
Gas Turbine Engine Fundamentals

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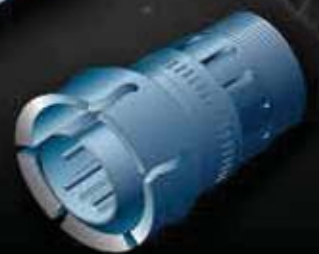
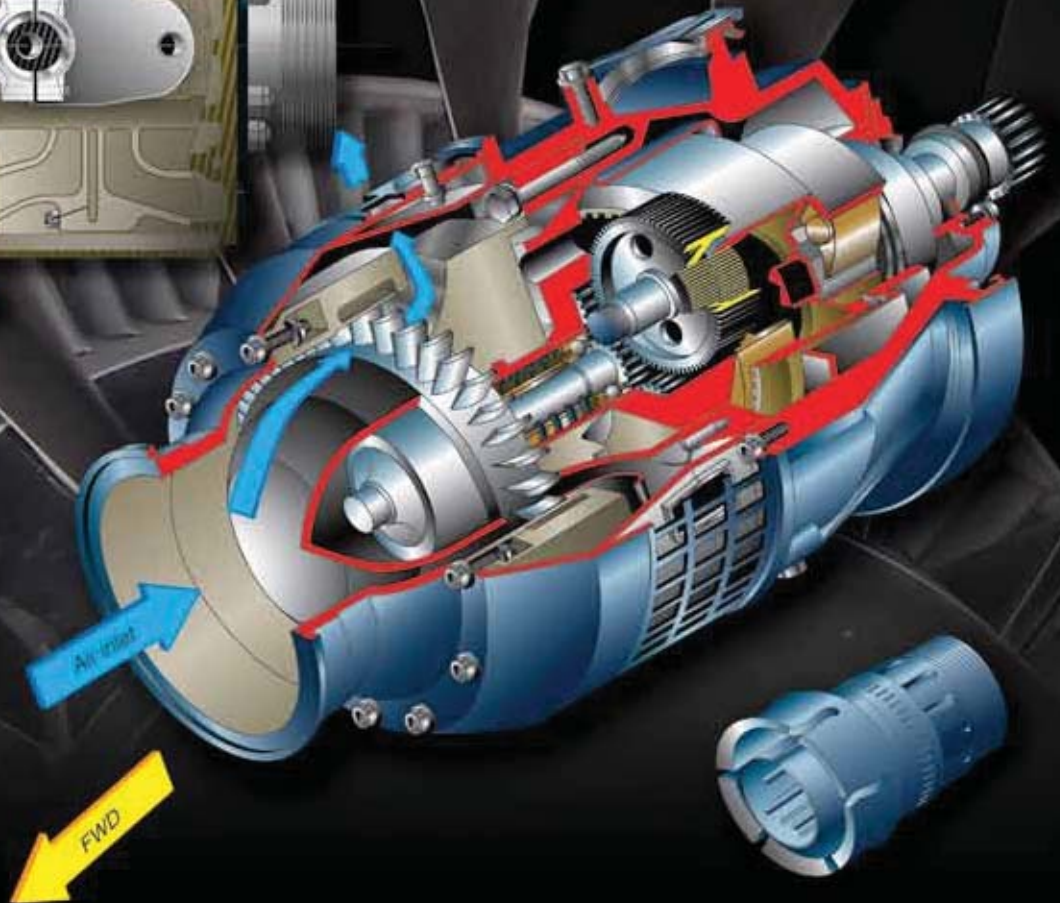
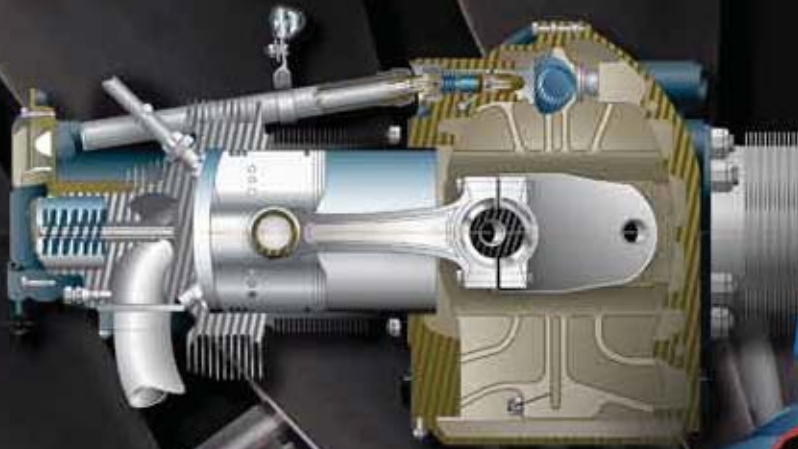
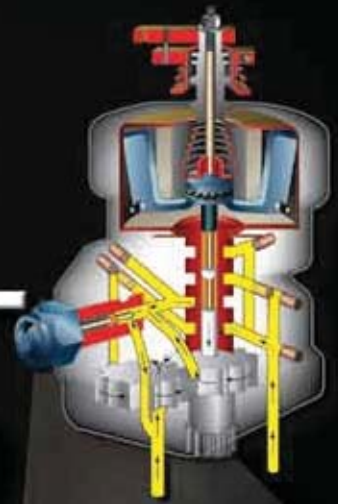
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Gas Turbine Engines

