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DOCUMENT TITLE

GAS TURBINE ENGINES (CASA ATPL)

CHAPTER 3 – ENGINE CONSTRUCTION PART 1

Version 2.0
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INTRODUCTION

Gas Turbine Engines are made up of five main sub-assemblies, they are;

1. Air Intake,
2. Compressor Assembly,
3. Combustion Section,
4. Turbine Assembly, and
5. Exhaust System.

AIR INTAKES

An air intake must be designed in such a way that it allows the most efficient delivery of air to the compressor, with the minimum loss of energy. To achieve this, the intake must be designed to incorporate the follow features;

- Be a Divergent Duct to deliver the air to the compressor at the highest static pressure possible. This enhances ram recovery and minimizes losses of pressure with changes in aircraft attitude. Refer to Figure 3-1.
- Ensure airflow is as Smooth as possible, and
- Ensure the airflow is Subsonic.

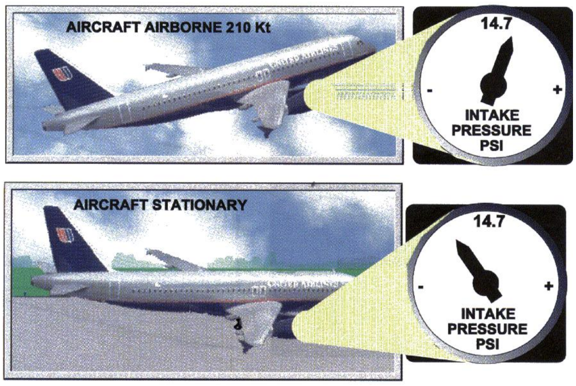

Figure 3-1 Ram Recovery

As axial flow compressor blades are of an aerofoil design, the airflow must be Subsonic and Free of Turbulence. This is to prevent the compressor from Stalling and Surging.

Aircraft that fly at supersonic speeds need to generate a shock wave in the intake. Airflow behind the shock wave is subsonic. Supersonic flight is not covered in this Text Book.

By looking at the design of the intakes on modern subsonic jet aircraft it can be seen that the most favoured design is a large circular aperture, with a relatively short distance between the intake and the first compressor stage. This allows the most efficient use of ram air in flight, and also with the minimum loss of ram air pressure with change in aircraft attitude. Refer to Figure 3-2.

Turbo-propeller engines have a smaller ducting behind the propeller. A combination of propeller and ram air is delivered to the compressor.

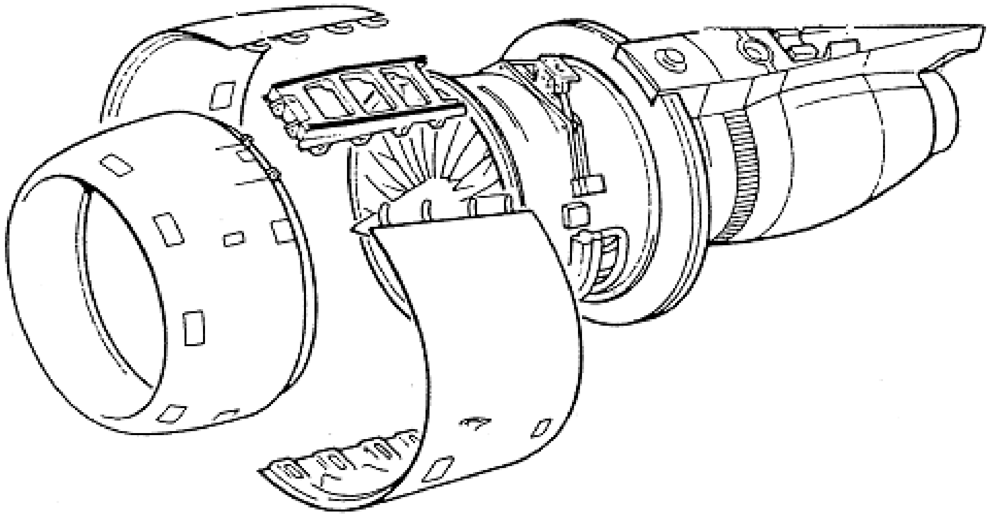

Figure 3-2 Engine Intake

OPERATIONAL PROBLEMS

Take Off

Aircraft with long ‘S’ type ducts, (B727 and Lockheed TriStar) are prone to Stall or Surge during high cross wind take-offs. Relative airflow displaced by the cross wind causes turbulence in the intake. Under some conditions the aircraft may have to be accelerated on the other engines before number two (center) thrust lever is advanced.

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. The intake should be inspected for damage prior to flight.

Icing

Inlet icing may occur typically where the ambient temperature is below + 10°C, with visible moisture. If this condition exists the pilot should activate the engine anti-icing system. It is a requirement that continuous ignition is activated with selection of engine anti-ice.

Foreign Object Damage (FOD)

Damage to compressor blades is invariably caused by ingestion of foreign objects while the aircraft is on or close to the ground, particularly on wing mounted engines. It is no coincidence that aft body mounted engines suffers much less with FOD.

In Flight Turbulence

Heavy in flight turbulence can seriously disrupt the airflow to the engines. Using the flight manual turbulence penetration speed and the correct RPM/EPR will reduce the possibility of compressor malfunction. It may also be a requirement to activate the continuous ignition to reduce the probability of engine ’flame out’.

Secondary Air Intake Doors

Secondary air inlet doors allow a supplementary airflow to reach the compressor face during high power operation when the aircraft is stationary or at low airspeeds with high angles of attack. These doors were fitted to early model turbojets such as the P&W JT3D. Refer to Figure 3-3.

Figure 3-3 Secondary Inlet Doors

COMPRESSOR ASSEMBLY

Gas turbine compressors fall into three main categories.

- Centrifugal Flow Compressors,
- Axial flow Compressors, and
- Compound Compressors.

