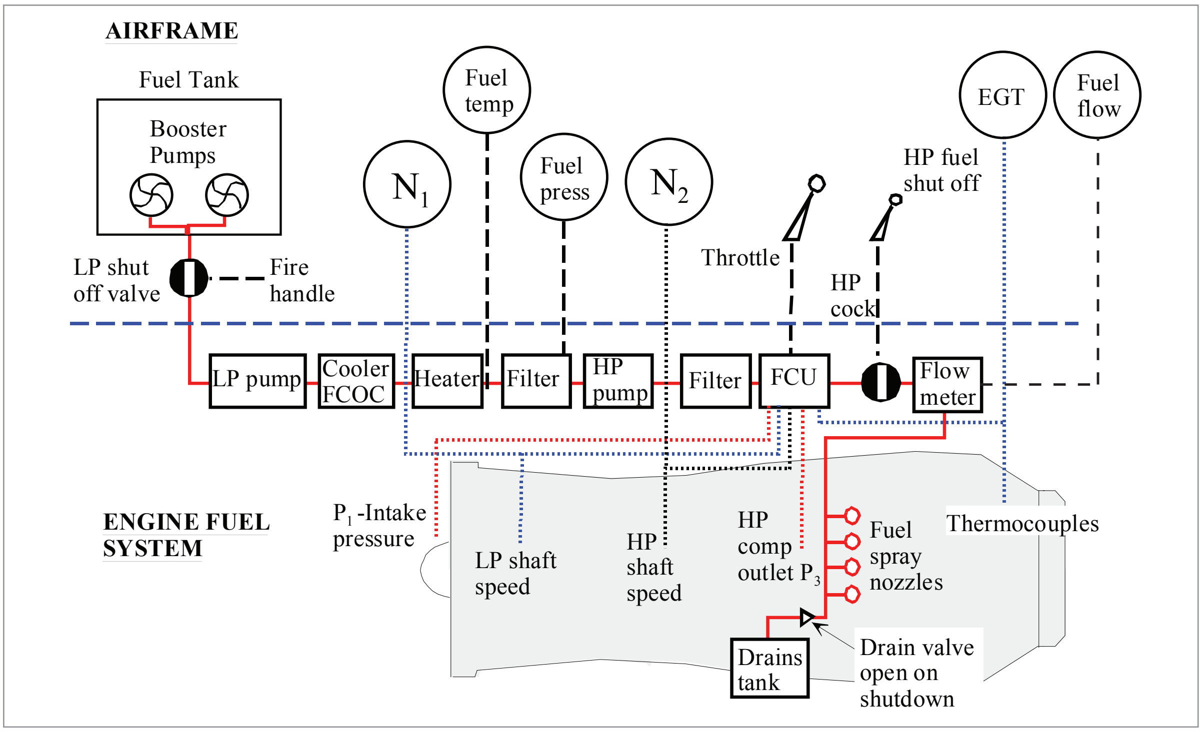


Figure 26.1

Low Pressure Pump (LP pump)

The fuel then enters the 'engine fuel system' and is delivered to the low pressure pump (LP pump) or backing pump. The LP pump is driven by the engine gearbox and supplies fuel to the HP pump. In the event of total failure of the fuel tank booster pumps the LP pump will 'suck' fuel from the fuel tank to allow the engine to remain running. In this event the aircraft MEL may require a reduction of altitude to prevent LP pump cavitation.

Cooler

A fuel-cooled oil cooler (FCOC) is fitted in the majority of gas turbine installations. The oil cooler serves the double purpose of cooling the oil and also heating the fuel to eliminate the formation of ice crystals which may block the components further downstream the system.

Heater

The next component, the fuel heater, completes the warming of the fuel and the elimination of ice crystals that may occur. It uses compressor delivery air to warm the fuel and may be automatic, working in conjunction with the FCOC to maintain a predetermined fuel temperature, or manual, selected by the flight engineer.

Filter

The fuel filter is in the low pressure side of the system and protects the delicate control components within the HP fuel pump and the fuel control unit (FCU) from any dirt or contamination.

Flowmeter

The flowmeter measures the instantaneous fuel flow in gallons/hour or kilograms/hour and may also include an integrator to sum the total amount of fuel used since the engine was started (totalizer).

Fuel pressure and temperature

May be sensed at this point in the system and indicated to the pilot to allow the system to be monitored.

The high pressure (HP) fuel pump.

The high pressure pump (HP pump) is driven by the engine high pressure shaft through the HP gearbox and raises the pressure and flow required for the demanded engine thrust setting. The high pressure fuel pump illustrated is representative of the type of pump employed in some engines, it is an axial piston type pump.

Other engines may use a spur gear type HP pump which is simpler but will still supply the pressure and flow required any excess is recycled back to the inlet side of the pump.

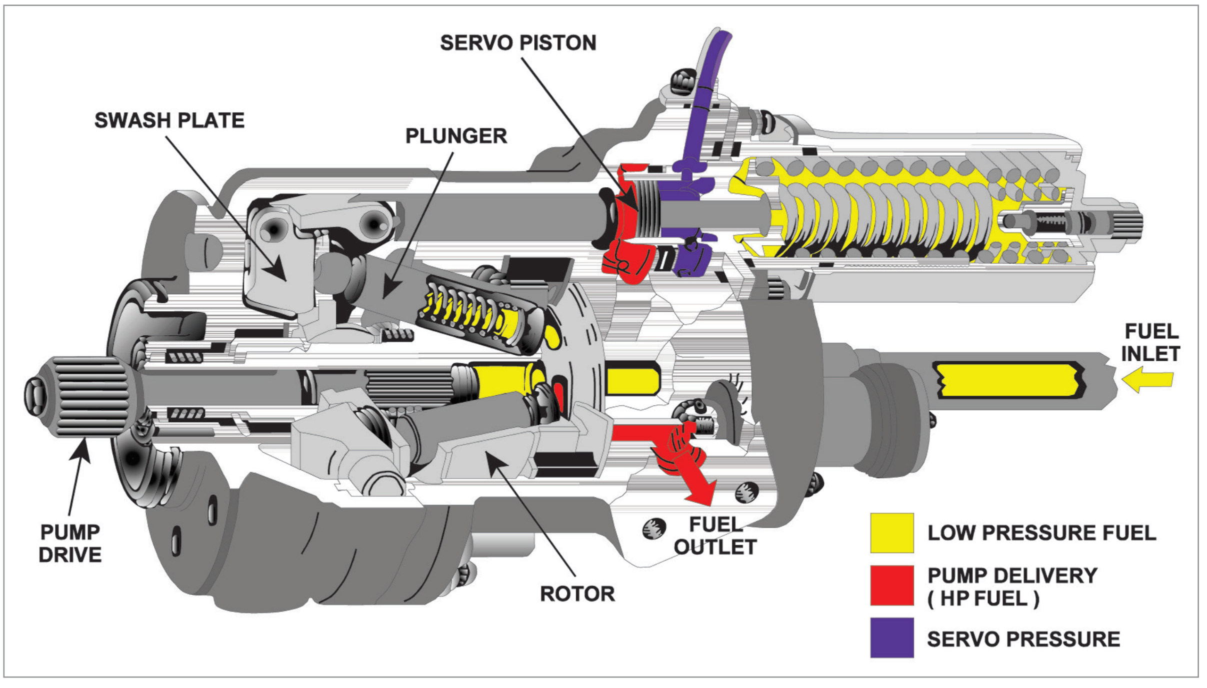


Figure 26.2 Axial piston type fuel pump (based on an original Rolls Royce drawing)

The Fuel Control Unit (FCU) or Fuel Flow Regulator (FFR)

The Fuel Control Unit (FCU) or Fuel Flow Regulator (FFR) controls the fuel flow for a given thrust setting. Various devices within the FCU are used to adjust the fuel flow to cater for variations in air intake pressure, engine acceleration control, exhaust gas temperature and compressor delivery pressure:

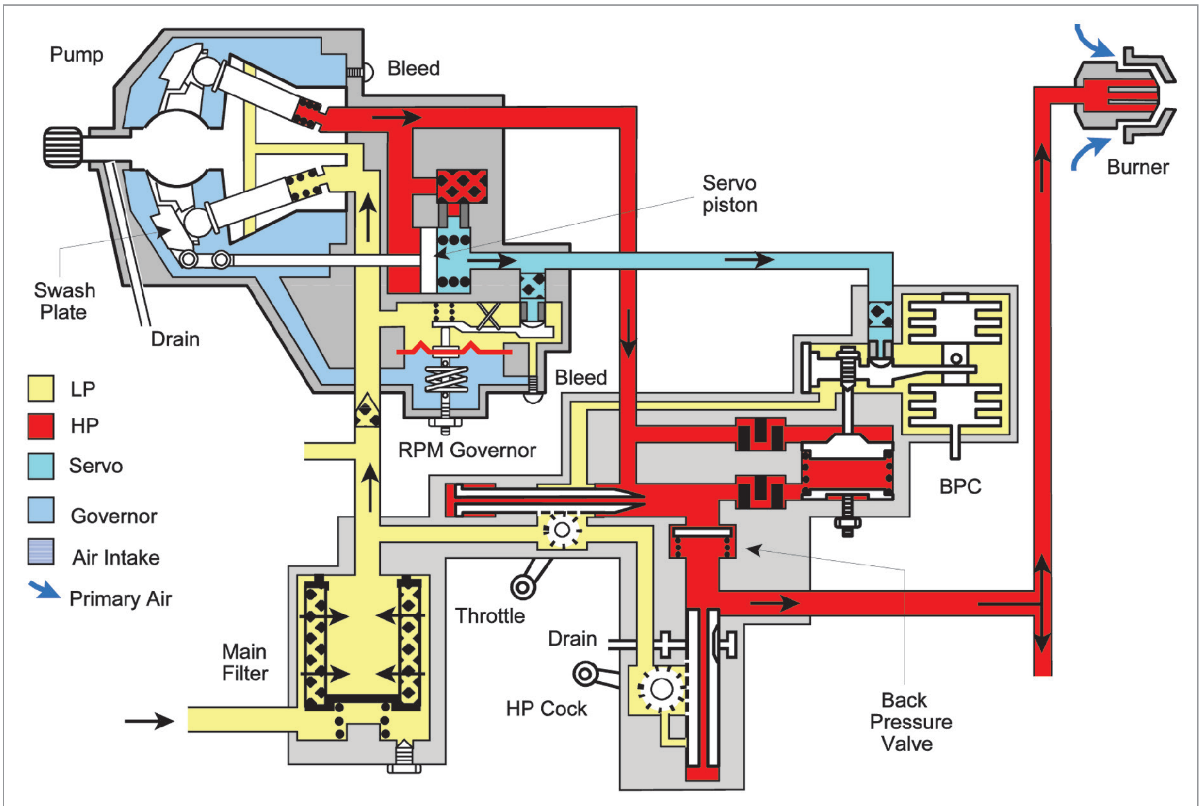


Figure 26.3 Hydro-mechanical fuel control

Altitude control

Variations in air intake pressure (P1) require that the fuel flow to the burners is changed accordingly so that a fixed rpm is maintained for a selected throttle position at all altitudes and airspeeds. This is achieved by the expansion or contraction of a capsule influenced by P1 pressure which in turn modifies the fuel flow accordingly. This capsule, known as the barometric pressure capsule (BPC), is incorporated in an 'altitude sensing unit' within the FCU.

Acceleration control

The addition of fuel is necessary to cause the engine to accelerate, however, too rapid an increase of fuel is the usual cause of compressor stall and surge. To regulate the fuel flow under conditions of engine acceleration, an 'acceleration control unit' is fitted within the fuel control unit. It receives information regarding engine intake pressure (P1) and compressor delivery pressure (P3 for a two spool engine) and uses this information to adjust a 'fuel metering plunger'. This effectively acts as a second throttle valve in series with the main throttle and regulates the fuel flow to achieve the maximum engine acceleration without causing stall or surge.

Exhaust gas temperature limiting

Exhaust gas temperature is probably the most important parameter in a gas turbine engine. To obtain maximum efficiency, the engine must be run at the highest possible temperature in the turbine without melting the materials from which it is made.

To achieve this and yet allow the engine to be a practical user friendly unit, automatic monitoring of the exhaust gas temperature is combined with a 'top temperature control' unit. This allows the pilot to select full power at any time without risking a meltdown in the turbine assembly.

Thermocouple probes are positioned in the gas stream either within the turbine or close after it. The output of these thermocouples is used to give an indication of the temperature at the rear of the engine, this is passed both to the cockpit instrumentation and to a 'temperature control signal amplifier'. The electrical output of this amplifier powers a solenoid which indirectly controls the fuel flow.

Power limiter

The ability of the compressor to withstand internal pressure is limited by the strength of the materials from which it is made. If the compressor casing is subjected to greater than its design maximum pressure it will break with possibly catastrophic consequences.

To prevent this happening, the FCU has a 'power limiter' device. This unit is signalled by both intake pressure (P1), and compressor delivery pressure (P3). The combination of these signals working through capsules and levers controls the fuel flow so that the maximum pressure ratio is not exceeded.

RPM limiter

The rotational speed of the compressor spools must be limited if they are to be prevented from self-destructing through excessive centrifugal forces. There are basically two methods of achieving rotational speed limitation.

The first method depends on an electrical signal proportional to the speed of the shaft. A tacho-generator or electronic speed sensor driven by the appropriate shaft sends signals to an amplifier, normally this amplifier is the same one that powers the temperature limiting circuits. Thus, if the output of the tacho-generator approaches a predetermined level, the fuel flow will be adjusted to prevent the maximum rpm being exceeded.

The second method is normally used to control the speed of rotation of the HP compressor shaft. This shaft drives the external gearbox which is responsible for powering the HP fuel pumps, among other things. Fitted within the HP fuel pump is a 'hydro-mechanical governor' which uses hydraulic pressure proportional to engine speed as its controlling parameter.

If engine speed exceeds a predetermined maximum pressure, a diaphragm opens valves to bleed off some of the servo piston pressure and limit fuel flow to the burners.

HP fuel cock (HP fuel shut off valve)

The HP fuel cock or HP fuel shut off valve shuts off the fuel between the FCU and the fuel spray nozzles (burners) and is the normal control for starting or stopping the engine. It may be mechanically controlled by a lever on the flight deck or electrically controlled by an actuator, also controlled by a switch on the flight deck.

Pressurizing and dump valve

A pressurizing and dump valve is used with a duplex fuel nozzle. At a preset pressure the pressurizing valve opens and allows fuel to flow into the main manifold as well as the pilot or primary manifold.

The dump valve allows the manifold fuel to be dumped into the drains tank when the engine is shut down to prevent fuel boiling in the manifold due to residual engine heat.

Drains Tank
A small tank which collects the unburnt fuel from the fuel manifold and combustion chamber after the engine is shut down or after a failed start. When the engine is running a pressure operated non-return valve will isolate the drains tank.

Electronic Engine Control

History
The goal of any engine control system is to allow the engine to perform at maximum efficiency, within the design safety limits and operating parameters for any given condition. The complexity of this task is proportional to the complexity of the engine.

In the early days of engine design, the pilot had direct, full control of the engine from start to shutdown: He/she had the task of starting the engines; deciding and controlling the power requirement for the stage of flight; monitoring the performance/condition indicators and shutting the engine down if safety parameters were exceeded. A bank of gauges and a simple mechanical linkage between the throttle lever in the cockpit and the fuel control unit on the engine was all the pilot had with which to control and monitor the engine. The throttle linkage fed pilot inputs to a fuel control unit (FCU) mounted on the engine which regulated the fuel flow according to acceleration, deceleration and altitude requirements. In addition, the FCU had an inbuilt rpm sensor that prevented the engine from overspeeding.

In the 1960s, the analogue electronic engine control came into being. The mechanical inputs to the FCU to communicate the desired engine settings were replaced by electrical inputs instead. This system was an improvement over the mechanical control system but had its own drawbacks, including electronic noise interference. It was first introduced as a component of the Rolls Royce Olympus 593 engine fitted to the Concorde.