Types and Construction

In a reciprocating engine, the functions of intake, compression, combustion, and exhaust all take place in the same combustion chamber. Consequently, each must have exclusive occupancy of the chamber during its respective part of the combustion cycle. A significant feature of the gas turbine engine is that separate sections are devoted to each function, and all functions are performed simultaneously without interruption.

A typical gas turbine engine consists of:

1. An air inlet,
2. Compressor section,
3. Combustion section,
4. Turbine section,
5. Exhaust section,
6. Accessory section, and
7. The systems necessary for starting, lubrication, fuel supply, and auxiliary purposes, such as anti-icing, cooling, and pressurization.

The major components of all gas turbine engines are basically the same; however, the nomenclature of the component parts of various engines currently in use varies slightly due to the difference in each manufacturer's terminology. These differences are reflected in the applicable maintenance manuals. One of the greatest single factors influencing the construction features of any gas turbine engine is the type of compressor or compressors for which the engine is designed.

Four types of gas turbine engines are used to propel and power aircraft. They are the turbofan, turboprop, turboshaft,

and turbojet. The term "turbojet" was used to describe any gas turbine engine used in aircraft. As gas turbine technology evolved, these other engine types were developed to take the place of the pure turbojet engine. The turbojet engine has problems with noise and fuel consumption in the speed range that airliners fly (.8 Mach). Due to these problems, use of pure turbojet engines is very limited. So, almost all airliner-type aircraft use a turbofan engine. It was developed to turn a large fan or set of fans at the front of the engine and produces about 80 percent of the thrust from the engine. This engine was quieter and has better fuel consumption in this speed range. Turbofan engines have more than one shaft in the engine; many are two-shaft engines. This means that there is a compressor and a turbine that drives it and another compressor and turbine that drives it. These two shafted engines use two spools (a spool is a compressor and a shaft and turbines that driven that compressor). In a two-spool engine, there is a high-pressure spool and a low-pressure spool. The low-pressure spool generally contains the fan(s) and the turbine stages it takes to drive them. The high-pressure spool is the high-pressure compressor, shaft, and turbines. This spool makes up the core of the engine, and this is where the combustion section is located. The high-pressure spool is also referred to as the gas generator because it contains the combustion section.

Turbofan engines can be low bypass or high bypass. The amount of air that is bypassed around the core of the engine determines the bypass ratio. As can be seen in *Figure 1-43*, the air generally driven by the fan does not pass through the internal working core of the engine. The amount of air flow in lb/sec from the fan bypass to the core flow of the engine is the bypass ratio.

$$\text{Bypass ratio} = \frac{100 \text{ lb/sec flow fan}}{20 \text{ lb/sec flowcore}} = 5:1 \text{ bypass ratio}$$

Some low-bypass turbofan engines are used in speed ranges above .8 Mach (military aircraft). These engines use augmenters or afterburners to increase thrust. By adding more fuel nozzles and a flame holder in the exhaust system extra fuel can be sprayed and burned which can give large increases in thrust for short amounts of time.

The turboprop engine is a gas turbine engine that turns a propeller through a speed reduction gear box. This type of engine is most efficient in the 300 to 400 mph speed range and can use shorter runways than other aircraft. Approximately 80 to 85 percent of the energy developed by the gas turbine engine is used to drive the propeller. The rest of the available energy exits the exhaust as thrust. By adding the horsepower developed by the engine shaft and the horsepower in the exiting thrust, the answer is equivalent shaft horsepower.