CENTRIFUGAL FLOW COMPRESSORS

The construction and operating principle of a centrifugal flow compressor bears a marked similarity to the supercharger previously described in the Piston Engines text. An impeller is used to compress the air for delivery to the combustion chamber. Various types of impeller designs are used in different engines, the simplest type being a single entry. The impeller may be double entry, or two single entry impellers may be used in series. Refer Figure 3-4. The impeller blades are constructed to form divergent passages away from the hub. At the hub, the blades are twisted slightly in the direction of rotation of the compressor. This is to assist the incoming air flow from the intake, into the convergent impeller vanes efficiently. The twisted part of the blade is sometimes referred to as a rotating guide vane. The turbine rotates the impeller at high speed with the effect that ambient air (ram air if in flight) is drawn into the centre of the impeller.

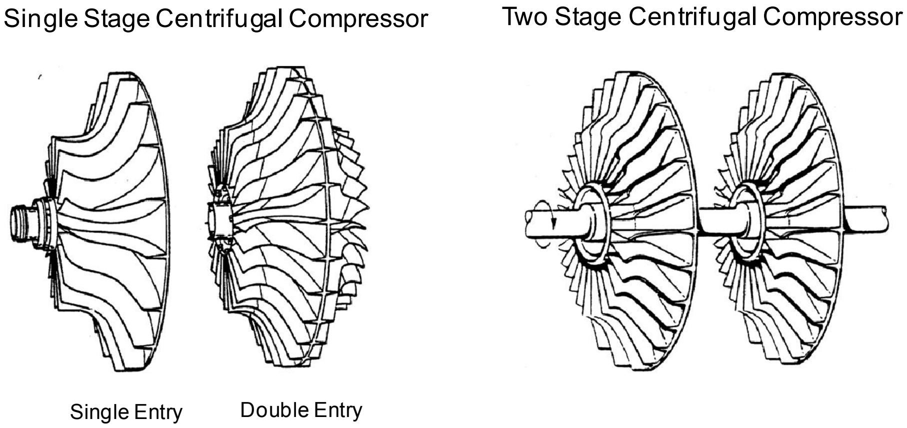

Figure 3-4 Centrifugal Compressors

The centrifugal effect causes the air to move outwards to the impeller blade tips, at the same time accelerating and increasing in pressure. The airflow leaving the impeller vanes flows into a diffuser. The diffuser may either be machined into the compressor casing, or a separate unit downstream from the compressor. The diffuser comprises of a number of vanes which are set in line with the outgoing airflow from the compressor. Each vane is a small divergent duct, and its function is to convert the heat energy caused by the compression of air, into pressure energy for delivery to the combustion chamber. The clearance between the impeller tips and the mouth of the diffuser vanes is constructed to be sufficiently close preventing loss of pressure due to air leakage, but sufficiently spaced to prevent any turbulent build up in the airflow. Refer to Figures 3-5 and 3-6.

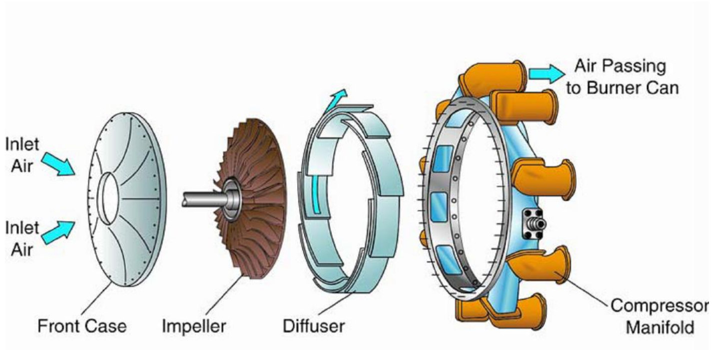

Figure 3-5 Centrifugal Compressor Components

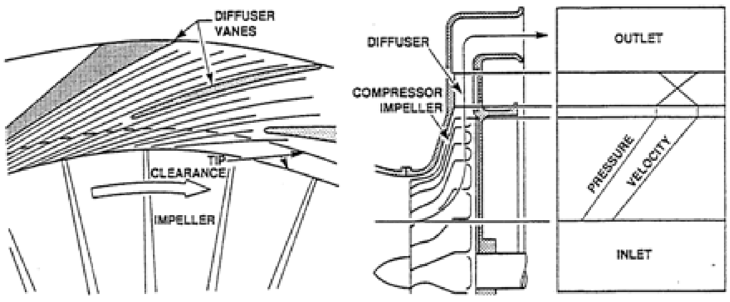

Figure 3-6 Centrifugal Airflow Features

Centrifugal Compressor Advantages

As the impeller is not of an aerofoil section, a Centrifugal Flow Engine is less prone to Stall and Surge, compared to an axial flow compressor. As it constructed out of one piece of steel it is Cheaper and More Robust. It also has a higher compression ratio per stage, which is used in Compound Compressor Engines to make them more compact.

Centrifugal Compressor Disadvantage

The main disadvantage is the lower overall compression ratio and therefore lower thermal efficiency. The pressure rise across the impeller is up to 6:1. When the diffuser is included, the total compression ratio is 15:1. This compares with up to 45:1 for modern Axial Flow Compressors.

AXIAL FLOW COMPRESSORS

As mentioned in the previous chapter, an axial flow compressor is made up of a series of rotors, stators and spools. One row of rotors, or rotating blades (which are attached to a compressor disc) and one row of stators, or stationary blades comprise one stage. A number of stages make up one spool, driven by a turbine. Refer to Figure 3-7.