In the 1970s the full authority digital electronic control system (FADEC) was born. The FADEC system significantly reduces the pilot's tasks and responsibilities with regard to controlling engine efficiency and monitoring the engine performance and condition. NASA and Pratt and Whitney were the first to experiment with a digital FADEC system; the successful outcome of which led to a Pratt & Whitney PW2000 being the first civil engine retrospectively fitted with FADEC.

Supervisory EEC
The Supervisory EEC system uses a computer which receives inputs from the pilot throttle lever angle (TLA) and/or FMS of required engine target operating parameters. Control of the fuel delivery is achieved by signalling the Fuel Control Unit (FCU) which then adjusts delivery to the burners varying swash-plate angle within the high pressure hydro-mechanical pump or, in the case of the gear-type pump, by adjusting the return (bypass) of the fuel to the pump inlet.

The EEC performs the functions necessary for engine operation and protection. The computer will monitor EPR, throttle lever angle (TLA), Mach number, engine inlet pressure and temperature and will maintain a constant thrust regardless of changes in air pressure, temperature or flight environment. Any fault within the EEC will cause the system to revert to ***manual control.***

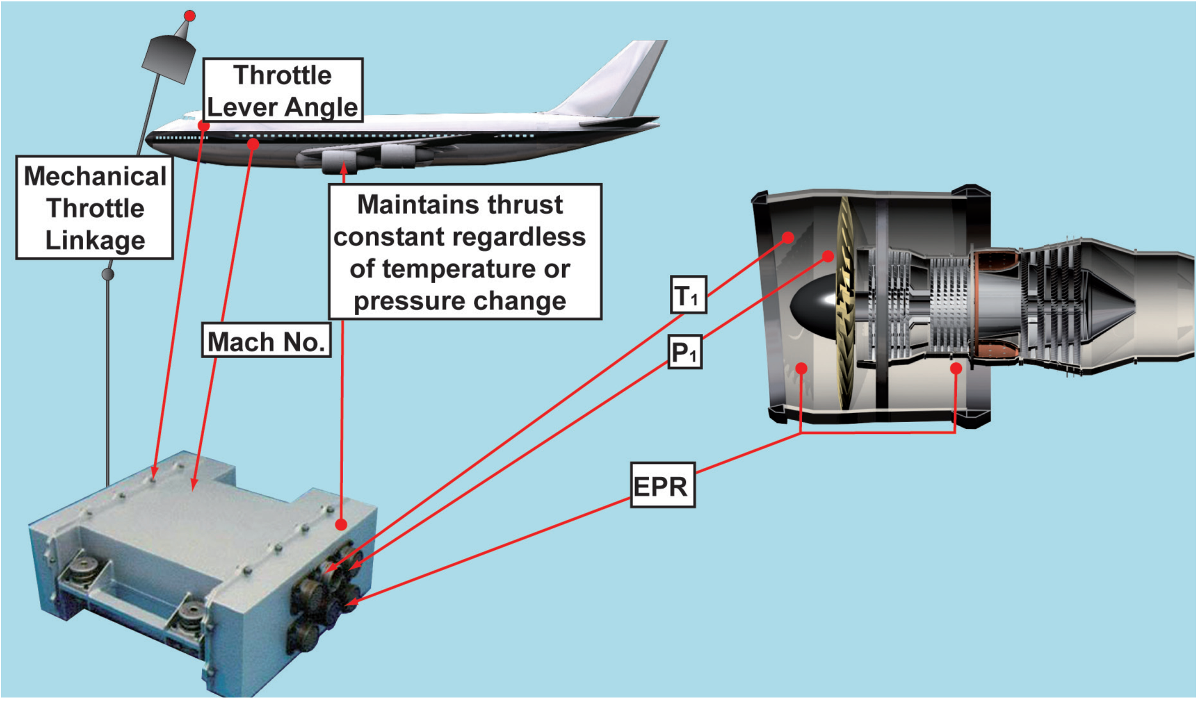


Figure 26.4 Supervisory EEC

In the event of EEC failure there is provision for ***manual reversion*** unlike the Full Authority Digital Engine Control (FADEC) system covered in the next topic.

Full Authority Digital Engine Control (FADEC)

Originally, the control and metering of the engine fuel system was carried out by a Fuel Control Unit (FCU) mounted on the engine. It incorporates the throttle, HP cock, hydro-mechanical governor and other devices to regulate and control fuel flow and power output. Control to the FCU from the flight deck was by mechanical means. However, as technology advanced the complex variable stroke swash-plate fuel pumps and hydro-mechanical means of controlling engine power output was replaced by a single channel digital electrical computer controlled system.

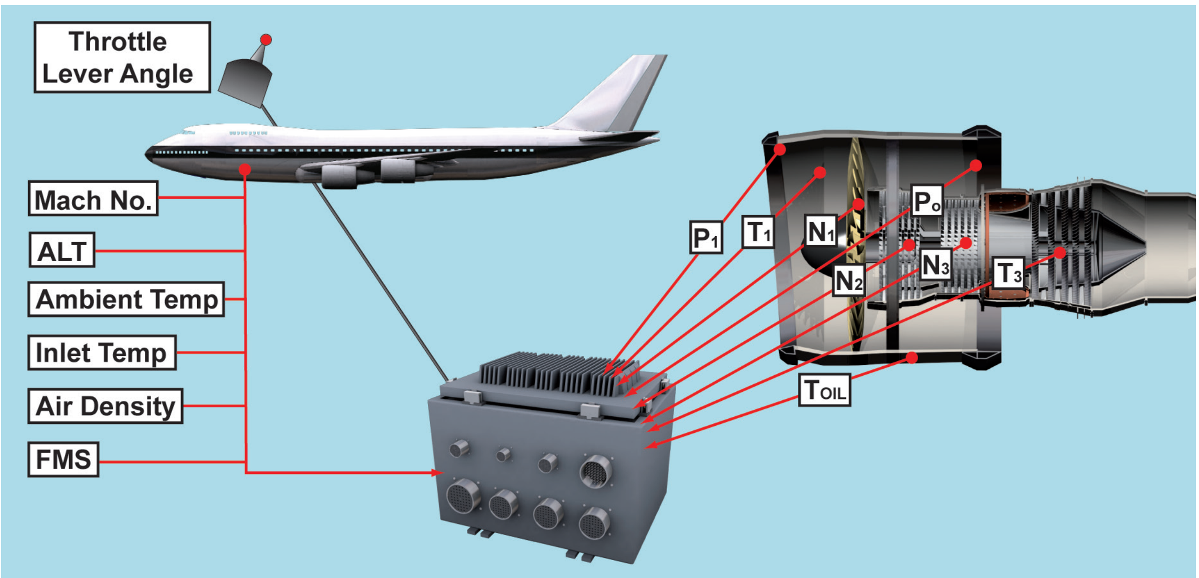


Figure 26.5 FADEC

At the time, the computer hardwear and software was sufficiently advanced to be able to control every aspect of engine monitoring and control but long term reliability had not been established. Consequently, the electronic system was used in a 'supervisory' capacity only and the pilot had the capability to over-ride the electronic system and return to mechanical control at any time.

In turn, as technology continued to advance, the single channel system of engine control and monitoring was superseded by a duel channel Full Authority Digital Electronics Control system (FADEC).

Duplication of the channels provided the FADEC system with built-in redundancy because only one channel is required to manage all aspects of engine monitoring and control. In addition, the EECs have a much improved level of reliability and an inbuilt fault tolerance system that allows the channel in command to operate safely even when some of its internal elements are not fully operational. As a result of the improvement in safety and long term reliability, the need to revert engine control back to the pilot in the event of malfunction was completely negated. The old 'supervisory' only function of the single channel system was upgraded to a full command role in the dual channel system and the modern FADEC has no manual reversion facility at all.

FADEC systems precisely control fuel flow, maximize engine performance, monitor engine inputs/outputs, reduce pilot workload, and minimize the risks to engine health. They incorporate, in a single housing, dual Electronic Engine Control (EECs) interfaces. One EEC is channel 'A' and the other channel 'B'. Each channel is in reality, a sophisticated computer which operates both in tandem and in isolation with each other to monitor and control all aspects of engine power output and performance.

Only one channel, 'A' or 'B' is necessary to monitor and control the engine but both channels independently analyse the raw data, which includes throttle lever position, outside air temperature, exhaust gas temperature and every other parameter that is needed for, or could affect the engine performance. The channels analyse the data independently and then compare results with each other and with the inbuilt limiting parameters set by the manufacturer. The built in test facility (BITE) incorporated into each channel continuously monitors the inputs and outputs to the EECs in order to detect and isolate failures. The healthiest channel, the one with the least faults, takes command of the engine but the channels will swap command whenever the health of the stand-by channel exceeds that of the channel in command. If any of the raw data is missing, corrupt or exceeds limits the channel in command will automatically default to the inbuilt values.

Once the raw data has been analysed, the channel in command uses the results to monitor and regulate the pressures and temperatures of the fuel and airflow through the engine from start to shutdown to ensure maximum performance whilst at the same time ensuring that structural and performance limitations are not exceeded. The EECs achieve this by operating the igniters, inlet guide vanes, variable stator vanes, compressor bleed valves, active clearance control, thrust reversers etc, as necessary. Such precise control and monitoring of the fuel and airflows maximizes engine efficiency, reduces costs, minimizes the risk to engine health, prolongs engine life and reduces pilot tasking.

The FADEC system has an additional safety facility: if any of the engine controls malfunction, preventing the channel in command from carrying out a specified function, the channel in command will attempt to move the appropriate control to a fail-safe position and will activate the appropriate failure warning on the centralized warning panel. For example, if a fault occurs to a compressor bleed valve such that it refuses to function properly, the channel in command will attempt to move it to the optimum safe position and will give a bleed valve failure warning on the ECAM/EICAS display.

FADEC comprises typically of the following:

- A Pilot Thrust lever input giving thrust lever angle (TLA) to the EEC
- Cathode Ray Tube (CRT) displays, giving indications of EPR, N1, N2, N3, EGT, FF, VIB, Oil pressure
- A dual channel electronic controller (EEC)
- A dedicated engine driven alternator providing principle power supply
- Actuators to operate VIGV, VSV, ACS and Bleed-Valve.
- Position feedback to EEC from engine sub-systems
- Fuel Metering Unit (FMU) which has integrated into it the HP Fuel Pump
- An input to Thrust Reverser control (if fitted)
- A facility for engine health monitoring (EHM) and data collection
- Sensors to feedback engine parameters

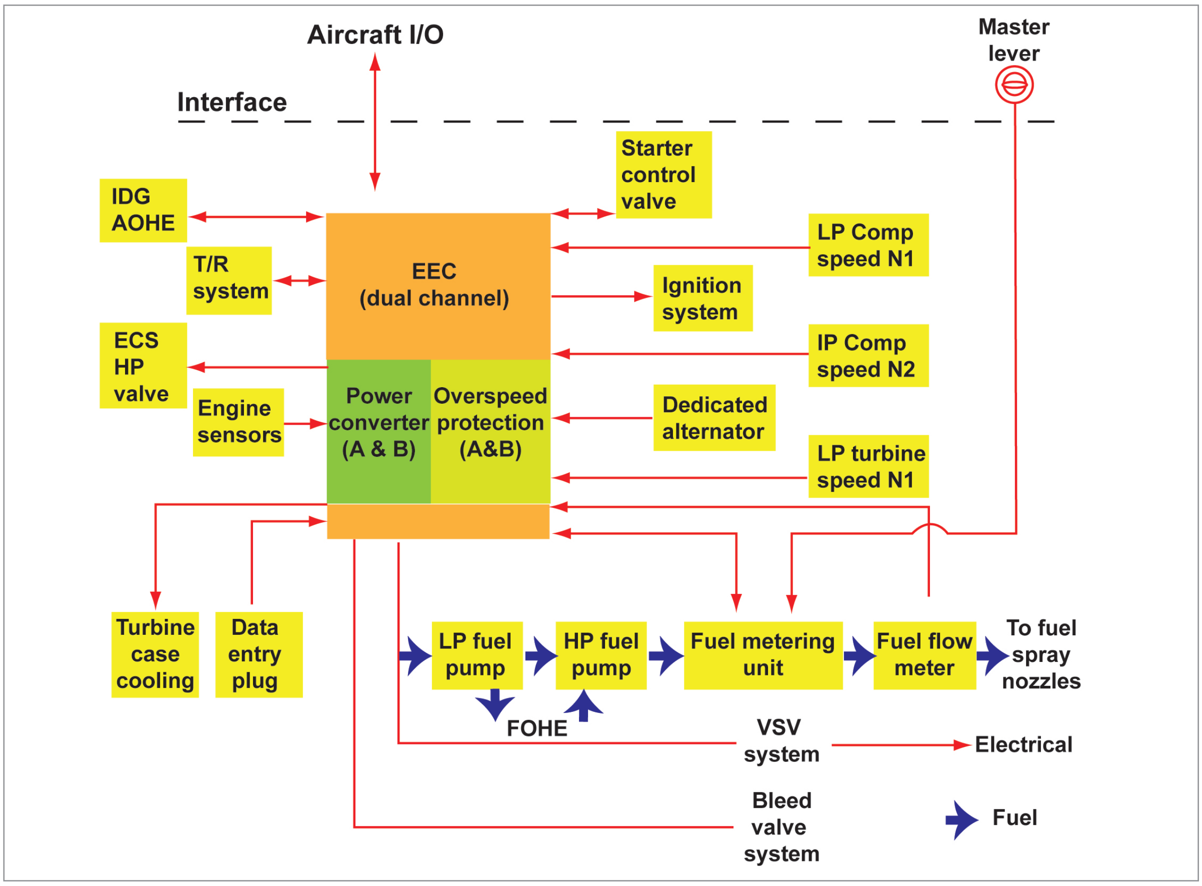


Figure 26.6 A typical FADEC structure

The main inputs to the FADEC EEC are the pilot's thrust lever angle (TLA) and preset EPR or N1 from the Flight Management System (FMS). With FADEC, traditional hydro-mechanical fuel-pump systems become redundant, and all parameters that would have affected pump delivery are now fed to a fuel metering valve (FMV) a bypass valve within the Fuel Metering Unit (FMU) which operates to vary the delivery rate to the burners according to the inputs received by the EEC. Excess fuel is fed back to the low-pressure side of the system.

Inputs to FADEC EEC:

- Thrust lever angle (TLA)
- Altitude (from ground level upwards)
- Mach number
- Ambient temperature
- Air inlet temperature
- Air demand (compressor bleeds)
- EGT

FADEC performs the following functions:

1. **Engine control and overspeed protection:**
    - Fuel control regulation for all stages of flight
    - Power management control
    - Fuel Metering Valve (FMV) control within the Fuel Metering Unit (FMU)
2. **Engine stall and surge protection:**
    - Variable bleed valve control (VBV)
    - Variable stator vane control (VSV)
    - Rotor active clearance control and start bleed system (RACSB) if fitted
    - High pressure turbine active clearance control (HPTACC) if fitted
    - Low pressure turbine active clearance control (LPTACC) if fitted
3. **Engine/Aircraft integration:**
    - Automatic and manual starting and restarting
    - Thrust reverser operation
    - Auto-thrust
    - Engine indication and engine maintenance data collection
    - Condition monitoring data collection

FADEC may take control by initiating an Engine Shutdown (ESD) the final closing down being a pilot action in the event of exceeding the following:

- N1
- N2
- Acceleration
- EGT

Typical applications

Prior to flight, the flight crew enters the data appropriate to the day's flight in the Flight Management System (FMS). The FMS takes environmental data such as temperature, wind, runway length, runway condition, cruise altitude etc., and calculates power settings for the different phases of flight. To initiate take-off the flight crew advance the throttles to a take-off detent or select an auto-throttle take-off if it is available. The FADECs compute the required takeoff thrust setting and apply it to the engines. There is no direct linkage between the throttle and the engine fuel control to open fuel flow. By moving the throttle the flight crew have merely sent an electronic signal to the EEC/ECU, which subsequently controls and monitors the fuel flow. The FADECs compute the appropriate thrust settings and apply them for climb, cruise and all other phases of flight.