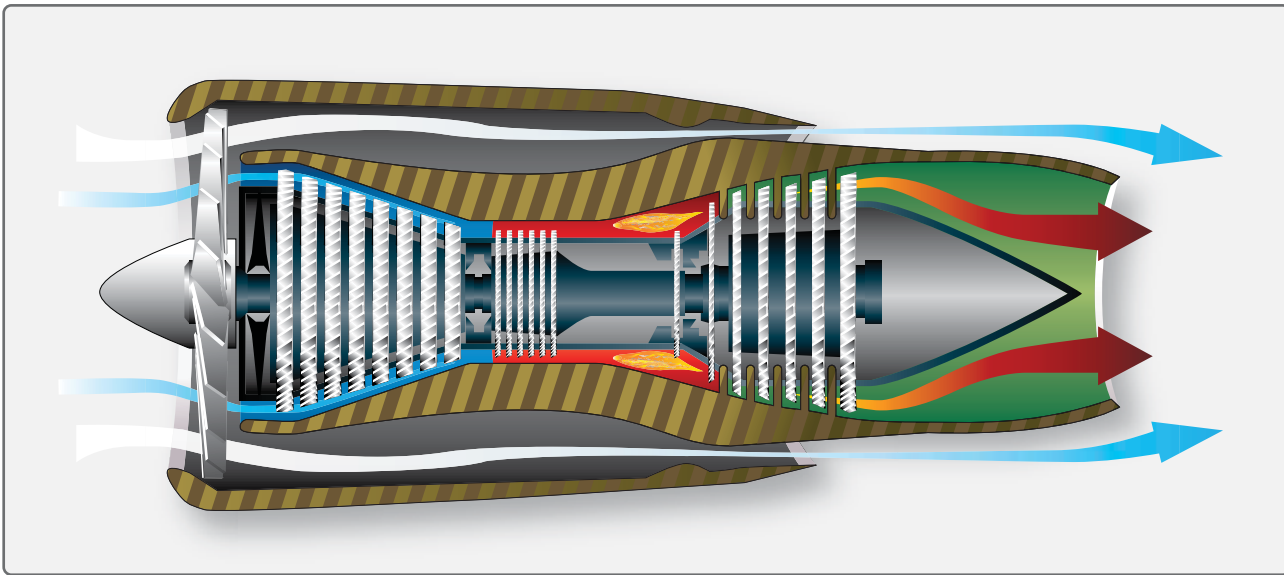


Figure 1-43. Turbofan engine with separate nozzles fan and core.

With regard to aircraft, the turboshaft engine is a gas turbine engine made to transfer horsepower to a shaft that turns a helicopter transmission or is an onboard auxiliary power unit (APU). An APU is used on turbine-powered aircraft to provide electrical power and bleed air on the ground and a backup generator in flight. Turboshaft engines can come in many different styles, shapes, and horsepower ranges.

Air Entrance

The air entrance is designed to conduct incoming air to the compressor with a minimum energy loss resulting from drag or ram pressure loss; that is, the flow of air into the compressor should be free of turbulence to achieve maximum operating efficiency. Proper inlet design contributes materially to aircraft performance by increasing the ratio of compressor discharge pressure to duct inlet pressure.

This is also referred to as the compressor pressure ratio. This ratio is the outlet pressure divided by the inlet pressure. The amount of air passing through the engine is dependent upon three factors:

1. The compressor speed (rpm)
2. The forward speed of the aircraft
3. The density of the ambient (surrounding) air

Turbine inlet type is dictated by the type of gas turbine engine. A high-bypass turbofan engine inlet is completely different from a turboprop or turboshaft inlet. Large gas turbine-powered aircraft almost always have a turbofan engine. The inlet on this type of engine is bolted to the front (A flange) of the engine. These engines are mounted on the wings, or

nacelles, on the aft fuselage, and a few are in the vertical fin. A typical turbofan inlet can be seen in *Figure 1-44*. Since on most modern turbofan engines the huge fan is the first part of the aircraft the incoming air comes into contact with, icing protection must be provided. This prevents chunks of ice from forming on the leading edge of the inlet, breaking loose, and damaging the fan. Warm air is bled from the engine's compressor and is ducted through the inlet to prevent ice from forming. If inlet guide vanes are used to straighten the air flow, then they also have anti-icing air flowing through them. The inlet also contains some sound-reducing materials that absorb the fan noise and make the engine quieter.



Figure 1-44. Typical turbofan inlet.

Turboprops and turboshafts can use an inlet screen to help filter out ice or debris from entering the engine. A deflector vane and a heated inlet lip are used to prevent ice or large chunks from entering the engine.