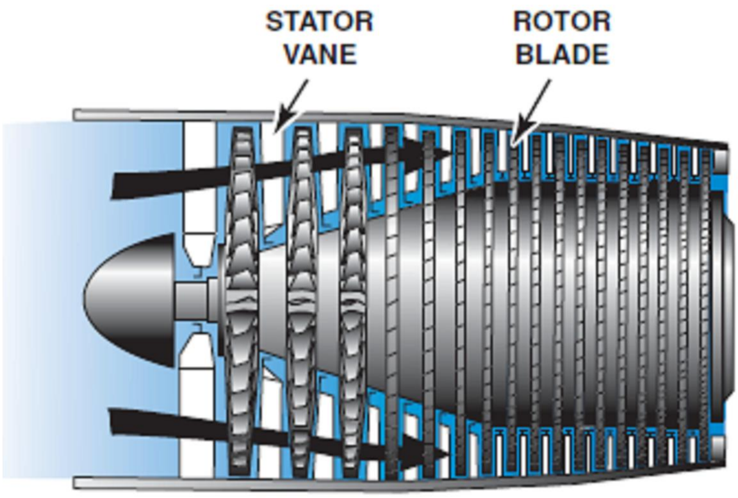

Figure 3-7 Single Spool Axial Flow Compressor

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 the centrifugal compressor,(both are divergent ducts). The pressure rise across each stage is quite small, the ratio being about 1.1 or 1.2:1. This means that in the first stage the pressure rise is only quite small, so to gain the compression ratios demanded by modern engines many stages are used. Refer Figure 3-8. The latest P&W, GE and RR Trent engines have compression ratios of 45:1.

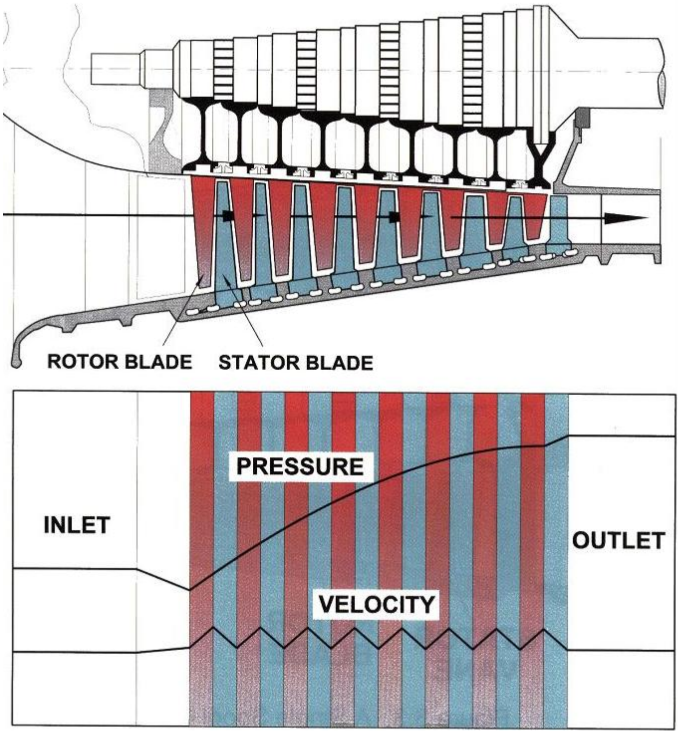

Figure 3-8 Compressor Pressure and Velocity Changes

Maintaining Axial Velocity

The space between the compressor outer casings is called the air annulus. To maintain the axial velocity of the air as it is compressed into an ever smaller volume, the air annulus must be reduced.

This gradual convergence is achieved by either tapering the compressor casing or the rotor drum or in some cases a combination of both. Refer Figure 3-9.

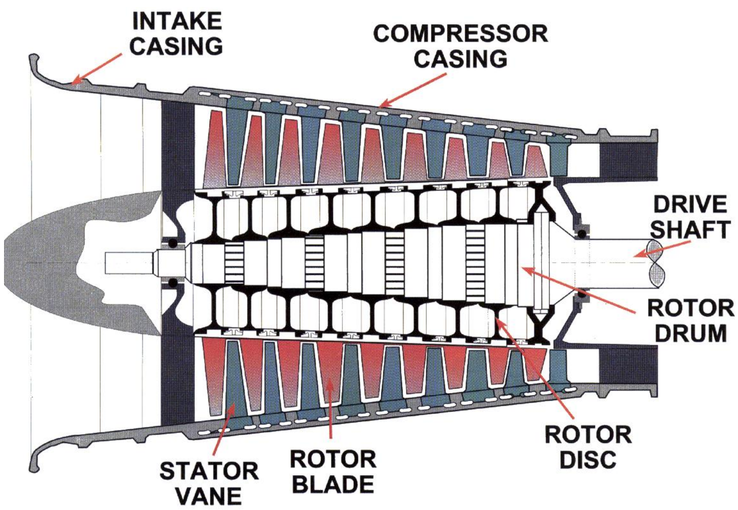

Figure 3-9 Maintaining Axial Velocity

Compressor Blade Attachment

The compressor blades are not rigidly attached to the compressor drum or disks, but are loose on their mountings so that they are free to rock. When the engine is running, centrifugal force holds the blades in the correct position. Allowing the blades to be loose prevents stresses at the root. This explains the clicking noise coming from the engine whilst it is windmilling on the ground. A common method of attaching blades is the dovetail method shown on Figure 3-10.

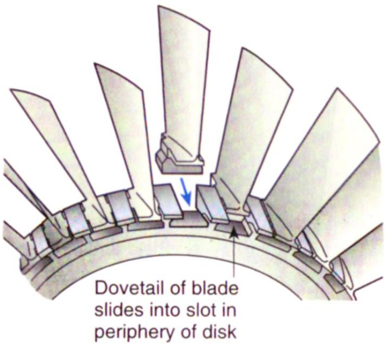

Figure 3-10 Blade Attachment

Compressor Blade Design

Since the velocity of the rotor blade varies from root to tip it is necessary to twist them to ensure that the airflow maintains a uniform axial velocity along the length of the blade to give a pressure gradient along their length. Refer to Figure 3-11.