During flight, small changes in operation are constantly being made to maintain efficiency. Maximum thrust is available for emergency situations if the throttle is advanced to full, but the FADEC system will control the engine acceleration to ensure that operating limitations are not exceeded.

The flight crew has no means of manually overriding the FADECs, and must accept whatever the FADECs provide. However, they do retain the facility to manually shut the engine down if and when it is required.

FADECs today are employed by almost all current generation jet engines and increasingly in newer piston engines, fixed-wing aircraft and helicopters.

The Advantages of the FADEC System

- Improved engine efficiency due to the precise management and control of the fuel system.
- Automatic engine protection against out of tolerance operations.
- Fault tolerant systems that function even if they are degraded.
- Improved safety because the FADEC computer is dual-channel and receives multiple inputs that provide redundancy in case of failure.
- Semi-automatic engine starting/restarting, abort or recycle an engine start.
- Better system integration with engine and airframe systems
- Long term health monitoring and fault diagnostics

- A reduction in the number of parameters to be monitored by the fight crew
- Automatic engine emergency responses such as an automatic thrust increase to avert a stall.

The Disadvantages of the FADEC System

True full authority digital engine controls have no form of manual override.

If a total FADEC failure occurs, the engine fails. The pilot has no way of manually controlling the engines other than to shut them down. As with any single point of failure, the risk can be mitigated by providing in-built redundancy.

Questions

1. **Fuel is heated from which of the following?**

   a. Air conditioning air
   b. Air from the compressor
   c. Air from the bootstrap
   d. Air from the turbine

2. **Fuel is heated to:**

   a. prevent waxing.
   b. ensure vapour losses are minimized
   c. make it more viscous
   d. make it easier to flow under all conditions

3. **Fuel booster pumps are situated in:**

   a. the fuel tanks
   b. the line between the main fuel tanks and the engine
   c. low pressure side of the engine
   d. high pressure side of the engine

4. **In a fuel-cooled oil cooler the .... is maintained .... than the ....**

   a. fuel pressure higher oil pressure
   b. oil pressure lower fuel
   c. fuel pressure same oil pressure
   d. oil pressure higher fuel pressure

5. **In a high bypass engine fuel pumps are driven by:**

   a. high pressure turbine
   b. high pressure compressor
   c. low pressure compressor
   d. intermediate compressor

6. **The effect of the high pressure compressor outlet pressure exceeding its maximum value would be:**

   a. pressure sensor input to fuel control unit (FCU), FCU reduce fuel, reduce rpm
   b. pressure sensor input to fuel control unit (FCU), FCU increase fuel, increase rpm
   c. pressure sensor input to fuel control unit (FCU), bleed valve open, bleed off excess volume of air
   d. pressure sensor input to fuel control unit (FCU), bleed valve open, bleed off excess pressure

7. **Which of the following is a normal stopping device for a gas turbine?**

   a. LP shut off valve close
   b. Fuel tank booster pumps select off
   c. HP shut off valve close
   d. Isolate electrics from engine

8. **Which of the following is a correct statement?**

   a. When an engine is running, the combustion chamber drain is closed by a pressure operated NRV
   b. When an engine is running, the combustion chamber drains tank is opened by a pressure operated NRV
   c. When the engine is shut down the drains tank closes to minimize fuel losses
   d. When the engine is shut down, residual fuel is syphoned directly back to the fuel tanks to minimize fuel losses

9. **The fuel flowmeter is situated:**

   a. between LP pump and the FCOC
   b. between LP pump and HP pump
   c. just after FCU
   d. between HP shut off valve and fuel nozzles

10. **An overheat in the turbine will result in:**

   a. an electrical signal from the thermocouple sent directly to the FCU and fuel being reduced
   b. an electrical signal from the thermocouple amplified then sent directly to the FCU and fuel flow being reduced
   c. pilot observing overheat on temperature gauge then subsequently throttling back the engine, therefore reducing fuel
   d. pilot observing overheat on temperature gauge then subsequently increasing rpm to increase airflow, to increase cooling air, to decrease turbine temperature

11. **Aircraft flying at FL420. If the booster pumps feeding the engine cease to work:**

   a. the engine would close down immediately
   b. the LP pump will draw fuel from the tank, but there may be a possibility of cavitation due to the low pressure and low boiling point of the fuel
   c. the LP pump will draw fuel from the tank, but there may be a possibility of cavitation due to the low pressure and higher boiling point of the fuel
   d. the LP pump will draw fuel from the tank, but there may be a possibility of cavitation due to the higher pressure and higher boiling point of the fuel

12. **The fuel-cooled oil cooler:**

   a. heats the oil and cools the fuel
   b. heats the fuel only
   c. cools the oil only
   d. heats the fuel and cools the oil

13. **On a cold day, the idle speed of a gas turbine engine which has no fuel control unit compensation:**

   a. is unaffected by temperature
   b. will increase
   c. will decrease
   d. will increase by no more than 4%

Answers

1	2	3	4	5	6	7	8	9	10	11	12	13
b	a	a	d	b	a	c	a	d	b	b	d	c

Chapter

27

Gas Turbines - Bleed Air

Bleed Air and Its Uses

Air bled from the engine compressor is used to internally cool and seal the engine and externally to service many aircraft user systems. In the modern turbofan aircraft these may include:

a) Air conditioning/pressurization

b) Hydraulic reservoir pressurization

c) Domestic water tank pressurization

d) Thrust reverser actuation

e) Air turbine motor (ATM) to drive hydraulic pump/electrical generator

f) Engine/airframe anti-icing

g) Fuel heaters

For external use air is typically bled from two sources, a continual low pressure bleed, taken from the outlet of the LP compressor, supplemented when required by a high pressure bleed, taken from the HP compressor.

During high power operation of the engine the LP bleed is usually of sufficient pressure to maintain the air-con/pressurization system. During low power operation the LP bleed pressure will fall and the HP bleed valve will open to ensure adequate pressure and flow.

The HP bleed valve is invariably scheduled to open when airframe anti-icing is selected as now the requirement is for hot air, the higher pressure the bleed the higher the temperature of the air.

All of the bleed air can be shut off from the engine if required by the operation of an isolation valve operable from the bleed air control panel on the flight deck. This valve will also be closed to isolate the engine bleed air when the fire handle is operated.

The diagram overleaf also shows fan outlet air being used to cool the bleed air in a precooler. Fan air can also be used for CSDU and engine oil coolers.

When air is bled from the compressor it must reduce the mass flow through the engine and therefore have a detrimental effect on thrust and reduce the cooling effect in the combustion chamber. This will cause an increase in rpm, EGT and SFC and a reduction in EPR.

Control of bleed air into the cabin is via the pack flow control valves. These enable the pilot to selectively control the air conditioning system and shut off individual packs in the event of a malfunction particularly involving smoke in the cabin.

Air conditioning bleeds from main engines or APU should also be closed during any ground de-icing operation to prevent toxic fumes entering the cabin.

Internal Air

Air bled for internal use is used for internal cooling, for instance the combustion chamber cooling or the turbine blade cooling, sealing of bearing or turbine disc areas.

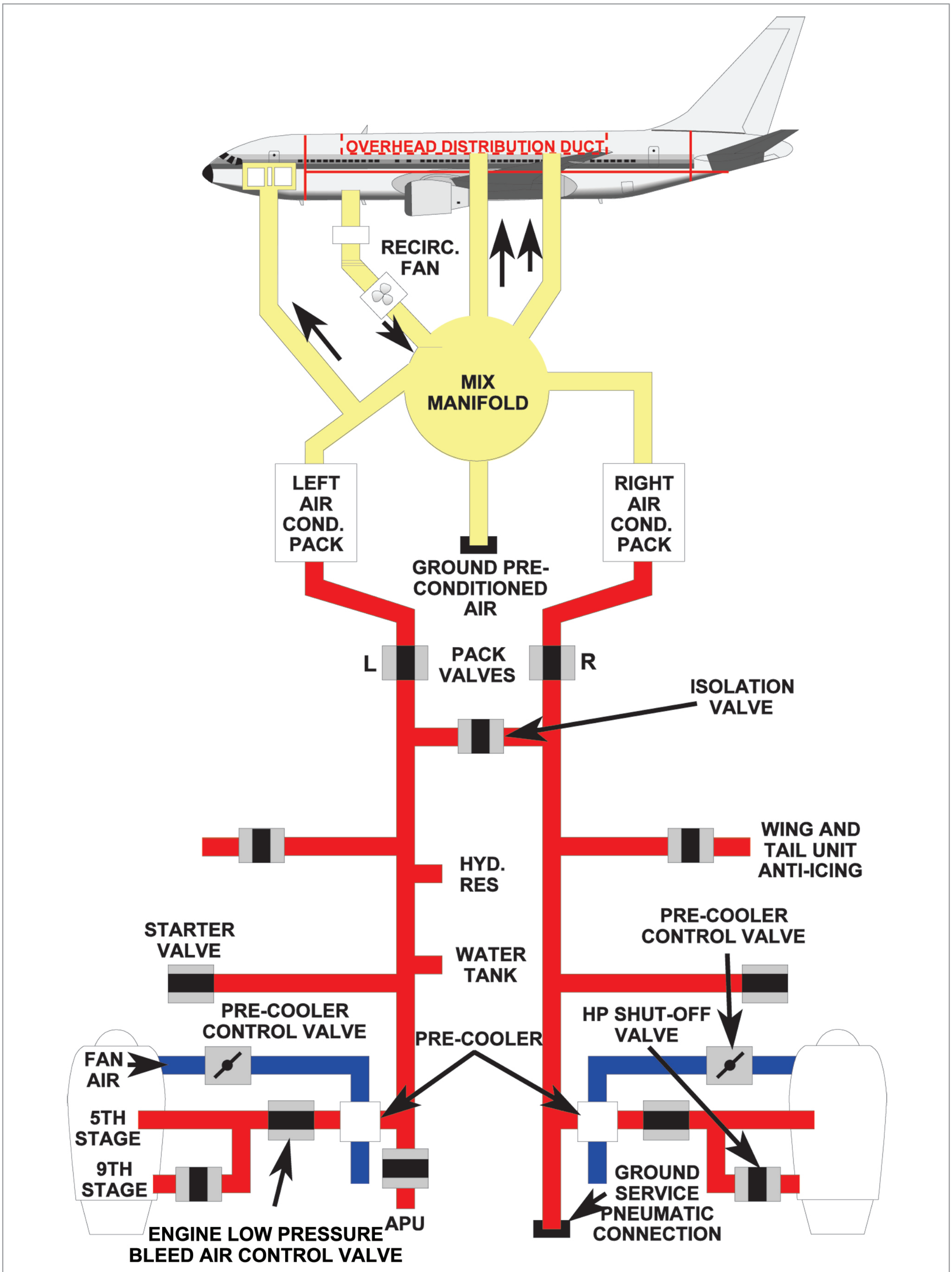


Figure 27.1

Air has considerable work done on it to raise its pressure as it passes through the engine, it is logical therefore to extract the air from as early a stage in the compressor as possible, commensurate with it being able to perform its function.

When the air has done its job, it is either dumped overboard, or alternatively ejected into the main gas stream at the highest possible pressure, thus achieving a small performance recovery.

Cooling

The main parts of the engine that require cooling are the combustion chamber and the turbine section. We have already discussed combustion chamber cooling in a previous chapter, it only remains to examine the cooling of the turbine section.

The gas turbine engine is a heat engine, high thermal efficiency is dependent upon high turbine entry temperatures. As stated earlier there is a limit to the amount of heat which can be released into the turbine from combustion, this limit is imposed by the materials from which the turbine blades and nozzle guide vanes are manufactured.

If these components are continuously cooled then the temperature of their operating environment can exceed the melting point of the material from which they are made.

The turbine discs are also heated, by conduction from the turbine blades, thus they are required to be cooled if disintegration from continued thermal stress is to be avoided.

Some modern turbofan engines use cooling air to control turbine blade tip clearance (active clearance control) by controlling turbine casing temperature. Also a feature of some engines is selective cooling of compressor rotor using bleed air. This controls thermal growth of the compressor blades in order to improve compressor efficiency.

Turbine Blade Cooling

Figure 27.2 shows the development of turbine blade cooling since its inception. Originally it was considered sufficient to pass low pressure compressor air through the blade (single pass internal cooling) and in so doing retain its temperature below the critical level at which excessive creep would occur.

The requirement for greater engine power and efficiency meant that higher gas temperatures were necessary. Low pressure compressor air was no longer able to provide the amount of cooling on its own, a supplementary source of cooling was required. Research showed that, by passing high pressure compressor air through the blade as well as the low pressure air (multi-feed), a reasonable increase in the gas temperature could be achieved before blade failure was experienced.

An additional increase was attained by creating a boundary layer effect (film cooling) by passing air through small holes in the leading and trailing edge of the blade. To some extent this boundary layer protected the turbine blade from the onslaught of the hot gases coming from the combustion chamber.

This was the type of blade which engines used for the following decade, eventually however events dictated that further advances in blade technology had to be made.

Designers and researchers reasoned that if passing air through the blade once could lower its temperature, then passing the air through more than once would lower it more. This proved to be true, eventually the optimum number of times the air could be passed through the blade was found to be five, (quintuple pass), and the quintuple pass, multi-feed internal cooling with extensive film cooling is presently considered to be state of the art in turbine blade manufacture.

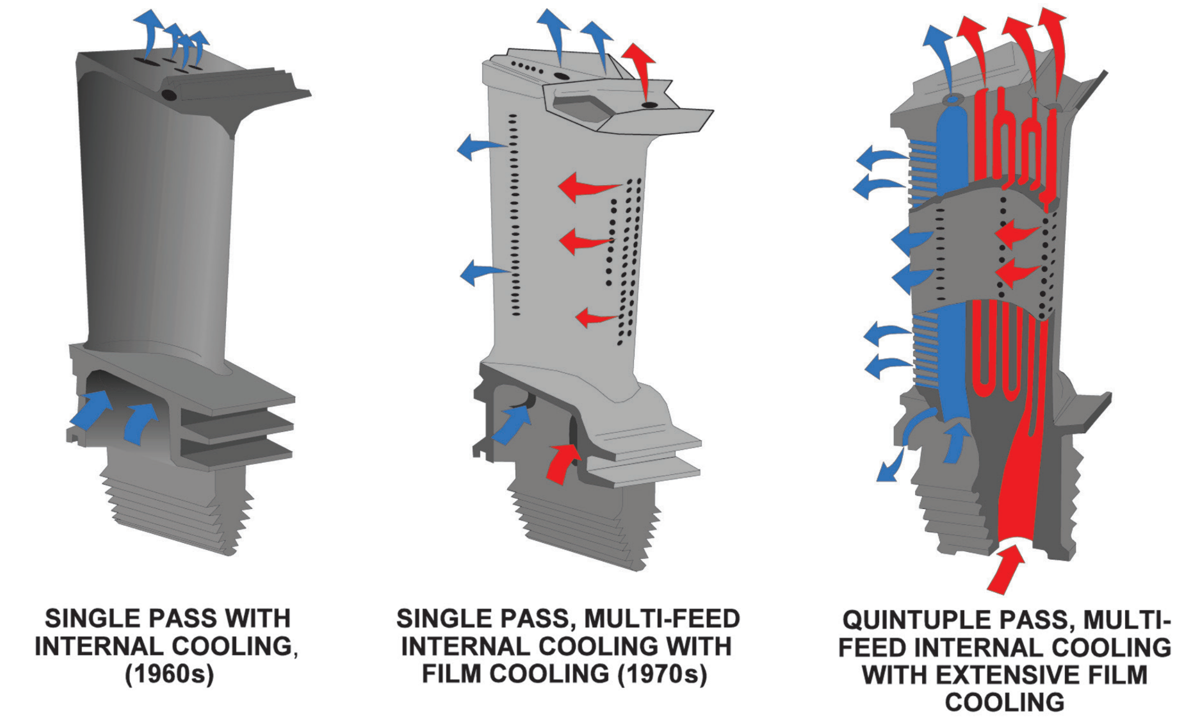


Figure 27.2 The development of turbine blade cooling

Nozzle Guide Vane Cooling

The nozzle guide vanes are cooled in a similar manner to that which is used in the turbine blades. The one major difference is that only high pressure compressor air is used. Examination of *Figure 27.3* will show a nozzle guide vane cooled by HP air supplemented by film cooling.