On military aircraft, the divided entrance permits the use of very short ducts with a resultant small pressure drop through skin friction. Military aircraft can fly at speeds above Mach 1, but the airflow through the engine must always stay below Mach 1. Supersonic air flow in the engine would destroy the engine. By using convergent and divergent shaped ducts, the air flow is controlled and dropped to subsonic speeds before entering the engine. Supersonic inlets are used to slow the incoming engine air to less than Mach 1 before it enters the engine.

Accessory Section

The accessory section of the gas turbine engine has various functions. The primary function is to provide space for the mounting of accessories necessary for operation and control of the engine. Generally, it also includes accessories concerned with the aircraft, such as electric generators and hydraulic pumps. Secondary functions include acting as an oil reservoir and/or oil sump and housing the accessory drive gears and reduction gears.

The arrangement and driving of accessories has always been a major problem on gas turbine engines. Driven accessories on turboprops are usually mounted on the accessory gear box, which is on the bottom of the engine. The location of the accessory gear box varies somewhat, but most turboprops and turboshafts have the accessory cases mounted to the back section of the engine.

The components of the accessory section of all gas turbine engines have essentially the same purpose, even though they often differ quite extensively in construction details and nomenclature.

The basic elements of the accessory section are:

1. The accessory case, which has machined mounting pads for the engine-driven accessories, and
2. The gear train, which is housed within the accessory case.

The accessory case may be designed to act as an oil reservoir. If an oil tank is utilized, a sump is usually provided below the front bearing support for the drainage and scavenging of oil used to lubricate bearings and drive gears. The accessory case is also provided with adequate tubing or cored passages for spraying, lubricating oil on the gear train and supporting bearings.

The gear train is driven by the engine high-pressure compressor through an accessory drive shaft (tower shaft) gear coupling, which splines with a gear box gear and the high-pressure compressor. The reduction gearing within the case provides suitable drive speeds for each engine accessory or component. Because the rotor operating rpm is so high, the accessory reduction gear ratios are relatively high. The accessory drives are supported by ball bearings assembled in the mounting pad bores of the accessory case. [Figure 1-45]



Figure 1-45. Typical turboprop accessory case.

Compressor Section

The compressor section of the gas turbine engine has many functions. Its primary function is to supply air in sufficient quantity to satisfy the requirements of the combustion burners. Specifically, to fulfill its purpose, the compressor must increase the pressure of the mass of air received from the air inlet duct, and then, discharge it to the burners in the quantity and at the pressures required.

A secondary function of the compressor is to supply bleed-air for various purposes in the engine and aircraft. The bleed-air is taken from any of the various pressure stages of the compressor. The exact location of the bleed ports is, of course, dependent on the pressure or temperature required for a particular job. The ports are small openings in the compressor case adjacent to the particular stage from which the air is to be bled; thus, varying degrees of pressure are available simply by tapping into the appropriate stage. Air is often bled from the final or highest pressure stage since, at this point, pressure and air temperature are at a maximum. At times it may be necessary to cool this high-pressure air. If it is used for cabin pressurization or other purposes to which excess heat would be uncomfortable or detrimental, the air is sent through an air conditioning unit before it enters the cabin.

Bleed air is utilized in a wide variety of ways. Some of the current applications of bleed air are:

1. Cabin pressurization, heating, and cooling;
2. Deicing and anti-icing equipment;
3. Pneumatic starting of engines; and
4. Auxiliary drive units (ADU).

Compressor Types

The two principal types of compressors currently being used in gas turbine aircraft engines are centrifugal flow and axial flow. The centrifugal-flow compressor achieves its purpose by picking up the entering air and accelerating it outwardly by centrifugal action. The axial-flow compressor compresses air while the air continues in its original direction of flow, thus avoiding the energy loss caused by turns. The components of each of these two types of compressor have their individual functions in the compression of air for the combustion section. A stage in a compressor is considered to be a rise in pressure.

Centrifugal-Flow Compressors

The centrifugal-flow compressor consists of an impeller (rotor), a diffuser (stator), and a compressor manifold. [Figure 1-46] Centrifugal compressors have a high pressure rise per stage that can be around 8:1. Generally centrifugal compressors are limited to two stages due to efficiency concerns. The two main functional elements are the impeller and the diffuser. Although the diffuser is a separate unit and is placed inside and bolted to the manifold, the entire assembly (diffuser and manifold) is often referred to as the diffuser. For clarification during compressor familiarization, the units are treated individually. The impeller is usually made from forged aluminum alloy, heat treated, machined, and smoothed for minimum flow restriction and turbulence.