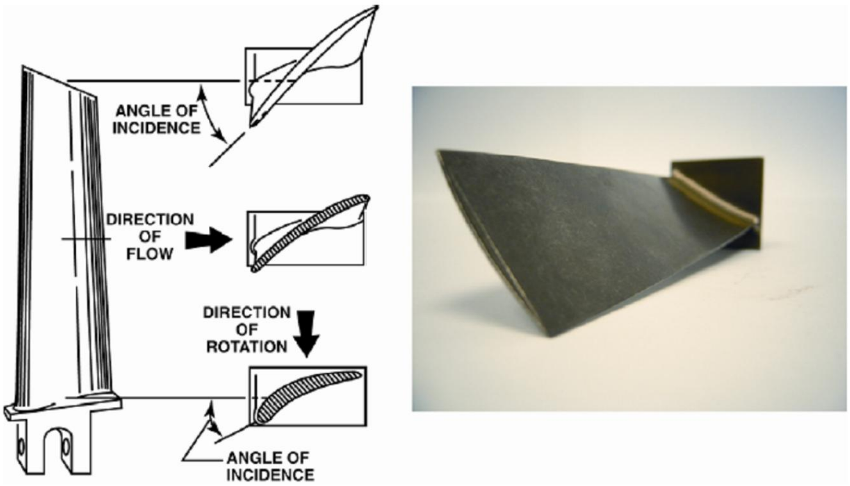

Figure 3-11 Blade Design

Axial Flow Compressor Advantages

Axial Flow Compressors are a highly efficient unit as they have a steady rise in pressure with a minimum energy loss. This <u>High Compression Ratio and a</u> much <u>Larger Mass Air Flow,</u> results in a much <u>Lower Thrust Specific Fuel Consumption (TSFC).</u> Refer Figures 3-12 and 3-13.

TSFC is defined as the quantity of fuel consumed in pounds per hour, divided by the thrust of the engine in pounds

Axial Flow Compressor Disadvantage

The main disadvantage is this type of compressor is more highly prone to Stall and Surge.

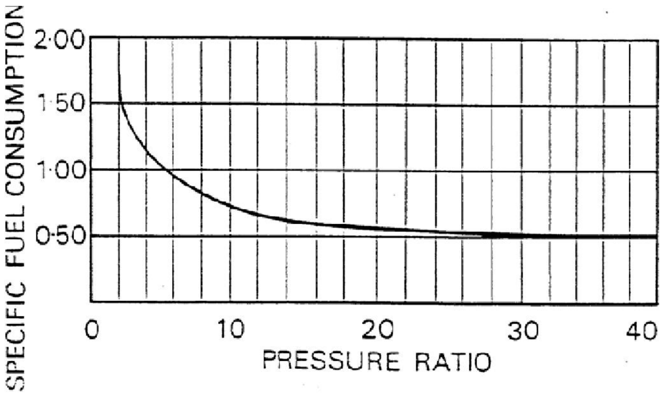

Figure 3-12 TSFC Vs Pressure Ratio

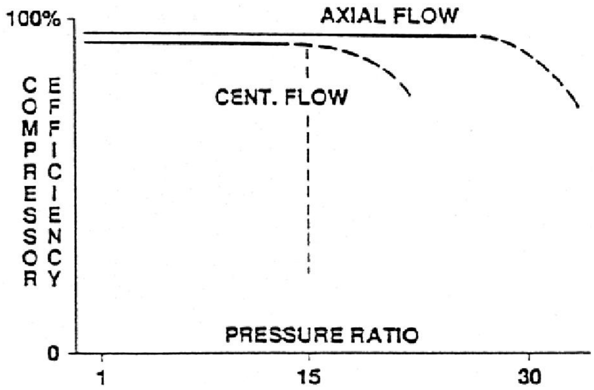

Figure 3-13 Compressor Efficiencies

Two Spool and Multi Spool Compressors

It soon became apparent that the higher pressure section of the compressor ran more efficiently at a higher RPM. The compressors were then split into a Low Pressure Spool (N_1) and a High Pressure Spool (N_2). This allowed both spools to run at their Ideal RPM, with an even Lower TSFC. Both spools are driven by their own turbines. Refer to Figure 3-14. Rolls Royce took this one step further and separated the Fan from the low pressure spool. The Fan, N_1, was separated from the low pressure (LP) spool, N_2 and the high pressure (HP) spool is N_3. All spools are driven by their own turbines. Refer to Figure 3-15