Turbine Disc Cooling

In the vast majority of gas turbine engines, the turbine blades are fixed to turbine discs. Heat conduction from the blades to the disc requires that the discs are cooled and prevented from suffering thermal fatigue from uncontrolled expansion and contraction.

Figure 27.3 shows how the front and rear faces of each of the turbine discs is cooled by high pressure compressor air, the actual pressure in each disc cavity being controlled by interstage seals.

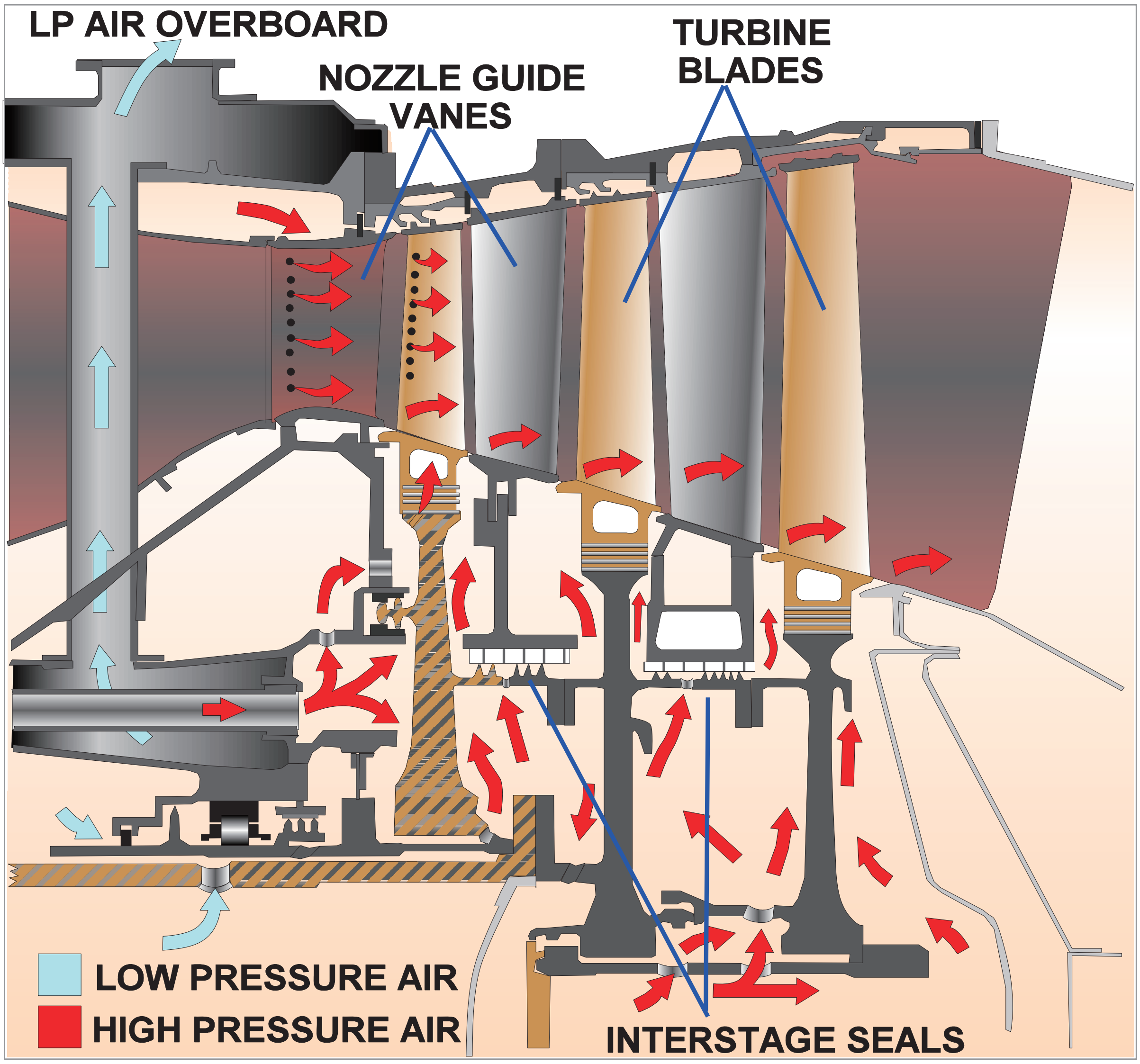


Figure 27.3 Cooling & sealing within the turbine area.

Sealing

To prevent the leakage of oil or air into spaces where it should not be, several different types of seal are in current use. Most of these seals work on the principle of the labyrinth (a maze). The labyrinth seal consists of fins which rotate within an annulus of oil, or in cases where the exterior of the seal is static, the annulus can consist of a soft abradable material or a honeycomb structure. In the case of the latter two, initial running of the engine makes the fins rub against the annulus material, cutting into it to give the minimum clearance.

During operation, there is a pressure drop across each fin which results in a restricted flow of air from one side of the seal to the other. When used to seal bearing chambers, the air pressure prevents oil leakage by flowing from the outside of the seal to the inside, this has the additional beneficial effect of inducing a positive pressure which assists the oil return to scavenge.

Where seals have to be placed between two rotating shafts, it is possible that there would be friction between the fins and the abradable material due to flexing of the shafts.

This would create high temperatures and the possibility of shaft failure. This is the situation in which the intershaft hydraulic seal is used, (*Figure 27.4*).

It was mentioned earlier that the air required to perform the cooling and sealing functions was taken from as early as possible in the compressor.

In the particular case of sealing air used in bearing chambers, it is taken from the intermediate stages of the compressor through air transfer ports in the compressor rotor drum, (*refer to Figure 27.4*), and passed through communicating passages to where it is required.

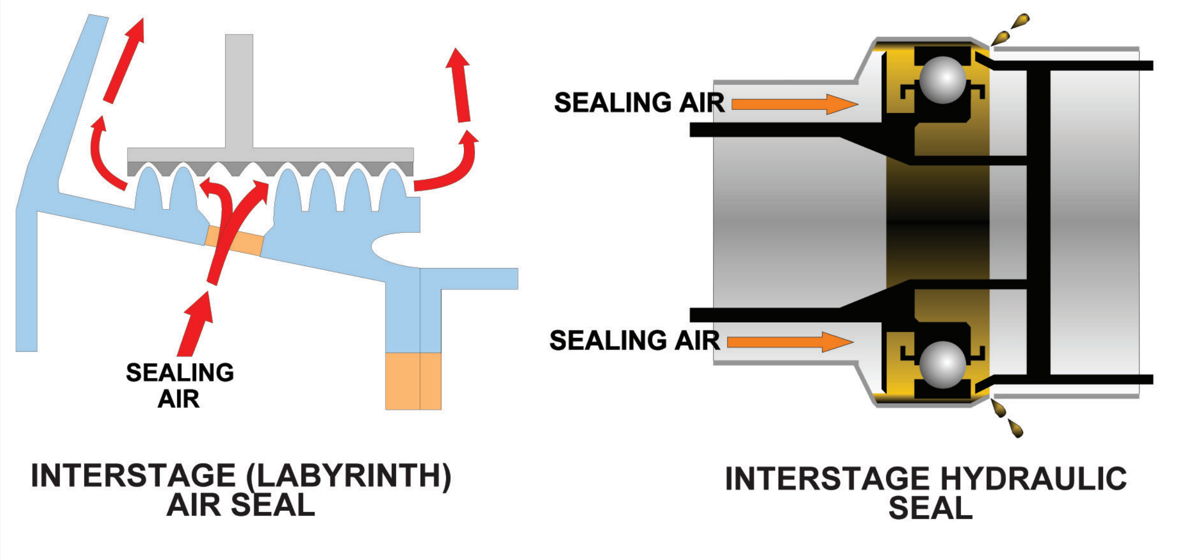


Figure 27.4 Types of interstage & intershaft seals

The intershaft hydraulic seal is an example of the first type of labyrinth seal mentioned in this section. The fin, or fins rotate close within an annulus of oil, any deflection of the shaft will cause the fin or fins to enter the oil and the seal will be maintained without generating any undue friction or heat.

An interstage seal, (*see Figure 27.4*), is used to either prevent or control leakage of air between sections of the engine which are operating at different pressures. The amount of pressure dropped across the seal depends upon the number of fins over which the air must pass. To create a larger pressure in one zone of the engine than another, all that has to be done is to pass the air over fewer fins into the high pressure zone than into the lower pressure zone, less pressure will be dropped before entry into the high pressure zone than into the low pressure zone.

The efficiency of all these seals depends basically upon two factors, firstly the mechanical design of the seal, and secondly the air pressure which is essential if it is to work at all. It is during periods of low engine power, for instance the selection of idle power during descent from high altitudes, that the greatest oil loss from a serviceable engine is suffered. Oil loss from a serviceable engine working at high power settings is almost negligible.

Disposal of Cooling and Sealing Air

When cooling and sealing has been carried out, the air which has been doing the job has to be disposed of. It can be seen from *Figure 27.3* that the HP air used for cooling is ejected into the exhaust stream. The LP air on the other hand is fed out through its own dedicated vent pipe.

On some engines the temperature of the air exiting through this vent pipe is monitored to give an indication of the integrity of the engine's internal construction.

Any failure which causes the temperature to exceed a predetermined maximum triggers a warning via a temperature sensor. The warning, which consists of a red warning light with the caption IEOH (internal engine overheat), requires a mandatory engine shutdown.

Questions

1. **An interstage air seal is used where:**

   a. engine sections are operating at different pressures
   b. engine sections are subjected to pressures of the same value
   c. it is more convenient
   d. it is difficult to obtain access during routine servicing

2. **An Internal Engine Overheat warning would necessitate:**

   a. the oil temperature to be closely monitored
   b. the EGT to be closely monitored
   c. the engine power to be reduced to idle
   d. the engine to be shut down

3. **Turbine blades are cooled by:**

   a. HP compressor air internally ducted through the blades
   b. HP air tapped from the combustion chambers
   c. air ducted from just before the intake guide vanes
   d. intermediate pressure air taken from the bleed valves

4. **Bleed air for engine anti-icing is provided by:**

   a. the bleed valves
   b. the turbine stages
   c. the compressor
   d. the combustion chambers

5. **The efficiency of a bearing chamber oil seal depends on its mechanical design and:**

   a. the fuel pressure
   b. compressor bleed air pressure
   c. the engine compression ratio
   d. the engine oil pressure

6. **With a bleed air anti-icing system the effect of selecting 'on' while maintaining thrust will:**

   a. decrease fuel consumption
   b. decrease specific fuel consumption
   c. increase specific fuel consumption
   d. specific fuel consumption will remain the same

7. **Which of the following ice removal methods does a modern jet aircraft normally utilize?**

   a. Hot air
   b. Rubber boots
   c. Electrical thermal blankets
   d. FPD freezing point depressant fluid

8. **With a bleed air anti-icing system the effect of selecting 'on' will have what effect?**

 a. EGT will decrease
 b. EGT will increase
 c. EGT will remain the same
 d. The ratio between exhaust pressure and intake pressure will increase

9. **The air obtained from the engine for air conditioning is essentially:**

 a. high pressure low volume
 b. high pressure high volume
 c. low pressure low volume
 d. low pressure high volume

Answers

1	2	3	4	5	6	7	8	9
a	d	a	c	b	c	a	b	d

Chapter

28

Revision Questions

Systems Revision Questions

1. The principle of operation of firewire is:

a. positive coefficient of impedance, negative coefficient of inductance
b. positive coefficient of resistance, negative coefficient of capacitance
c. positive coefficient of inductance, negative coefficient of impedance
d. positive coefficient of capacitance, negative coefficient of resistance

2. What type of fire extinguisher would be used on a propane fire?

a. Foam
b. Water
c. Dry powder
d. Sand

3. On what principle do smoke detectors work?

a. Resistance and capacitance
b. Ionization and impedance
c. Optical and ionization
d. Inductance and light diffraction

4. An ion detector detects:

a. smoke and fire
b. smoke
c. overheat
d. light

5. If an artificial feel unit were fitted it would be connected:

a. in parallel with the primary controls
b. in series with the primary controls
c. in series with the secondary controls
d. in parallel with the secondary controls

6. In a twin jet fuel system what is the function of a feeder box?

a. To equally distribute the fuel to each tank during refuelling
b. To prevent pump cavitation
c. To feed fuel to the volumetric top-off unit
d. To control the amount of fuel remaining during fuel dumping

7. A twin jet aircraft would normally be refuelled by which of the following methods?

a. Overwing refuelling
b. Suction refuelling
c. Open line refuelling
d. Pressure refuelling

8. The fuel tanks of a modern passenger airliner are filled by:

a. gravity
b. fuel is sucked in by the aircraft pumps
c. fuel is pumped in by the fuel truck
d. the VTO system

9. The purpose of a refuelling volumetric top off unit (VTO) is:

a. to keep the feeder box full of fuel at all times
b. to close the fuelling valve when the tank is full
c. to close the surge check valves in the outboard tanks to keep the tank full until the centre tank fuel has been used
d. to close the tank vent system when the tank is full

10. Fuel tank booster pumps are:

a. spur gear pumps – high pressure
b. centrifugal pumps – high pressure
c. spur gear pumps – low pressure
d. centrifugal pumps – Low pressure

11. The advantage of a float type fuel gauging system is:

1. simple
2. compensates for variations of SG
3. reads fuel quantity by mass
4. compensates for change of aircraft attitude

a. 3 & 4
b. 2 & 3
c. 1 only
d. 1 & 3

12. The function of the baffles in a fuel tank is:

a. to prevent movement of fuel to the wingtip
b. to prevent fuel surge (or sloshing) during manoeuvring
c. to prevent pump cavitation
d. to reduce fuel flow at altitude

13. The function of baffle check valves in a fuel tank is:

a. to reduce fuel flow at altitude
b. to prevent fuel surge during manoeuvring
c. to prevent pump cavitation
d. to prevent movement of fuel to the wingtip

14. A magneto is switched off by:

a. open circuiting the primary circuit
b. grounding the secondary circuit
c. open circuiting the secondary circuit
d. grounding the primary circuit

15. An impulse coupling in a magneto is provided to:

a. generate high voltage and advance the spark for starting
b. increase the energy to the spark plug as the rpm increases
c. generate high voltage and retard the spark for starting
d. allows a low energy value when ‘continuous ignition’ is selected

16. A turbosupercharger impeller is driven by:

a. a connection through a gearbox connected to the crankshaft
b. diversion of exhaust gases by the wastegate using energy that would otherwise have been wasted
c. excess torque from the reduction gearbox
d. a ram air turbine

17. A cylinder head temperature gauge measures:

a. the temperature of the hottest cylinder
b. the temperature of all the cylinders and gives an average reading
c. the temperature of the coolest cylinder
d. the temperature of the two cylinders furthest away from each other divided by two

18. EPR is measured by the ratio of:

a. turbine pressure to combustion chamber inlet pressure
b. high pressure compressor inlet pressure to exhaust pressure
c. low pressure compressor inlet pressure to high pressure compressor outlet pressure
d. exhaust pressure to low pressure compressor inlet pressure

19. Where is EGT measured?

a. In the jet pipe
b. HP turbine outlet
c. HP compressor outlet
d. Combustion chamber

20. In a bootstrap air conditioning system what is the first thing the air does?

a. Goes through the primary heat exchanger, compressor then secondary heat exchanger
b. Goes through the compressor, turbine, secondary heat exchanger
c. Goes through the turbine, compressor and secondary heat exchanger
d. Goes through the compressor, secondary heat exchanger, turbine