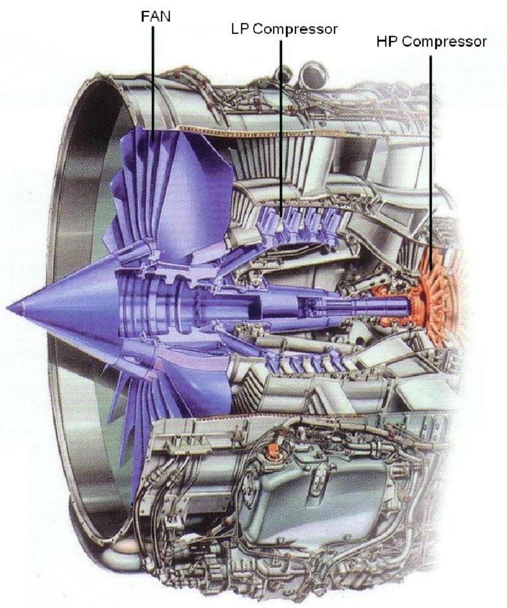

Figure 3-14 Two Spool Compressor

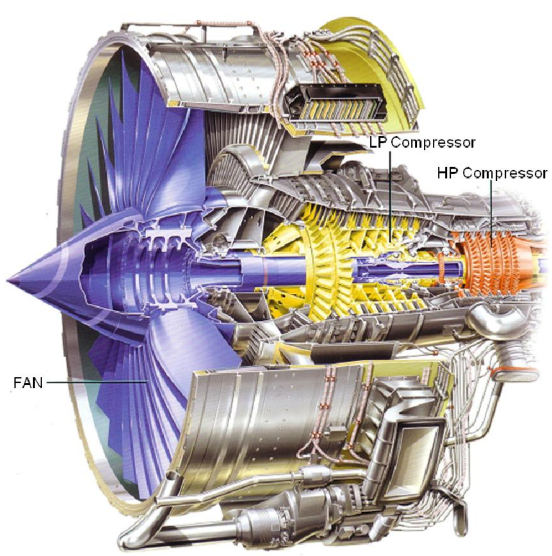

Figure 3-15 Three Spool Compressor

Low By-pass Turbofan Engines Twin spool compressors are used in the construction of Low By-Pass Engines. All intake air passes through the low pressure (LP) compressor which forms the first spool. The airflow then divides, with only part being directed into the high pressure (HP) compressor. The remaining air then By-Passes the HP compressor, the combustion chamber and the turbine, rejoining the cycle at the exhaust nozzle. The two different compressors are driven by different turbines, and are constructed to offer high engine pressure ratios. This is a Low By-Pass Ratio Engine, usually with a by-pass ratio of 2:1, (P&W JT8D in the B727). Refer to Figure 2-2 in Chapter 2.

High By-pass Turbofan Engines Development of the low by-pass engine soon produced the High By-Pass Turbofan Engine used by modern aircraft manufacturers. This engine uses two or three compressor spools driven by two or three separate turbines. The first compressor is a single stage low pressure fan of large diameter, referred to as N_1, through which all the intake air passes. About 20% of the air then passes through two more compressors, which are referred to as N_2 or intermediate stage, and N_3 or high pressure stage. Refer to Figure 2-3 in Chapter2.

The majority of the accelerated airflow expelled by the fan passes direct to the atmosphere by a large duct surrounding the compressor casing, complementing the total thrust. The by-pass ratio on current engines exceeds 8:1. This type of engine produces a large amount of thrust, with the operating benefits of a low TSFC and noise emission. Today, Thrust Specific Fuel Consumption (TSFC) is commonly used in reference to all types of jet engines; however, SFC more correctly refers to Turbo-propeller engines and compares Horsepower/Fuel consumption rather than Thrust/Fuel consumption.

COMPOUND COMPRESSORS

These compressors are usually found in engines with a free turbine, (Turbo Shaft Engines). The unit consists of an Axial Flow Low Pressure Compressor and a Centrifugal Flow High Pressure Compressor. Both compressors are driven by their respective turbines.

The high pressure centrifugal compressor has a much higher compression ratio per stage and has the air flow discharged radially, allowing for the use of a reverse flow combustion section. This configuration allows the engine to be shorter and more compact. As with most free turbine engines, compound compressor type engines do not produce thrust. Refer to Figure 3-16.

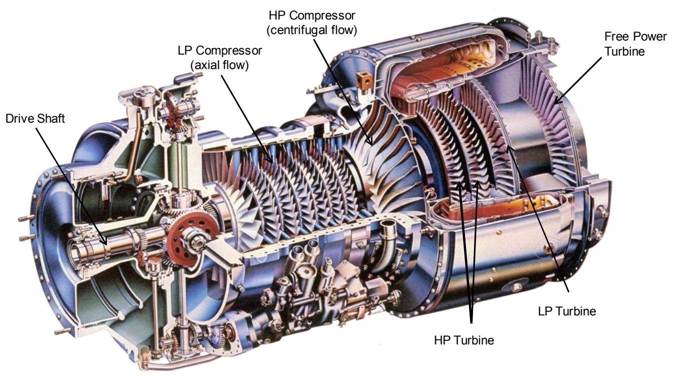

Figure 3-16 Compound Compressors

Fan Blade Design

The fan blades of older engines have been fitted mid-span supports called snubbers or clappers to overcome resonance vibration that can cause the fan blade to fail. Unfortunately, they are in the most aerodynamically efficient area of the blade. Modern engines have wide cord fan blades that have no snubbers or clappers. They employ a lightweight construction consisting of titanium with a honeycomb core. Refer to Figure 3-17.

Figure 3-17 Fan Blades

Effects of Blade Damage

It is important for the pilot to understand that the compressor is a finely balanced piece of equipment, and the efficiency of the whole engine is greatly affected by the way the compressor operates. If a blockage occurs in the inlet to the compressor, such as a bird, the airflow through the entire compressor will be disturbed, resulting in a different pressure and harmonic frequency being produced through the compressor. If this condition exists for too long, stress fatigue and cracking can occur with the eventual failure of the whole compressor.

If the compressor ingests matter such as cans, luggage labels or any other foreign objects, serious damage can occur. It is possible to blend the blades to remove small nicks and dents, but greater damage will result in an engine change. The effect of dust and especially sand needs to be clearly understood by pilots and flight in these conditions avoided as much as possible. Sand particles blast the blades and rapidly erode the leading edge of the compressor blades, dramatically reducing engine efficiency. Flying close to the sea or in salt spray has a similar effect on compressor and propeller blades, often leaving a thin layer of salt along the leading edges.

DIFFUSERS

The diffuser for a typical gas turbine engine is that portion of the air passage between the compressor and the combustion chamber or chambers. The diffuser is a divergent duct located between the rear face of the compressor and the forward face of the combustion chamber. The purpose of the diffuser is to reduce the velocity of the air and prepare it for entry into the combustion area. As the velocity of the air decreases, its static pressure increases in accordance with Bernoulli's principle. As the static pressure increases, the dynamic pressure decreases. The diffuser is the point of highest pressure within the engine. It is normal for the high pressure bleed point for the bleed air manifold to be tapped off from the diffuser. Refer to Figure 3-18.

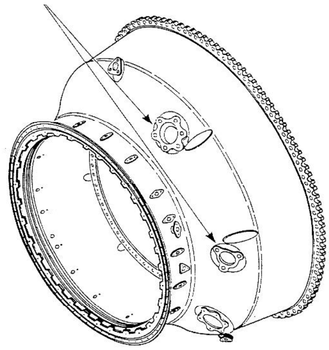

Figure 3-18 Diffuser

COMBUSTION SECTION

The purpose of the combustion chamber is to burn fuel to further increase the temperature of the air leaving the diffuser. It is important to remember that the gas turbine engine is a constant pressure engine, meaning that the combustion process occurs at a constant pressure. In accordance with the gas laws, if pressure remains constant, volume will increase proportionally with temperature, (Charles' Law).

Combustion Chamber Airflow

Figure 3-18.shows the air leaving the diffuser is further slowed down and then divided into Primary and Secondary airflows;

Primary Airflow accounts for 20% to 25% of the air leaving the diffuser. This air is then mixed with fuel at the Stoichometric Ratio, (optimum ratio) of 15:1. The ratio is 15 parts air to 1 part fuel. The mixture is then burnt. Refer to figure 3-20.

By being passed through the flare and the swirl vanes, the velocity of the air is reduced, and it also starts the recirculation which is required if the flame is not to be extinguished. Refer to Figure 3-18.

Secondary Airflow accounts for the remaining 75% to 80%.of the airflow and is used for cooling and dilution purposes. Cooling air is passed between the inner liner and the outer casing of the combustion chamber. It then enters the inner flame tube and dilutes the air to a temperature that the turbine can withstand.

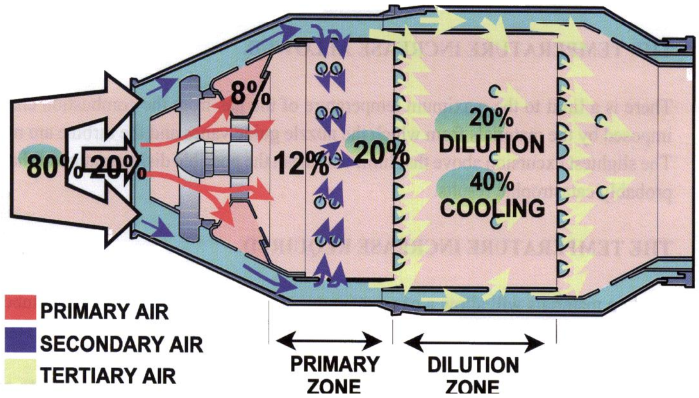

Figure 3-18 Division of Airflow in the Combustion Chamber

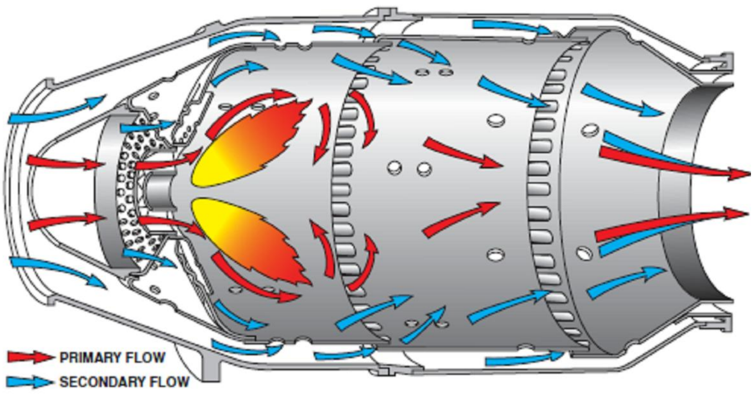

Figure 3-19 Flame Pattern and Stabilisation

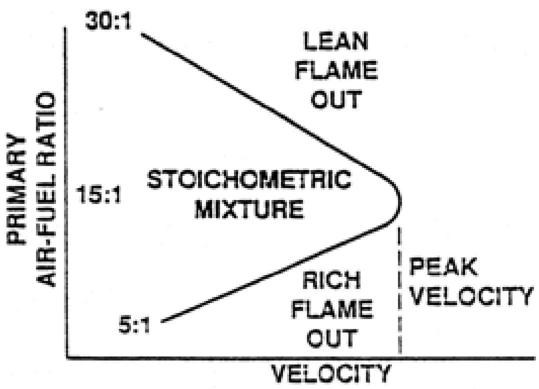

Figure 3-20 Air/Fuel Ratio Vs Velocity

<u>The limiting factor on how much fuel can be burnt, and thus how much power can be developed, revolves around the maximum temperature that the turbine blades can withstand</u>. Turbine assemblies are designed to operate at a maximum air temperature and all burning should take place inside the actual combustion chamber. The flame temperature can exceed 2000 °C. Modern turbines can only withstand temperatures of around 1100 °C.

TYPES OF COMBUSTION CHAMBERS

There are four main types of combustion chambers;

- Multiple or Can Type,
- Can-Annular (or Turbo-Annular),
- Annular, and
- Reverse Flow.

Multiple or Can Type chambers which were the original combustion chamber design are not frequently used today. They consist of individual chambers located evenly around the engine and connected only by flame cross over ducts or interconnect tubes which allow efficient light up and flame propagation during start and equalise pressure during normal operation. Their thermal efficiency was poor as much of the heat was lost through the chamber walls. The chambers are arranged around the engine. Each chamber has an inner flame tube surrounded by its individual casing. The air enters the flame tube via a snout located at the very front of the flame tube, and through holes in the side of the flame tube. Refer to Figure 3-21.