21. How are the loads on an aircraft busbar connected?

a. They are in series so that current reduces through the busbar as loads are switched off
b. They are in parallel so that voltage reduces through the busbar as loads are switched off
c. They are in parallel so that current reduces through the busbar as loads are switched off
d. They are in series so that voltage reduces through the busbar as loads are switched off

22. In a modern airliner what is the hydraulic fluid used?

a. Synthetic
b. Mineral
c. Mineral/alcohol
d. Vegetable

23. **The correct extinguisher to use on a brake fire would be:**

a. foam
b. dry powder
c. CO_2
d. water

24. **An aircraft is certified to fly higher than 25 000 ft and to carry a maximum of 240 passengers, it is configured to carry 200 and actually has 180 passengers on board. The minimum number of drop-down oxygen masks provided must be:**

a. 180
b. 200
c. 220
d. 240

25. **The passenger oxygen drop-down mask stowage doors are released:**

a. by a lanyard operated by a barometric capsule
b. mechanically
c. electrically for chemical oxygen generators and pneumatically for gaseous system
d. manually by the cabin crew

26. **In a centrifugal compressor:**

a. the air enters the eye tangentially and leaves the periphery axially
b. the air enters the periphery axially and leaves the eye tangentially
c. the air enters the eye radially and leaves the tip tangentially
d. the air enters the impeller axially at the eye and leaves at the periphery tangentially

27. **What happens to pressure, temperature and velocity of the air in the diffuser of a centrifugal compressor?**

a. Velocity increase, pressure and temperature decrease
b. Velocity decrease, pressure and temperature increase
c. Velocity, pressure and temperature increase
d. Velocity, pressure and temperature decrease

28. **The type of smoke detection system fitted to aircraft is:**

a. optical and ionization
b. chemical
c. electrical
d. magnetic

29. **The flight deck warning on activation of an engine fire detection system is:**

a. warning bell
b. gear warning
c. warning light and warning bell
d. warning light

30. **Hydraulic reservoirs are pressurized by:**

a. ram air in flight only
b. separate helium gas system
c. air from the air conditioning system
d. engine bleed air from turbine engine

31. **The purpose of a hydraulic fuse is to:**

a. allow the parking brake to remain on overnight if required
b. allow a reduced pressure to the wheel brake system to avoid locking the wheels
c. prevent over-pressurizing the reservoir as altitude increases
d. prevent loss of system fluid if the pipeline to a brake unit should rupture

32. **A shuttle valve will:**

a. allow the accumulator to be emptied after engine shutdown
b. reduce pump loading when normal system pressure is reached
c. automatically switch to a more appropriate source of hydraulic supply
d. operate on a rising pressure, higher than the Full Flow relief valve

33. **With regard to an air cycle type ECS pack, where is the water separator fitted?**

a. After the humidifier
b. Before the cold air unit compressor
c. Between the compressor and turbine
d. After the cold air unit turbine

34. **In the event that an emergency decent causes the cabin pressure to decrease below ambient pressure:**

a. the outward relief valve will open
b. the outflow valve will close
c. the inward relief valve will open
d. the safety valve will close

35. **The purpose of a ditching control valve is:**

a. to close the outflow valves
b. to open outflow valves
c. to allow rapid depressurisation
d. to dump the toilet water after landing

36. **In a bleed air anti-icing system the areas that are heated are:**

a. the whole of the wing
b. wing leading edge slats and flaps
c. wing leading edges and slats
d. trailing edge flaps

37. **On a modern turboprop aircraft the method of anti-icing/de-icing the wings is:**

a. fluid
b. pneumatic boots
c. electrical heater mats
d. hot air bled from the engines

38. If an aircraft maximum operating altitude is limited by the pressure cabin, this limit is due to:

a. the maximum positive pressure differential at maximum operating ceiling
b. the maximum positive pressure differential at maximum cabin altitude
c. the maximum number of pressurization cycles
d. the maximum zero fuel mass at maximum pressure altitude

39. Long haul aircraft are not used as short haul aircraft because:

a. checklists would be too time consuming to complete
b. it would use too much fuel
c. some tanks will be empty the whole time imposing too much strain on the aircraft
d. structures are given fatigue lives based on their use

40. The properties of Duralumin are:

1. aluminium/copper base
2. aluminium/magnesium base
3. hard to weld
4. easy to weld
5. good thermal conductivity
6. poor resistance to air corrosion

a. 1, 3 and 5
b. 2, 3 and 5
c. 1, 2 and 3
d. 4, 5 and 6

41. An undercarriage leg is considered to be locked when:

a. it is down
b. the amber light is on
c. mechanically locked by an 'over-centre' mechanism
d. the actuating cylinder is at the end of its travel

42. An underinflated tyre on a dry runway:

a. increases wear on the shoulder
b. increases wear on the crown
c. increases viscous aquaplaning speed
d. will cause the tyre temperature to reduce

43. Kreuger flaps are positioned:

a. towards the wing tip
b. at the wing inner leading edge
c. along the whole leading edge
d. at the wing trailing edge

44. What are flaperons?

a. Combined spoiler and flap
b. Combined elevators and flaps
c. Combined ailerons and elevators
d. Combined flap and ailerons

45. What is the purpose of inboard ailerons:?

a. To reduce wing bending at high speed
b. To reduce wing twisting at low speed
c. To reduce wing bending at low speed
d. To reduce wing twist at high speed

46. What is the purpose of trim tabs?

a. To reduce stick forces in manoeuvres
b. To reduce stick holding forces to zero
c. To increase control effectiveness
d. To reduce control effectiveness

47. Smoke hoods protect:

a. full face and provide a continuous flow of oxygen
b. mouth and nose and provide a continuous flow of oxygen
c. full face and provide oxygen on demand
d. mouth and nose and provide oxygen on demand

48. Oxygen supplied to the flight deck is:

a. gaseous, diluted with ambient air if required
b. chemically generated and diluted with cabin air if required
c. gaseous, diluted with cabin air if required
d. chemically generated, diluted with ambient air if required

49. If during pressurized flight the outflow valve closes fully due to a fault in the pressure controller the:

a. skin will be overstressed and could rupture
b. safety valve opens when the differential pressure reaches structural max diff
c. the inward relief valve will open to prevent excessive negative differential
d. ECS packs are automatically closed down

50. In a fan jet engine the bypass ratio is:

a. internal mass airflow divided by external mass airflow
b. external mass airflow divided by internal mass airflow
c. internal mass airflow divided by mass fuel flow
d. mass fuel flow divided by mass fuel flow

51. The thrust reverser light illuminates on the flight deck annunciator when the:

a. thrust reverser doors have moved to the reverse thrust position
b. thrust reverser doors have been selected but the doors have not moved
c. thrust reverser doors are locked
d. thrust reverser doors are unlocked

52. In very cold weather the pilot notices slightly higher than normal oil pressure on start up. This:

a. indicates an oil change is required.
b. is indicative of a blocked oil filter.
c. is acceptable providing it returns to normal after start up.
d. is abnormal but does not require the engine to be shut down.

53. **If a fuel tank having a capacitive contents gauging system is empty of fuel but has a quantity of water in it:**

a. the gauge will show full scale high
b. the gauge will show the mass of the water
c. the gauge will show empty
d. the gauge needle will 'freeze'

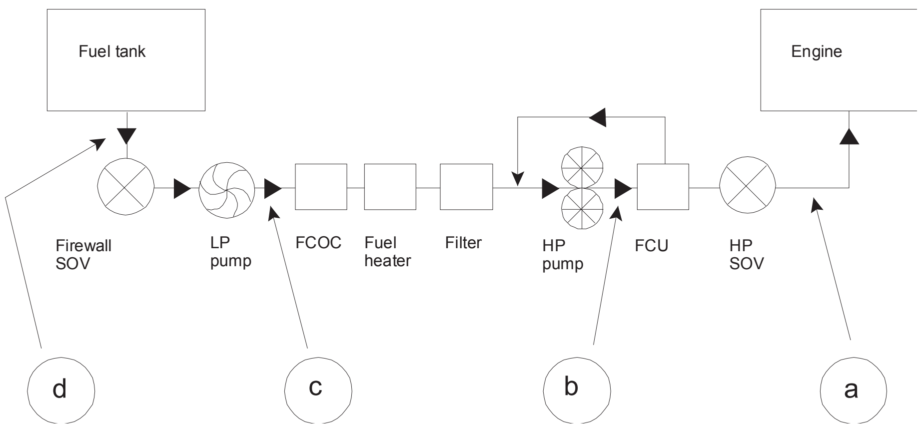
54. **In a four stroke engine, when the piston is at BDC at the end of the power stroke the position of the valves is:**

	Inlet	Exhaust
a.	closed	closed
b.	open	open
c.	open	closed
d.	closed	open

55. **What is the effect on EGT and EPR if a bleed valve is opened?**

a. Increase, increase
b. Decrease, decrease
c. Decrease, increase
d. Increase, decrease

56. **Refer to the following diagram for a modern turbofan engine – where is fuel flow measured?**



57. **Where is torque measured in a turboprop engine?**

a. Accessory gearbox
b. Reduction gearbox
c. At the turbine
d. At the constant speed unit oil pump

58. **Propeller blade angle is:**

a. the angle between the blade chord and the plane of rotation
b. the angle between the relative airflow and the chord
c. dependent upon rpm and TAS
d. the difference between effective pitch and geometric pitch

59. Why is a propeller blade twisted?

a. To reduce the thrust at the root of the blade
b. To prevent the blade from fully feathering
c. To reduce the tip speed
d. To even out the thrust force along the length of the blade

60. For calculating resistances in parallel the formula is:

a. $\frac{1}{R_T} = \frac{1}{R_1} \times \frac{1}{R_2} \times \frac{1}{R_3}$
b. $R_T = R_1 + R_2 + R_3$
c. $R_T = R_1 \times R_2 \times R_3$
d. $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

61. When a fuse operates it is .... and when a circuit breaker operates it is ....

a.	high current	low current
b.	low current	high current
c.	non re-settable	re-settable
d.	re-settable	non re-settable

62. A hot busbar is one that:

a. supplies galley power
b. is permanently connected to the battery
c. carries all of the non-essential loads
d. is connected to the battery in an emergency

63. In an AC distribution system what is the purpose of the GCB?

a. Maintains constant frequency
b. Connects the load busbar to the synchronizing busbar
c. Controls generator field excitation
d. Connects a generator output to its load busbar

64. An aircraft which uses DC as the primary source of power, AC for the instruments may be obtained from:

a. CSDU
b. rectifier
c. inverter
d. TRU

65. Persistent over excitation of one generator field will cause:

a. the GCB and BTB to trip
b. the BTB and exciter control relay to trip
c. the GCB and exciter control relay to trip
d. the GCB and SSB to trip

66. **When a battery is nearly discharged, the:**

a. voltage decreases
b. voltage and current decrease
c. current increases because voltage has dropped
d. electrolyte boils

67. **The state of charge of an aircraft battery on an aircraft with a voltmeter would be checked:**

a. on load
b. off load
c. with the battery negative terminal disconnected
d. by monitoring the electrolyte resistance

68. **In a paralleled AC distribution system what regulates the real load?**

a. Torque from the CSDU (CSD)
b. Field excitation from the voltage regulator
c. Synchronizing circuits in the BTB
d. A potentiometer on the flight engineer's panel

69. **If the oil temperature gauge of the CSD is in the red what would action is required?**

a. Throttle back and allow to cool down
b. Auto disconnect
c. Manually disconnect and reconnect on the ground
d. Disconnect, then when cooled reconnect

70. **What is a transistorized static inverter in a DC circuit used for?**

a. Convert AC to DC
b. Provide field excitation current
c. Provide AC for instruments
d. To supply power to the emergency lights

71. **If the load increases on a 'constant speed AC generator' what does the voltage regulator do?**

a. Increases generator speed
b. Decreases field excitation
c. Remains the same
d. Increases field excitation

72. **Incorrect bonding of the aircraft structure could cause:**

a. corrosion at skin joints
b. CB trips
c. static on the radio
d. VOR interference

73. The characteristics of a Unipole system are:

1. Lighter
2. Easier fault finding
3. More likely to short circuit
4. Less likely to short circuit
5. It is not a single wire system

a. 2, 4 and 5.
b. 1, 2 and 3.
c. 2, 4 and 1.
d. 1, 4 and 5.

74. The frequency of an AC generator is dependent upon?

a. the rpm of the rotor
b. the number of poles in the rotor
c. the rpm and number of poles in the rotor
d. the number of poles in the rotor and the number of phase windings in the stator

75. With an almost discharged battery there will be:

a. a decrease of voltage with increasing load
b. increase of current with decrease of voltage
c. decrease of current with increasing load
d. increase of voltage with increasing load

76. When is an engine overheat firewire system activated:

a. When an overheat is detected all along the length of both firewire loops
b. When an overheat affects one detector loop at a point anywhere along its length
c. When an overheat is detected all along the length of one firewire loop
d. When an overheat affects both detector loops at a point anywhere along their length

77. In an air cycle air conditioning system what is the function of the ground-cooling fan?

a. To re-circulate air through the mix manifold
b. To draw cooling air over the turbine
c. To blow air into the compressor
d. To draw cooling air over the heat exchangers

78. How do you control power in a jet engine?

a. By controlling the mixture ratio
b. By controlling the fuel flow
c. By controlling the airflow
d. By controlling the bleed valves

79. **In a normally aspirated piston engine carburettor icing can occur:**

a. between 0°C and −10°C
b. at more than +10°C
c. only at less than +10°C if there is visible moisture
d. only above 5000 ft

80. **In a gas turbine engine fuel system why is the fuel heater before the filter?**

a. To prevent 'waxing'
b. To help vaporization of the fuel
c. To prevent water in the fuel freezing and blocking the filter
d. To prevent the fuel from freezing and blocking the filter

81. **What is the purpose of the FCOC (Fuel-cooled Oil Cooler)?**

a. To maintain the oil at the correct temperature
b. To heat the fuel and cool the oil
c. To heat the oil and cool the fuel
d. To bypass oil to the engine if the oil pressure filter becomes blocked

82. **What is the purpose of the torque links in a landing gear leg?**

a. To prevent the wheel rotating around the leg
b. To prevent shimmy
c. To transfer the brake torque to the wheel
d. To position the wheels in the correct attitude prior to landing

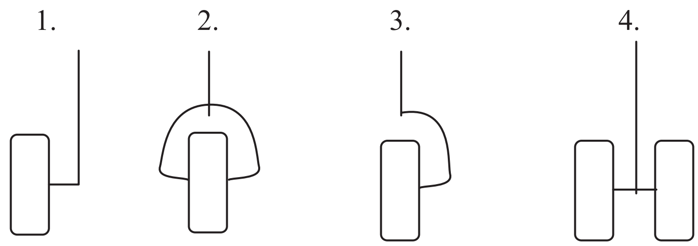
83. **An artificial feel system is needed in the pitch channel if the:**

a. airplane has a variable incidence tailplane
b. elevators are controlled through a reversible servo system
c. elevator is controlled through a servo tab
d. elevators are controlled through an irreversible servo system

84. **Auto brakes are disengaged:**

a. when the ground spoilers are retracted
b. when the speed falls below 20 kt
c. on the landing roll when the autopilot is disengaged
d. by the pilot

85. **In the following diagram the landing gear arrangements shown are:**



	1.	2.	3.	4.
a.	fork	cantilever	levered	tandem
b.	cantilever	dual	fork	tandem
c.	cantilever	fork	half fork	dual wheel
d.	half fork	dual wheel	cantilever	fork

86. **In an aircraft with a fuel dumping system it will allow fuel to be dumped:**

a. down to a predetermined safe value
b. down to unuseable value
c. to leave 15 gallons in each tank
d. down to maximum landing weight

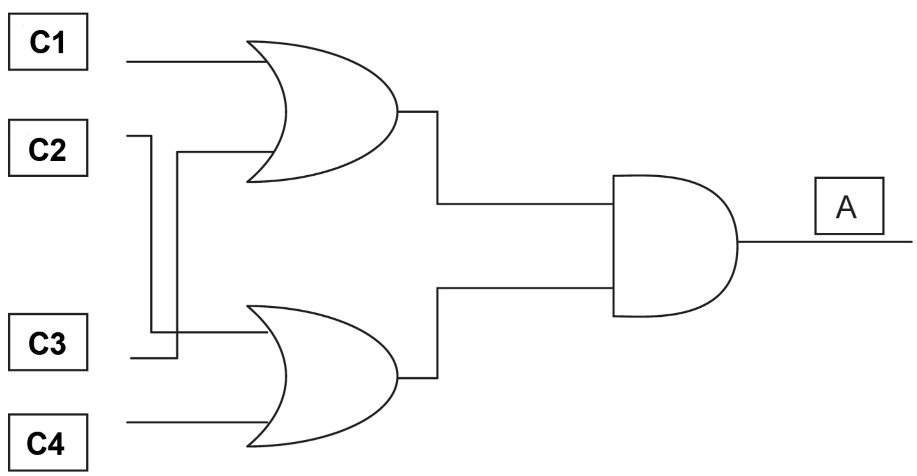
87. **What does 'octane rating' when applied to AVGAS refer to?**

a. The waxing point of the fuel
b. The ability of the fuel to disperse water
c. The anti-knock value of the fuel
d. The volatility of the fuel

88. **How are modern passenger jet aircraft fuel tanks pressurized?**

a. By nitrogen from a storage cylinder
b. By ram air through the vent system
c. By bleed air from the pneumatic system
d. By a volumetric top off unit

89. **Refering to the following diagram:**



To get logic 1 output at A there must be a logic 1 input at:

a. C1 and C2 only
b. C1 and C3 only
c. C2 and C4 only
d. C3 only

90. **In which of the following areas would an overheat/fire warning be provided?**

a. Fuel tank
b. Cabin
c. Tyres
d. Wheel/undercarriage bay

91. An axial flow compressor when compared to a centrifugal compressor:

a. takes in less air and is less prone to rupturing
b. takes in more air and is more prone to rupturing
c. takes in more air and is less prone to rupturing
d. takes in less air and is more prone to rupturing

92. Hydraulic pressure typically used in the system of large transport aircraft is:

a. 2000 - 3000 psi
b. 3000 - 4000 psi
c. 1000 - 2000 psi
d. 4000 - 5000 psi

93. The EGT indication on a piston engine is used:

a. to control the cooling air shutters
b. to monitor the oil temperature
c. to assist the pilot to adjust the fuel mixture
d. to indicate cylinder head temperature

94. A gas turbine engine having a single spool, the compressor will rotate:

a. at the same speed as the turbine
b. slower than the turbine
c. faster than the turbine
d. independently of the turbine

95. Because of its function an 'AND' gate may also be referred to as:

a. invert or not gate
b. any or all gate
c. all or nothing gate.
d. either or gate.

96. What type of hydraulic fluid is used in a modern passenger jet aircraft?

a. Mineral based
b. Phosphate ester based
c. Vegetable based
d. Water based

97. In a 4 stroke engine when does ignition occur in each cylinder?

a. After TDC for starting and then before TDC every 2nd rotation of the crankshaft
b. Before TDC for starting and then after TDC every 2nd rotation of the crankshaft
c. After TDC for starting and then before TDC every rotation of the crankshaft
d. Before TDC for starting and then after TDC every rotation of the crankshaft

98. When smoke appears in the cockpit, after donning the oxygen mask the pilot should select:

a. normal
b. 100%.
c. diluter
d. emergency

99. Which part of the gas turbine engine limits the temperature?

a. Combustion chamber
b. Turbine
c. Compressor
d. Exhaust

100. What makes the non-rigid fittings of compressor and turbine blades rigid when the engine is running?

a. Spring locks
b. Thrust and drag forces
c. Aerodynamic and centrifugal force
d. Tapered bead seats

101. What ice protection system is used on most modern jet transport aircraft?

a. Liquid
b. Electrical
c. Hot air
d. Pressure operated boots

102. What frequency is commonly used in aircraft electrical distribution systems?

a. 200 Hz
b. 400 Hz
c. 100 Hz
d. 50 H

103. When does the engine High Pressure fuel shut off valve close?

a. After a booster pump failure
b. When the engine fuel switch is selected ‘on’ during engine start
c. When flight idle is selected
d. When the engine fuel switch is selected ‘off’ during engine shutdown

104. When does the Low Pressure fuel shut off valve close?

a. When the fire handle is pulled
b. When the engine fuel switch is selected ‘on’ during engine start
c. When flight idle is selected
d. After a booster pump failure

105. What voltage is supplied to booster pumps on a modern jet airliner?

a. 115 V AC single phase
b. 200 V AC three phase
c. 28 V DC from an inverter
d. 12 V DC from the battery

106. **An engine having a 'free turbine':**

a. there is a mechanical connection between the power output shaft and the free turbine
b. there is no mechanical connection between the power output shaft and the free turbine
c. there is a mechanical connection between the compressor and the propeller shaft
d. air enters via compressor inlet on the turbine

107. **If the pressure controller malfunctions during the cruise and the outflow valve opens what happens to:**

i) cabin ROC ii) cabin Alt iii) differential pressure

a.	i) increase	ii) decrease	iii) decrease
b.	i) decrease	ii) increase	iii) decrease
c.	i) increase	ii) increase	iii) decrease
d.	i) increase	ii) increase	iii) increase

108. **What controls cabin pressurization?**

a. ECS pack mass flow controller
b. outflow valve
c. engine bleed valve
d. inflow valve

109. **If the fire handle is pulled in an aeroplane with an AC generator system what disconnects?**

a. Exciter control relay and GCB
b. GCB and BTB
c. BTB and GCU
d. Exciter control relay only

110. **Which components constitute a crank assembly?**

a. crankshaft, camshaft, valve springs
b. crankcase, crankshaft, pistons and connecting rods
c. crankshaft, pistons and connecting rods
d. propeller, crankshaft, connecting rods

111. **One stage of an axial compressor:**

a. Comprises a row of stators followed by a rotor disc
b. Has a compression ratio of 2:1
c. Comprises a rotor disc followed by a row of stators
d. Has a compression ratio of 0.8

112. **If a CSD overheat warning is shown:**

a. the CSD can be disconnected and the pilot must control the alternator himself
b. the pilot must throttle back to reduce the load on the alternator
c. the CSD can be disconnected then reconnected later when the temperature has reduced
d. the CSD can be disconnected but not used for the rest of the flight

113. A new tyre with wear on the tread and parallel grooves:

a. can be repaired once only
b. can be repaired several times
c. can never be repaired
d. is fit for use only on a nose-wheel

114. An emergency exit assisted escape device must be fitted if the door sill height is above:

a. 8 ft with the aircraft on the landing gear with the nosewheel extended
b. 8 ft with the aircraft on the landing gear with the nosewheel collapsed
c. 6 ft with the aircraft on the landing gear with the nosewheel extended
d. 6 ft with the aircraft on the landing gear with the nosewheel collapsed

115. In a compensated capacitance fuel contents system what happens to a fuel weight of 8000 lb if its volume increases by 5%?

a. Decreases by 5%
b. Increases by 5%
c. Remains the same
d. Increases by 5% for every degree rise in temperature

116. How do aircraft spoilers work?

a. Lower surfaces only, symmetrical and asymmetrical operation
b. Lower surfaces only, symmetrical operation
c. Upper surfaces only, symmetrical and asymmetrical operation
d. Upper surfaces only, symmetrical operation

117. What is the total volume in the cylinder of a four stroke engine?

a. A value equal to the cubic capacity
b. Swept volume minus clearance volume
c. Volume between TDC and BDC
d. Swept volume plus clearance volume

118. After the power stroke on a piston engine the poppet valve sequence is:

a. exhaust valve opens, inlet valve opens, exhaust valve closes
b. exhaust valve closes, inlet valve opens, exhaust valve opens
c. inlet valve opens, exhaust valve closes, inlet valve closes
d. inlet valve closes, exhaust valve closes, inlet valve opens

119. What speed does the LP compressor run at?

a. The speed of the LP turbine
b. The speed of the HP turbine
c. Half the engine speed
d. Constant speed

120. **What happens to the angle of attack of a fixed pitch propeller as the aircraft accelerates down the runway?**

a. Increases
b. Decreases
c. Remains the same
d. Blade angle changes to compensate for forward speed

121. **What happens to the AoA of a VP propeller with increasing TAS if the rpm and throttle levers are not moved?**

a. Blade angle remains constant to compensate for forward speed
b. Increases
c. Decreases
d. Remains the same

122. **Where are smoke detectors fitted?**

a. Toilets
b. Toilets and cargo compartments A, B, C, D, E
c. All cargo compartments
d. Toilets and cargo compartments B, C, E

123. **What colour is the hydraulic liquid in a modern jet airliner?**

a. Purple
b. Red
c. Yellow
d. Pink

124. **On what principle does a fuel flowmeter work?**

a. Volume and viscosity
b. Quantity of movement
c. Capacitive dielectric
d. Pressure and temperature

125. **What is engine pressure ratio?**

a. The ratio of turbine outlet pressure to compressor inlet pressure
b. The ratio of turbine inlet pressure to compressor inlet pressure
c. Turbine outlet pressure × compressor outlet pressure
d. Compressor inlet pressure divided by turbine outlet pressure

126. **On what principle does the fuel contents gauging system work on a modern large aircraft?**

a. Capacity affected by dielectric therefore changing EMF of system
b. Capacity affected by dielectric therefore changing resistivity of system
c. Changes in dielectric causes changes in capacitance
d. Change in dielectric causes change in distance between plates and therefore changes capacitance

127. What are the advantages of a nicad battery?

1. More compact.
2. Longer shelf life.
3. Even voltage over total range before rapid discharge.
4. Higher voltage than lead acid type.

a. 2, 3, and 4
b. 1, 2, 3 and 4
c. 1, 2 and 4
d. 1, 2 and 3

128. What would happen if the wastegate of a turbocharged engine seized in the descent?

a. Compressor will overspeed
b. Blow the turbine blades off
c. MAP may exceed its maximum permitted value in the induction manifold
d. rpm may exceed its maximum permitted value

129. When is spark plug fouling most likely to occur?

a. In the climb if you have not adjusted the mixture
b. Cruise power
c. In the descent if you have not adjusted the mixture
d. Max take-off power

130. Why, in the bootstrap system, is the air compressed before it enters the heat exchanger?

a. To provide a constant mass flow to the cabin
b. To ensure maximum pressure and temperature drop across the turbine
c. To ensure most rapid cooling through the heat exchanger
d. To provide a constant temperature airflow to the cabin

131. What is a ram air turbine (RAT) which drives a hydraulic pump used for?

a. Nose wheel steering
b. Flap extension
c. Landing gear extension if the normal system fails
d. Flight controls in case of failure of the engine driven system

132. As altitude increases what does the mixture control do to the fuel flow?

a. Increases flow due to reduced air density
b. Increases flow due to increased air density
c. Reduces flow due to reduced air density
d. Reduces flow due to increased air density

133. What is the coefficient of friction on an aquaplaning (hydroplaning) tyre?

a. 0
b. 0.1
c. 0.5
d. 1.0

134. What is the purpose of the diluter demand valve in the emergency oxygen system?

a. To supply air only when inhaling
b. To dilute oxygen with air in crew oxygen system
c. To dilute oxygen with air in passenger oxygen system
d. To supply oxygen only when inhaling

135. What limits the max. temperature in a gas turbine engine?

a. Temperature in the combustion chamber
b. Temperature at the exhaust
c. Temperature at the turbine
d. Temperature entering the combustion chamber

136. What is the purpose of a surge box inside a fuel tank?

a. Collect sediment at the bottom of the tank
b. Ventilate the tank during high pressure refuelling
c. Allow movement of fuel between tanks while refuelling
d. Prevent sloshing of fuel away from pump inlet during abnormal manoeuvres

137. Emergency oxygen is provided by:

a. one system for both flight deck and cabin
b. two independent systems, one for flight deck, one for cabin
c. two systems each capable of supplying the flight deck and cabin
d. three systems, one for the flight deck, one for the passengers and one for the cabin crew

138. A 12 volt lead acid battery has a broken connection in a cell, the battery:

a. provides 1/12th less voltage for the same time
b. provides 1/12th less voltage for 1/12th less time
c. is unserviceable
d. will suffer from thermal runaway

139. A changeover relay:

a. allows an APU to connect to its busbar
b. allows a GPU to connect to its busbar
c. allows connection of AC to an unserviceable generator's busbar
d. allows an alternate source to supply an essential busbar

140. A relay is:

a. a motorway breakdown service
b. a mechanically operated switch
c. an electrically operated switch
d. another name for a solenoid

141. Fuel heaters are fitted:

a. in the wing fuel tanks
b. in the fuselage fuel tanks
c. in the engine fuel system mounted on the engine
d. all of the above

142. **The engine fire extinguisher system is activated:**

a. after the engine has been shut down
b. automatically when a fire warning is sensed
c. by the pilot when required
d. automatically after a time delay to allow the engine to stop

143. **An unpressurized aircraft is flying above FL100 and therefore must have sufficient oxygen for:**

a. both pilots immediately and the cabin crew plus all passengers after 30 minutes above FL100 but below FL130
b. both pilots only
c. both pilots and all passengers
d. both pilots immediately and the cabin crew plus some passengers after 30 minutes above FL100 but below FL130

144. **Aircraft above a certain capacity must carry a crash axe, it is provided to:**

a. cut through the aircraft fuselage to allow escape
b. enable access behind panels and soundproofing to aid fire fighting
c. cut firewood in a survival situation
d. restrain disorderly passengers

145. **The function of stringers in the construction of the fuselage is:**

a. to withstand shear stress
b. to provide an attachment for insulation
c. to provide support for the skin and to absorb some of the pressurization strain as tensile loading
d. to provide an alternate load path in the event of the failure of a frame

146. **The requirement for an aircraft to have a fuel dumping system is:**

a. all aircraft in the Transport Category having a maximum take-off mass (MTOM) of 75 000 kg or greater
b. all aircraft manufactured after 1997 having a MTOM of 7500 kg or more
c. aircraft whose maximum landing mass (MLM) is significantly lower than its maximum take-off mass (MTOM)
d. all aircraft with a seating capacity of 250 or more

147. **At what height is it mandatory for one of the flight deck crew to wear an oxygen mask?**

a. 25 000 ft
b. 32 000 ft
c. 37 000 ft
d. 41 000 ft

148. **A Volumetric Top-off unit (VTO), is provided in a fuel system to:**

a. vent the tank to atmosphere when its full
b. allow a main feed tank to be maintained at a predetermine level automatically, while being fed from an auxiliary tank
c. allow the main tank to automatically maintain a predetermined fuel pressure
d. prevent too much fuel from being dumped

149. **The type of engine layout shown on page 430 is:**

a. two spool
b. turbo fan
c. free turbine
d. prop fan

150. **The precautions to be taken during refuelling are:**

a. GPU may not be running during refuelling
b. all earthing of aircraft parts to ground equipment must be completed before filler caps are removed
c. passengers may be boarded (traversing the refuelling zone)
d. no radar or HF radios under test within 10 metres

151. **What prevents an impulse coupling operating at speeds above start speed, considering that it has flyweights?**

a. Electro-magnetic induction
b. Hydraulic clutch
c. Centrifugal force
d. On/off switch

152. **What type of fire extinguisher must be on a flight deck?**

a. Water
b. Dry powder
c. Special fluid
d. Halon

153. **In a Bramah press one piston has an area of 0.05 m^2 and has a force of 10 N acting on it. If the area of the second piston is 0.5 m^2, what force will it produce?**

a. 1 N
b. 20 N
c. 25 N
d. 100 N

154. **What is the reason for putting the horizontal stabilizer on top of the fin?**

a. To be more efficient at high speed
b. No need for anti-icing
c. Create a pitch up by making the aeroplane tail heavy
d. To be out of the way of the wing down wash