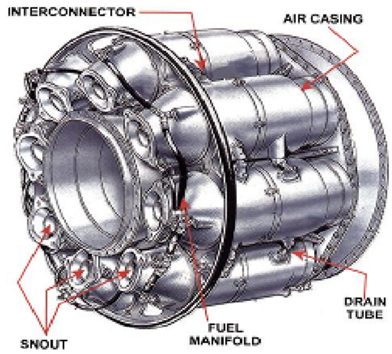

Figure 3-21 Multiple Can Combustion Chambers

Can-Annular or Turbo-Annular chambers are constructed in a similar manner to the multiple types, except that the individual chambers are enclosed in a single inner and outer chamber. Air is allowed to pass around the cans to provide additional cooling and improve thermal efficiency. Refer to Figure 3-22.

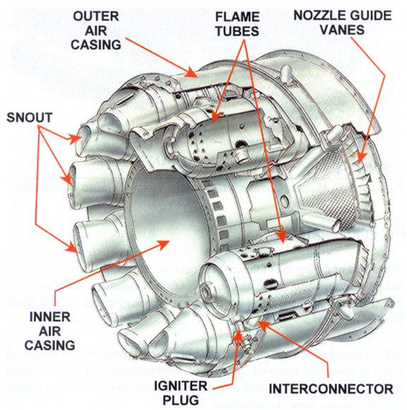

Figure 3-22 Can Annular Combustion Chamber

Annular combustion chambers are single circular flame tubes which are enclosed by an outer shield. The Annular chamber is constructed in a similar manner to the can types, and performs the same functions. It is more robust and provides a more even temperature and pressure and is more thermally efficient than the can types. The combustion chamber is only 75% the length of other configurations.

It does have the disadvantage, for any malfunction the whole assembly must be changed. Refer to Figure 3-23.

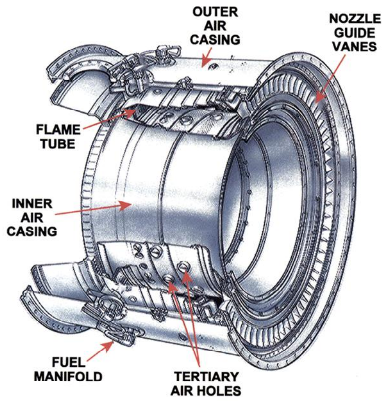

Figure 3-23 Annular Combustion Chamber

Reverse Flow Annular This system is frequently used in small turbo-prop engines fitted with Compound Compressors (Pratt and Whitney PT6). Because the turbines are within the combustion chamber area it allows the engine to be lighter and shorter. Reversing the flow also allows the combustion chamber to preheat the compressor discharge air. This helps compensate for the loss of efficiency resulting from the combustion chamber exiting forward. Refer to Figure 3-24.

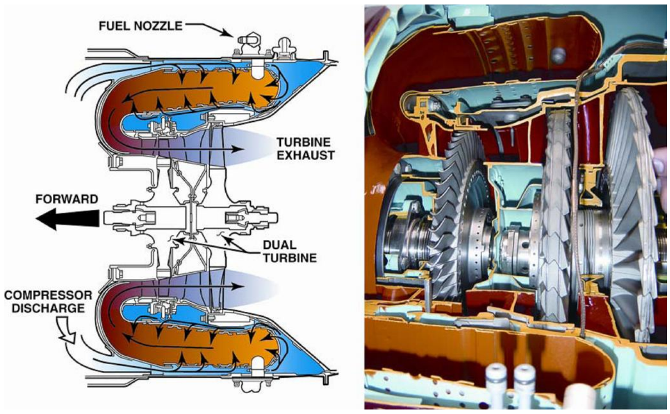

Figure 3-24 Reverse Flow Annular Combustion Chamber

The combustion efficiency of gas turbine engines remains at virtually 100% for all normal operations, there being a very slight decrease (about 2%) with increase in altitude to cruise level. This does, however, assume that the correct air/fuel ratio is maintained throughout these operations. All engines have lean, and rich mixture limits, and operation outside these limits will lead to the flame being extinguished, a condition referred to as flame-out. Refer back to Figure 3-20.

The most likely time for an engine to "flame-out" is at low power settings with high mass airflow which will result in a lean mixture. This situation may occur when descending from a high altitude with minimum power set, or if the thrust levers are closed too quickly particularly at high altitude. Should a flame-out occur it will normally be possible to re-light the engine and restore the correct fuel/air ratio, by operating in accordance with the flight manual for in flight starting.

In-flight starting is covered in Chapter 7.

COMBUSTION CHAMBER DRAIN

Combustion chambers are normally fitted with a drain valves. The purpose of this valve is to allow any excess fuel, which may accumulate prior to ignition in the chamber during start up, to drain out preventing a hot start, they are spring biased in the open position, and once the engine has started combustion, the internal pressure forces them into the closed position. Refer to Figure 3-25.

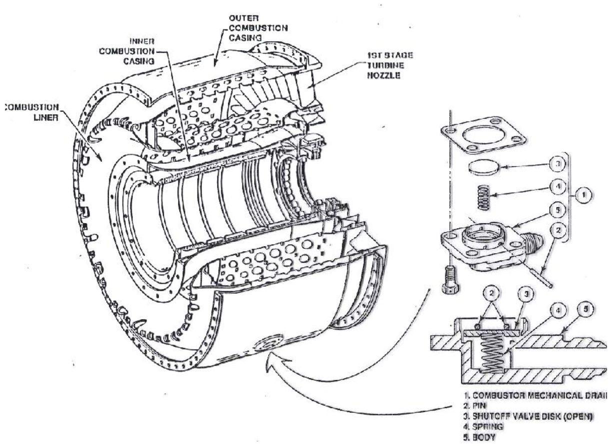

Figure 3-25 Combustion Chamber Drain Valve

FUEL SPRAY NOZZLES

The fuel nozzle or burner is the gas turbine equivalent of the fuel injector. Its purpose is to supply finely atomised fuel to mix with the airflow entering the combustion chamber. They are located in the inlet to the combustion chamber, usually between the swirl vanes. There are various types of burners, the most common being;

- Simplex,
- Duplex, and
- Fuel Atomisers.