155. **Where are thermal plugs fitted?**

a. Wheel rim
b. Cargo bay
c. Fuel tank
d. Oil tank

156. In a non-stressed skin aircraft, bending loads acting on the wings are taken by:

a. skin
b. spars
c. stringers
d. ribs

157. In a stressed skin aircraft, bending loads acting on the wings are taken by:

a. ribs and stringers
b. stringers and spars
c. spars and skin
d. spars and stringers

158. Hydraulic fluid:

a. needs no special treatment
b. is harmful to eyes and skin
c. is a fire hazard
d. is harmful to eyes and skin, and is also a fire hazard

159. In a modern carburettor, mixture is controlled via:

a. airflow
b. airflow, fuel flow and temperature
c. fuel flow
d. airflow and fuel flow

160. The demand valve of a diluter demand oxygen regulator in normal mode operates when:

a. the pressure to the regulator is more than 500 psi
b. user breathes in
c. user requires 100% oxygen
d. diluter control is in the 'normal' position

161. Torque links on an undercarriage come under most stress:

a. during crosswind landings
b. during pushback
c. when making tight turns when taxiing
d. after take-off

162. If cabin pressure is decreasing, the cabin VSI will indicate:

a. zero
b. climb
c. descent
d. reducing pressure

163. The battery in a search and rescue beacon (SARB) should last for:

a. 72 hours
b. 48 hours
c. 24 hours
d. 12 hours

164. A shuttle valve is used to:

a. restrict the rate of operation of a system
b. select the most suitable system pressure
c. allow two supplies to be available to a service
d. to allow a constant volume pump to idle

165. The temperature of hydraulic fluid is measured:

a. after the cooler
b. in the reservoir
c. at the actuator
d. at the pumps

166. Electrical heating devices:

a. consume little power
b. are used for preventing ice on small areas (e.g. pitot head, windscreen only)
c. are used for de-icing small areas
d. can de-ice large areas because there is a large excess of electrical power available

167. Reverse thrust lights come on when:

a. reverser doors are unlocked
b. when reverse power above idle is selected
c. when reverse thrust is selected in flight
d. when the doors move towards the stowed position inadvertently

168. The magnetos are switched off and the engine continues to run <u>normally</u> .The cause of this fault is:

a. a wire from the magneto coming in contact with the metal aircraft skin
b. hotspots existing in cylinder
c. carbon deposits on spark plug
d. grounding wire from magneto being broken

169. An aircraft is to fly at 29 000 ft. When should the oxygen briefing take place?

a. Before 10 000 ft
b. Before 14 000 ft
c. At 20 000 ft
d. Before take-off

170. What is the purpose of the magneto impulse coupling?

a. To give a retarded spark during starting
b. Reduce the rate of rotation of the magneto
c. Advance the ignition and give a hotter spark during starting
d. Automatically increases spark rate at high engine speeds

171. The excess cabin altitude alerting system must operate to warn the crew at:

a. 8000 ft
b. 10 000 ft
c. 13 000 ft
d. 14 000 ft

172. The 'torsion box' of a modern aircraft wing structure consists of:

a. spars, skin, frames and stringers
b. spars, skin, frames and ribs
c. spars, skin, longerons and ribs
d. spars, skin, stringers and ribs

173. A device in a hydraulic system which acts in the same way as a diode in an electrical circuit is a:

a. restrictor valve
b. sequence valve
c. fuse
d. one way check valve

174. What does three green lights represent when the landing gear is selected down?

a. The gear is down
b. The gear is down and locked
c. The gear and doors are down and locked
d. The gear is travelling between up and down

175. Which is the correct statement regarding a large aircraft fitted with both inboard and outboard ailerons?

a. The outboard ailerons are used only when the landing gear is selected down
b. The outboard ailerons are used only when the landing gear is retracted
c. The inboard ailerons are used only when the flaps are retracted
d. The inboard ailerons are only used when the flaps are extended

176. How do differential ailerons work?

a. Increase lift on down going wing and decrease lift on up going wing
b. Increase drag on up going wing and decrease drag on down going wing
c. Equalize the drag on up going and down going wings
d. Equalize the lift on up going and down going wings

177. What is the effect of heating flight deck windows?

a. To demist the interior of the window if normal demist does not function correctly
b. To protect the windows against bird strike
c. To protect the windows against ice formation
d. To protect the windows against bird strike and ice formation

178. If an aircraft suffers decompression what happens to the indications on a cabin VSI, cabin altimeter and differential pressure gauge?

a. VSI up, altimeter up, differential pressure gauge down
b. VSI, altimeter, differential pressure gauge all unchanged
c. VSI down, altimeter up, differential pressure gauge down
d. VSI up, altimeter down, differential pressure gauge down

179. **What happens if a gaseous oxygen cylinder is over-pressurized?**

a. A pressure relief valve vents the excess pressure into the atmosphere
b. A bursting disc vents the complete contents of the cylinder(s) to atmosphere
c. A pressure regulator will prevent the excess pressure damaging the system
d. A pressure relief valve vents the excess pressure into the fuselage

180. **If a fuel sample appears cloudy, this is:**

a. an indication of air in the fuel
b. normal
c. due to the addition of FSII
d. an indication of water in the fuel

181. **Fuel tanks accumulate moisture, the most practical way to limit this in an aircraft flown daily is to:**

a. secure the filler cap tightly and plug the drains
b. drain the tank at the end of each day
c. fill the tank after each flight
d. drain the water before flight

182. **How much fuel can be jettisoned?**

a. A specific amount
b. The captain decides
c. All
d. A specified amount must remain

183. **The DLL of a transport aircraft is:**

a. 1.5g
b. 2.5g
c. 3.4g
d. 3.75g

184. **A current limiter fuse:**

a. will rupture below fault conditions
b. has a high melting point so carrying a considerable current overload before rupturing
c. is not used in TRU protection
d. has a low melting point so will rupture quickly if a current overload occurs

185. **What type of electrical motor is used as a starter motor?**

a. Series
b. Shunt
c. Compound
d. Induction

186. **The power for LP fuel pumps is:**

a. 28 V DC
b. 28 V AC
c. 115 V DC
d. 200 V AC

187. What is a relay?

a. Solenoid valve
b. Magnetic switch
c. Converts electrical energy into heat energy
d. Used in starter motor circuit

188. An aircraft is in straight and level flight at a constant cabin altitude when the crew notice the rate of climb indicator reads –200 ft/min. What will be the sequence of events?

a. Crew should begin a climb to regain cabin altitude
b. Cabin altitude will increase to outside atmospheric pressure
c. Cabin altitude will descend to, and continue beyond normal max. diff., at which point the safety valves will open
d. Cabin altitude will increase to, and continue beyond normal max. diff., at which point the safety valves will open

189. What is the frequency band for ADF?

a. Hectometric and kilometric
b. Metric
c. Centimetric
d. Decimetric

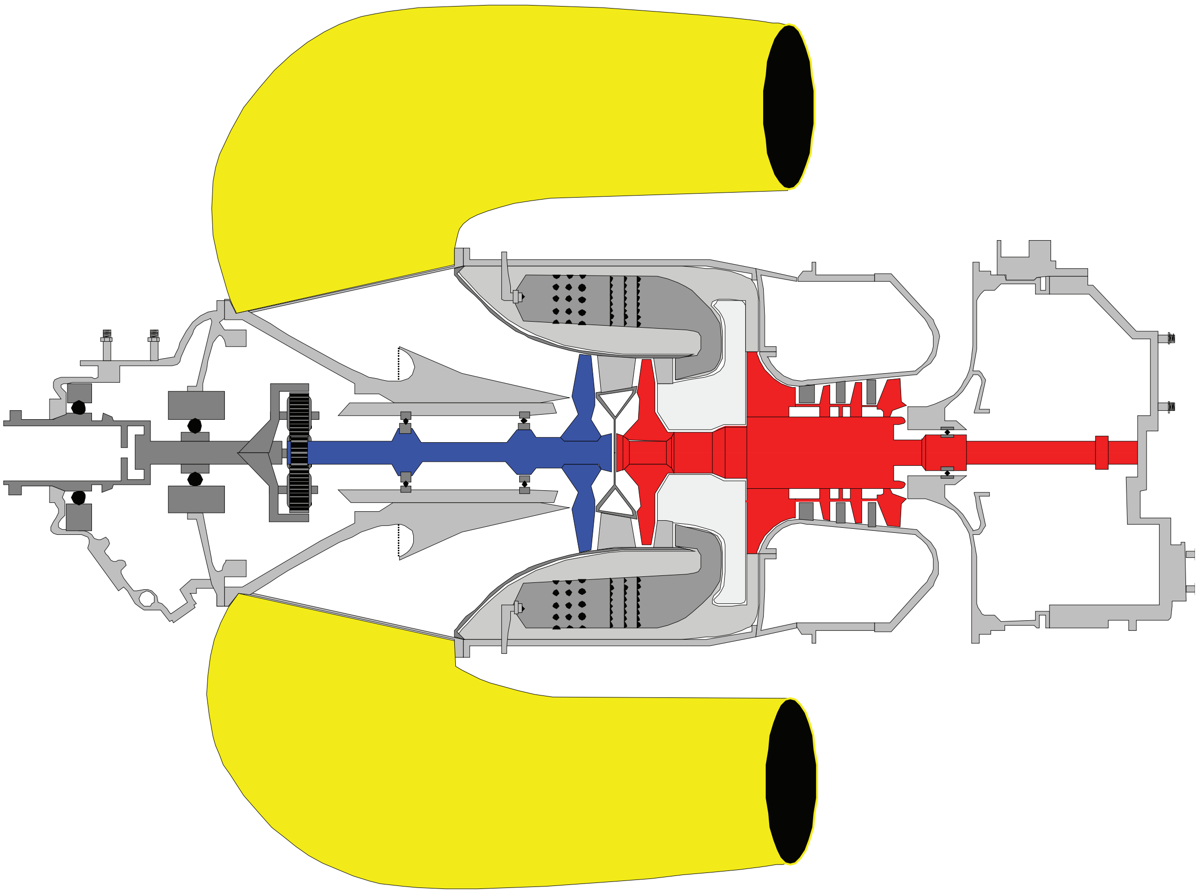


Illustration for Question 149, page 424

Answers to Systems Revision Questions

1	2	3	4	5	6	7	8	9	10	11	12
d	a	c	b	a	b	d	c	b	d	c	b
13	14	15	16	17	18	19	20	21	22	23	24
d	d	c	b	a	d	b	a	c	a	b	c
25	26	27	28	29	30	31	32	33	34	35	36
c	d	b	a	c	d	d	c	d	c	a	c
37	38	39	40	41	42	43	44	45	46	47	48
b	b	d	a	c	a	b	d	d	b	a	c
49	50	51	52	53	54	55	56	57	58	59	60
b	b	d	c	a	d	d	a	b	a	d	d
61	62	63	64	65	66	67	68	69	70	71	72
c	b	d	c	c	b	a	a	c	c	d	c
73	74	75	76	77	78	79	80	81	82	83	84
b	c	a	d	d	b	c	c	b	a	d	d
85	86	87	88	89	90	91	92	93	94	95	96
c	a	b	c	a	d	b	b	c	a	c	b
97	98	99	100	101	102	103	104	105	106	107	108
a	d	b	c	c	b	d	a	b	a	c	b
109	110	111	112	113	114	115	116	117	118	119	120
a	c	c	d	b	d	c	c	d	c	a	b
121	122	123	124	125	126	127	128	129	130	131	132
d	d	a	b	a	c	d	c	a	b	d	c
133	134	135	136	137	138	139	140	141	142	143	144
a	b	c	d	b	c	d	c	d	c	d	b
145	146	147	148	149	150	151	152	153	154	155	156
c	c	d	b	c	b	c	d	d	d	a	b
157	158	159	160	161	162	163	164	165	166	167	168
c	d	c	b	c	b	b	c	b	b	a	d
169	170	171	172	173	174	175	176	177	178	179	180
d	a	b	d	d	b	c	c	d	a	b	d
181	182	183	184	185	186	187	188	189			
c	d	b	b	a	d	b	c	a			

Practice Systems Examination Paper

1. With reference to stringers they:

a. integrate the strains due to pressurization to which the skin is subjected and convert them into a tensile stress
b. provide sound and thermal insulation
c. perform no structural role
d. withstand shear stresses

2. How can wing bending moments be reduced in flight?

a. By using aileron up float and keeping the centre section fuel tanks full for as long as possible
b. By having tail mounted engines and using aileron down float
c. Using aileron up float and using the fuel in the wing tanks last
d. By having wing mounted engines and using the wing fuel tanks first

3. Kreuger flaps are positioned on the:

a. trailing edge
b. leading edge
c. outboard leading edge
d. inboard leading edge

4. The purpose of inboard ailerons is to reduce wing:

a. bending at high speed
b. twisting at high speed
c. bending at low speed
d. twisting at low speed

5. The 'torsion box' of a modern aircraft wing structure consists of:

a. spars, skin, frames and stringers
b. spars, skin, frames and ribs
c. spars, skin, longerons and ribs
d. spars, skin, stringers and ribs

6. Which is the correct statement regarding a large aircraft fitted with both inboard and outboard ailerons?

a. The outboard ailerons are used only when the landing gear is selected down
b. The outboard ailerons are used only when the landing gear is retracted
c. Only the inboard ailerons are used when the flaps are retracted
d. Only the inboard ailerons are used when the flaps are extended

7. What is the effect of heating flight deck windows?

a. To demist the interior of the window if normal demist does not function correctly
b. To protect the windows against bird strike
c. To protect the windows against ice formation
d. To protect the windows against bird strike and ice formation

8. **Differential ailerons work by:**

   a. increasing lift on down going wing and decreasing lift on up going wing
   b. increasing drag on up going wing and decreasing drag on down going wing
   c. equalizing the drag on up going and down going wings
   d. equalizing the lift on up going and down going wings

9. **An artificial feel system is:**

   a. connected in series with an irreversible servo system
   b. connected in parallel with an irreversible servo system
   c. connected in parallel with a reversible servo system
   d. connected in series with a reversible servo system

10. **Why are two longitudinal trim switches fitted to the control column?**

    a. There are two trim motors
    b. Fast trimming at low altitude and a slower rate at higher altitudes
    c. As a safety precaution to reduce the possibility of trim runaway
    d. To prevent both pilots operating the trim at the same time

11. **On a modern jet transport the hydraulic reservoirs are normally pressurized:**

    a. by a separate helium gas supply
    b. by air from the air conditioning system
    c. by engine bleed air
    d. in flight only

12. **A device in a hydraulic system which acts in the same way as a diode in an electrical circuit is a:**

    a. restrictor valve
    b. sequence valve
    c. fuse
    d. one way check valve

13. **A ram air turbine may be used to provide emergency hydraulic power for:**

    a. landing gear extension
    b. flight controls
    c. nose wheel steering
    d. leading edge flap extension only

14. **An under inflated tyre on a dry runway:**

    a. decreases viscous hydroplaning speed
    b. causes the tyre temperature to fall
    c. increases wear on the shoulder
    d. increases wear on the crown

15. **If an aircraft suffers decompression what happens to the indications on a cabin VSI, cabin altimeter and differential pressure gauge?**

    a. VSI up, altimeter up, differential pressure gauge down
    b. VSI, altimeter, differential pressure gauge all unchanged
    c. VSI down, altimeter up, differential pressure gauge down
    d. VSI up, altimeter down, differential pressure gauge down

16. **An aircraft is in straight and level flight at a constant cabin altitude when the crew notice the rate of climb indicator reads –200 ft/min. What will be the sequence of events?**

    a. Crew should begin a climb to regain cabin altitude
    b. Cabin altitude will increase to outside atmospheric pressure
    c. Cabin altitude will descend to, and continue beyond normal max. diff., at which point the safety valves will open
    d. Cabin altitude will increase to, and continue beyond normal max. diff., at which point the safety valves will open