Simplex Fuel Nozzles were the first type of burner developed, and consisted of a single spray orifice. Fuel spray pattern was adjusted by varying the supply pressure. The supply pressure had to be reasonably high as flow through a fixed orifice is proportional to the square root of the pressure drop across it, and therefore impractical for low speed engines or high altitude operations. The use of simplex burners is limited to small constant speed engines such as Auxiliary Power Units. Refer to Figure 3-26.

Duplex Fuel Nozzles have two separate spray orifices. One orifice provides finely atomised fuel for starting and low power settings, while both are used to provide the fuel pattern for high power settings. This is controlled by a pressurizing valve. Refer to Figure 3-27.

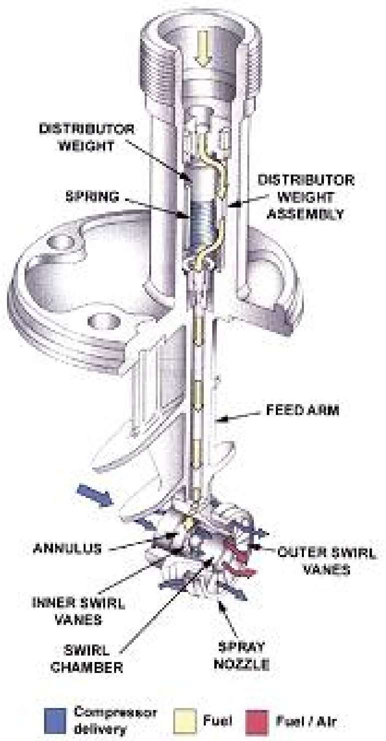

Figure 3-26 **Simplex Fuel Nozzle**

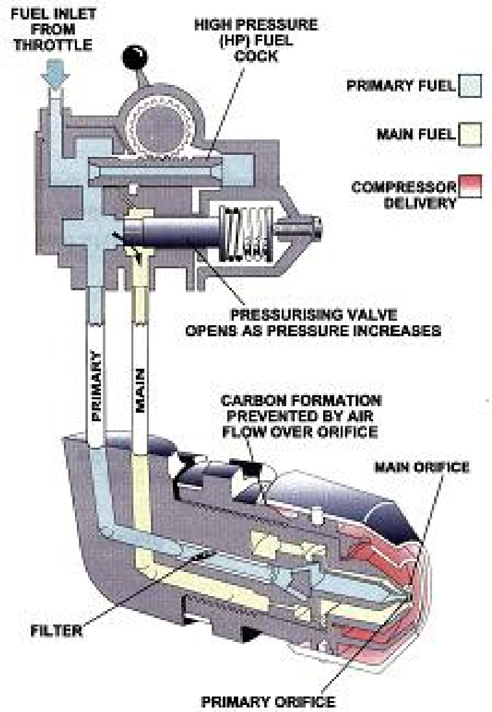

Figure 3-27 **Duplex Fuel Nozzle**

Fuel Atomiser or vaporising systems are used in modern turbofans .The fuel is sprayed from feed tubes which are positioned inside the flame tube. Primary air is then fed into the flame tube through the fuel feed tube opening and also through holes in the flame tube entry section. Refer to Figure 3-28.

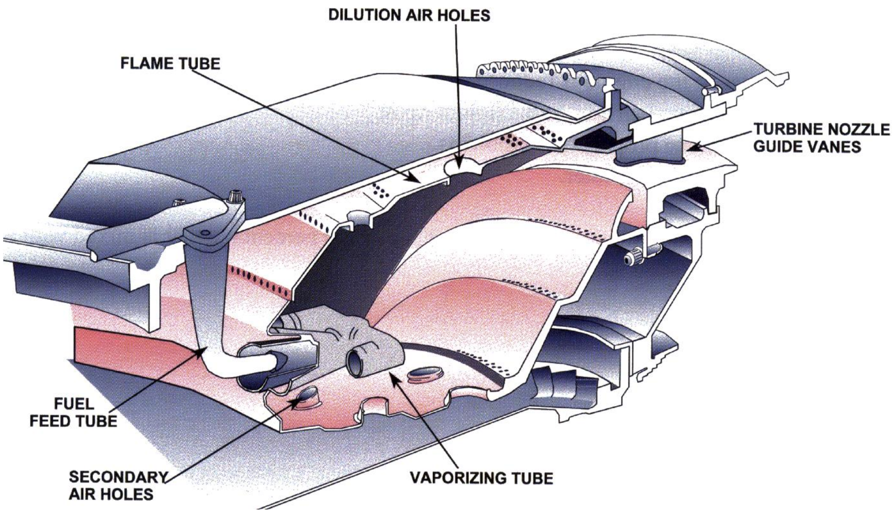

Figure 3-28 **Atomised Fuel Feed**

IGNITION SYSTEMS

The ignition system on a gas turbine engine is only required for start, as combustion is continuous once the engine is running. The ignition system is normally manually selected to "ON" during the start and cancelled automatically once the engine has reached self-sustaining speed, which is the speed at which the engine will accelerate without further assistance from the starter motor.

The start of the gas turbine engine can occur in a wide variety of operating conditions and a reliable, efficient ignition system is required. Most gas turbine engines use a dual high energy ignition system. Each high energy ignition unit is connected to an igniter plug located at different locations in the Primary zone of the combustion chamber. The system operates on either 28 V DC or 115 V AC or both.

In addition to starting the engines, the use of the igniters is recommended for landing and take-off as well as flight through heavy rain or turbulence. They are manually selected on during icing conditions, or automatically by the ice detection system in the more modern engines.

Most engines are fitted with a special ignition system for continuous use.

Ignition will be covered in more detail in Chapter 7 Starting and Ignition.