17. **What is the purpose of the ground cooling fan in a bootstrap air cycle conditioning system?**

    a. To draw cooling air over the turbine
    b. To draw cooling air over the heat exchangers
    c. To blow air onto the compressor
    d. To re-circulate air through the mixing manifold

18. **If the outflow valves failed closed in flight the effect would be:**

    a. to damage the aircraft skin
    b. to increase cabin pressure to max differential
    c. to increase cabin altitude
    d. to shut down the air conditioning system

19. **Modern transport aircraft fuel booster pumps are generally:**

    a. centrifugal and powered by DC induction motors
    b. centrifugal and powered by AC induction motors
    c. spur gear and powered by DC induction motors
    d. spur gear and powered by AC induction motors

20. **Modern passenger aircraft fuel tanks are pressurized by:**

    a. low pressure bleed air
    b. low pressure inert gas system
    c. the air discharged by the air conditioning system
    d. ram air through the vent system

21. **Where are the fuel heaters fitted on jet aircraft?**

    a. In each tank
    b. On the engine
    c. They are not required
    d. Centre tank only

22. **The fuel cross feed system enables fuel to be:**

    a. supplied to the outboard engines from any outboard tank
    b. transferred from the centre tank to the wing tanks only
    c. supplied to any engine mounted on a wing from any tank within that wing
    d. supplied to any engine from any tank

23. The areas heated by a bleed air system on a modern jet passenger transport are:

a. leading edges of all aerofoil surfaces
b. leading edges of all aerofoil surfaces including flaps
c. leading edges of all aerofoil surfaces including slats (where fitted)
d. upper surfaces of the wings only

24. The principle upon which the vibrating probe (Rosemount) ice detector is based is:

a. inferential
b. accretion
c. ice removal
d. evaporation

25. Which one of the following ice protection systems can only be used as a de-icing system?

a. Mechanical
b. Electrical
c. Chemical
d. Thermal

26. Because of its function an AND gate is also referred to as an:

a. all or nothing gate
b. any or nothing gate
c. invert or not gate
d. either or gate

27. The stators of a three phase alternator are separated by:

a. 60 degrees
b. 90 degrees
c. 120 degrees
d. 180 degrees

28. If a CSDU overheat warning occurs, the:

a. CSDU can be disconnected and not used for the rest of the flight
b. pilot must throttle back the effected engine
c. CSDU can be disconnected and then re-connected when it has cooled down
d. CSDU must be disconnected and the alternator is controlled directly by the pilot

29. What is disconnected if the fire handle is pulled in an aircraft with an AC generator system?

a. Generator control relay (exciter control relay) and GCB
b. GCB
c. BTB
d. Generator control relay (exciter control relay) and BTB

30. **A generator that produces 400 Hz at 6000 rpm has how many pole pairs?**

a. 12
b. 8
c. 6
d. 4

31. **If a 12 volt, 6 cell battery has one dead cell:**

a. it cannot be used
b. it can be used but the output voltage is reduced by 1/12
c. it can be used but the output voltage and capacity are reduced by 1/12
d. it can be used but the output capacity is reduced by 1/12

32. **Incorrect bonding of the aircraft structure could cause:**

a. corrosion at skin joints
b. circuit breaker trips
c. static on the radio
d. VOR interference

33. **'Earth Return' system means that:**

a. both battery and earth terminals are connected to the voltage regulators' shunt field
b. battery positive and generator negative terminals are connected to a/c structure
c. battery negative terminal is connected to the generator negative terminal with low resistance cable
d. battery and generator negative terminals are connected to the aircraft structure

34. **The frequency of an AC generator is dependent upon:**

a. poles only
b. poles and rpm
c. rpm only
d. load

35. **In an aircraft which uses DC as the primary source of power, AC for the instruments may be obtained from:**

a. a rectifier
b. the AC busbar
c. a TRU
d. an inverter

36. **The wavelength of a VOR is:**

a. metric
b. decimetric
c. hectometric
d. centimetric

37. **What is the wavelength that corresponds to the frequency 121.95 MHz?**

a. 246 m
b. 2.46 cm
c. 2.46 m
d. 24.6 m

38. **Skip distance is longest by .... and with a .... frequency.**

a.	day	low
b.	day	high
c.	night	low
d.	night	high

39. **The skip zone of an HF transmission will increase with:**

a. an increase in frequency and an increase in height of the reflective (refractive) layer
b. an increase in frequency and a decrease in height of the reflective (refractive) layer
c. an decrease in frequency and an increase in height of the reflective (refractive) layer
d. an decrease in frequency and a decrease in height of the reflective (refractive) layer

40. **How are the loads on an aircraft busbar connected?**

a. In parallel so that the current reduces through the busbar as loads are switched off
b. In parallel so that the voltage reduces through the busbar as loads are switched off
c. In series so that the current reduces through the busbar as loads are switched off
d. In series so that the voltage reduces through the busbar as loads are switched off

41. **Hot or vital busbars are:**

a. heated by bleed air
b. connected directly to the battery
c. connected directly to the DC generator
d. connected directly to the AC generator

42. **A static inverter is a:**

a. transistorized unit that converts AC to DC
b. transistorized unit that converts DC to AC
c. fixed unit that changes DC voltages
d. fixed unit that changes AC voltages

43. **If AC generators are connected in parallel the reactive loads are balanced by adjusting the:**

a. frequency
b. torque of the CSDU
c. energizing current
d. voltage

44. The voltage regulator of a DC generator is connected in:

a. series with the armature and parallel with the shunt field
b. parallel with the armature and parallel with the shunt field
c. series with the armature and series with the shunt field
d. parallel with the armature and series with the shunt field

45. If the frequency of a series capacitive circuit increases, what happens to the current?

a. It increases
b. It decreases
c. It stays the same
d. It increases or decreases

46. Which is the correct statement(s) with regard to flight crew oxygen requirements for a pressurized aircraft:

1. at all times when the cabin pressure altitude exceeds 13 000 ft
2. at all times when the cabin pressure altitude is between 10 000 ft and 13 000 ft except for the first 30 mins
3. in no case less than 30 mins if certificated below 25 000 ft
4. in no case less than 2 hours if certificated above 25 000 ft

a. 1, 2, 3 and 4
b. 1 and 2
c. 1, 2 and 3
d. 2 and 3

47. The advantages of a chemical oxygen generator system are:

1. it is a self-contained system
2. it can be filled from outside the pressure hull
3. the flow of oxygen can be regulated
4. it can be turned off
5. it is relatively light

a. 1 and 5
b. 1, 2 and 4
c. 2 and 4
d. 1, 2, 3, 4 and 5

48. An aircraft operating at FL350 must have sufficient supplementary oxygen available for 100% of passengers for a descent from its maximum certificated operating altitude to allow a descent to:

a. 13 000 ft in 30 minutes
b. 15 000 ft in 4 minutes
c. 15 000 ft in 10 minutes
d. 10 000 ft in 4 minutes

49. The passenger oxygen drop down mask stowage doors are released:

a. barometrically operated latch
b. electrically for chemical generator systems and pneumatically for gaseous systems
c. electrically for gaseous systems and pneumatically for chemical generator systems
d. by the cabin crew

50. The fire extinguisher system for an engine is activated:

a. automatically immediately a fire is sensed
b. automatically once the engine has been shut down
c. by the pilot immediately a fire is detected
d. by the pilot once the engine has been shut down

51. The flight deck warning of an engine fire is:

a. individual warning lights and bells
b. a common light and common aural warning
c. aural warning only
d. individual warning lights and a common aural warning

52. High cylinder head temperatures on a piston engine are associated with:

a. mass ratio of 1:15
b. cruise mixture setting
c. a weak mixture
d. a rich mixture

53. In a gas turbine the maximum gas temperature is reached:

a. in the combustion chamber
b. at the turbine exit
c. across the turbine
d. in the cooling air around the turbine

54. When TAS increases the pitch angle of a constant speed propeller:

a. increases
b. decreases
c. remains constant
d. decreases and then returns to its original angle

55. From the list select the conditions for highest engine performance:

1. low temperature
2. low humidity
3. high pressure
4. high temperature
5. high humidity
6. low pressure

a. 1, 2 and 6
b. 1, 3 and 5
c. 3, 4 and 5
d. 1, 2 and 3

56. A torque meter is situated:

a. between the engine and propeller
b. on the auxiliary gearbox
c. between the turbine and the gearbox
d. in the spinner housing

57. A reverse thrust door warning light is illuminated when:

a. the reverser doors are unlocked
b. the thrust levers are lifted beyond ground idle
c. the reverse thrust mechanism is not operating correctly
d. asymmetric reverse thrust has been selected

58. Adjusting the mixture of piston engines as aircraft altitude increases is necessary to:

a. increase fuel flow to compensate for decreasing air density
b. decrease fuel flow to compensate for decreasing air density
c. increase fuel flow to compensate for increasing air density
d. decrease fuel flow to compensate for increasing air density

59. The power output of a piston engine can be calculated by multiplying:

a. force by distance
b. work by velocity
c. pressure by moment arm
d. torque by rpm

60. When high pressure bleed valves open they:

a. reduce the EPR
b. increase the fuel flow
c. reduce the EGT
d. increase the thrust

61. The fan stage of a ducted fan engine is driven by the:

a. LP turbine
b. IP turbine
c. HP turbine
d. HP compressor through reduction gearing

62. In a four stroke engine, ignition occurs:

a. before TDC every 2nd rotation of the crankshaft
b. at TDC every 2nd rotation of the crankshaft
c. after TDC every 2nd rotation of the crankshaft
d. before TDC every rotation of the crankshaft

63. A fixed pitch propeller blade has wash-out from root to tip in order to:

a. keep the local angle of attack constant along the blade length
b. keep the pitch angle constant along the blade length
c. keep the local angle of attack at its optimum value along the blade length
d. decrease the blade tangential speed from root to tip

64. The alpha range of a variable pitch propeller is between:

a. feather and flight fine pitch stop
b. feather and ground fine pitch stop
c. flight fine pitch stop and reverse stop
d. ground fine pitch stop and reverse stop

65. With the CSU governor in the underspeed condition, oil will be directed to:

a. increase the blade angle
b. decrease the blade angle
c. decrease the rpm
d. open the throttle valve

66. In a fan jet engine the bypass ratio is:

a. internal mass airflow divided by external mass airflow
b. external mass airflow divided by internal mass airflow
c. internal mass airflow divided by mass fuel flow
d. mass fuel flow divided by internal mass airflow

67. In a normally aspirated piston engine carburettor icing can occur:

a. between 0°C and –10°C
b. at more than +10°C
c. only at less than +10°C if there is visible moisture
d. above 5000 ft only

68. At what speed does the LP compressor run?

a. The speed of the LP turbine
b. The speed of the IP turbine
c. The speed of the HP turbine
d. Constant speed

69. The magnetos are switched off and the engine continues to run normally. The cause of this fault is:

a. a wire from the magneto coming into contact with aircraft metal skin
b. hotspots in the cylinder
c. carbon fouling of the spark plugs
d. grounding wire from the magneto broken

70. The volume of the scavenge pump(s) in an engine lubrication system is greater than that of the pressure pump(s) in order to:

a. prevent cavitation of the oil system feedlines
b. ensure heat is dissipated more efficiently
c. compensate for thermal expansion of the lubricating fluid
d. ensure that the engine sump remains dry

71. Variable inlet guide vanes are fitted to gas turbine engines to:

a. increase the mass flow at high speeds
b. prevent a compressor stall at low engine speed
c. prevent a compressor stall at high engine speeds
d. decelerate the flow into the compressor

72. The theoretically correct air to fuel ratio for efficient combustion in a gas turbine under constant speed conditions is:

a. 5:1
b. 15:1
c. 25:1
d. 40:1

73. A gas turbine engine power change is achieved by adjusting the amount of:

a. fuel supplied and the amount of air entering the compressor
b. fuel supplied
c. air supplied
d. fuel supplied and the amount of air entering the turbine

74. What happens to the pressure and velocity of the gas stream from root to tip across the nozzle guide vanes?

a. Both remain constant
b. Both increase
c. Velocity increases, pressure decreases
d. Velocity decreases, pressure increases

75. What is a crank assembly?

a. Crankcase, crankshaft, pistons and connecting rods
b. Crankshaft, pistons and connecting rods
c. Propeller, crankshaft and connecting rods
d. Camshaft, pistons and connecting rods

76. The effect of climbing at rated rpm but less than rated boost is to:

a. increase full throttle height
b. reduce full throttle height
c. produce no change to the full throttle height
d. reduce the time to full throttle height

Answers to Practice Systems Examination Paper

1	2	3	4	5	6	7	8	9	10	11	12
a	c	d	b	d	c	d	c	b	c	c	d

13	14	15	16	17	18	19	20	21	22	23	24
b	c	a	c	b	b	b	d	b	d	c	b

25	26	27	28	29	30	31	32	33	34	35	36
a	a	c	a	a	d	a	c	d	b	d	a

37	38	39	40	41	42	43	44	45	46	47	48
c	d	a	a	b	b	d	d	a	a	a	c

49	50	51	52	53	54	55	56	57	58	59	60
b	d	d	c	a	a	d	a	a	b	d	a

61	62	63	64	65	66	67	68	69	70	71	72
a	a	a	a	b	b	b	a	d	d	b	b

73	74	75	76
b	d	b	a

Explanations to Practice Systems Examination Paper

9. Book 2

Feel system shown in parallel. Fully powered controls are irreversible servo systems.

This question seems to be getting at the difference in the value of the dielectric i.e. Fuel 2.1, water 80 something, so if the tank was full of water the value of capacitance would be so high that the gauge would read full scale.

12. Book 2

See also electrical system book 3.

15. Book 2

As cabin pressure rapidly falls, cabin altitude increases, cabin vertical speed indicates up and differential pressure falls.

16. Book 2

As the cabin pressure builds up due to perhaps the outflow valves closing un-commanded, the differential pressure will increase, the cabin alt will show a descent, and the differential will increase until max diff is achieved when the safety-valves will open to prevent structural damage.

30. Book 3

Calculations as follows:

$$\frac{\text{No. of poles}}{2} \times \frac{\text{rpm}}{60} = \text{Freq}$$

$$\frac{\text{No. of poles}}{2} \times \frac{6000}{60} = 400$$

$$\frac{\text{No. of poles}}{2} \times 100 = 400$$

$$\text{No. of Poles} \times 100 = 400 \times 2$$

$$\text{No. of Poles} \times 100 = 800$$

$$\text{No. of Poles} = \frac{800}{100} = 8 \text{ Poles}$$

$$\text{Answer is} = \frac{8}{2} = 4 \text{ Pole Pairs}$$

34. Book 3 See calculation for Q30

45. Book 3

Calculation as follows:

$$Xc = \frac{1}{2\pi\ fc}$$

$$Xc\ (\Omega) = \frac{1}{2\pi\ fc}$$

Therefore if frequency increases, it follows:

$Xc\ (\Omega) = \dfrac{1}{2\pi\ fc}$ where frequency increases:

Xc (Ω) must decrease (Reactance)

Take the value of reactance, and, using Ohms' law to find the current (I), it follows:

$I = \dfrac{V}{R}$ (With R reducing)

I (Current) must increase.

Therefore if the Frequency increases in a capacitive circuit, the Current (I), must Increase.

55. Highest engine performance is produced under highest density conditions i.e. those of lowest temperature, low humidity and highest pressure. There are many references to this in:

a. Powerplant

b. Principles of flight

c. Aircraft Performance

59. Book 4 From the Power formula P×L×A×N×E Force = Press × Area (P × A)

Torque/Work = Force x Distance (P×L×A)

Power, the Rate of doing Work = (P×L×A×E) where 'E' is effective rpm

63. Book 4 Wash-out (or blade-twist) is the name given to the reduction of blade angle from root to tip.

66. Book 4 It is the air mass passing through the bypass duct (external mass flow) divided by the air mass passing through the core (internal mass flow) of the engine.

Chapter

29

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