In most types, the impeller is fabricated from a single forging. This type impeller is shown in Figure 1-46. The impeller, whose function is to pick up and accelerate the air outwardly to the diffuser, may be either of two types—single entry or double entry. The principal differences between the two types of impellers are size and ducting arrangement. The double-entry type has a smaller diameter, but is usually operated at a higher rotational speed to assure sufficient airflow. The single-entry impeller, shown in Figure 1-47, permits convenient ducting directly to the impeller eye (inducer vanes) as opposed to the more complicated ducting necessary to reach the rear side of the double-entry type. Although slightly more efficient in receiving air, the single-entry impeller must be large in diameter to deliver the same quantity of air as the double-entry type. This, of course, increases the overall diameter of the engine.



Figure 1-47. Single-entry impeller.

Included in the ducting for double-entry compressor engines is the plenum chamber. This chamber is necessary for a double-entry compressor because the air must enter the

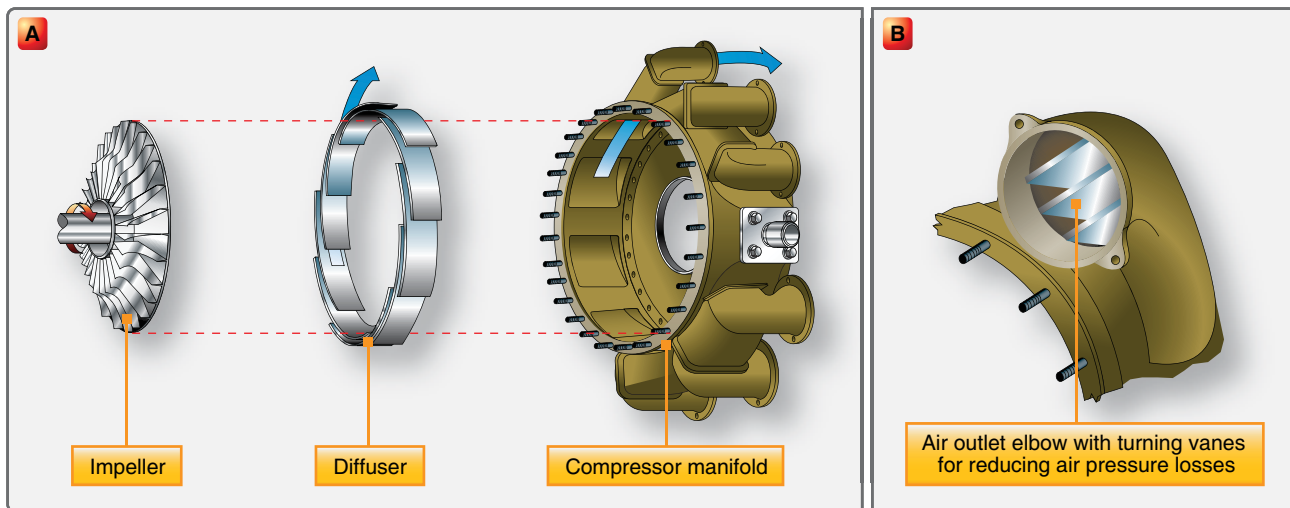


Figure 1-46. (A) Components of a centrifugal-flow compressor; (B) Air outlet elbow with turning vanes for reducing air pressure losses.

engine at almost right angles to the engine axis. Therefore, in order to give a positive flow, the air must surround the engine compressor at a positive pressure before entering the compressor. Included in some installations as necessary parts of the plenum chamber are the auxiliary air-intake doors (blow-in doors). These blow-in doors admit air to the engine compartment during ground operation, when air requirements for the engine are in excess of the airflow through the inlet ducts. The doors are held closed by spring action when the engine is not operating. During operation, however, the doors open automatically whenever engine compartment pressure drops below atmospheric pressure. During takeoff and flight, ram air pressure in the engine compartment aids the springs in holding the doors closed.

The diffuser is an annular chamber provided with a number of vanes forming a series of divergent passages into the manifold. The diffuser vanes direct the flow of air from the impeller to the manifold at an angle designed to retain the maximum amount of energy imparted by the impeller. They also deliver the air to the manifold at a velocity and pressure satisfactory for use in the combustion chambers. Refer to *Figure 1-46A* and note the arrow indicating the path of airflow through the diffuser, then through the manifold.

The compressor manifold shown in *Figure 1-46A* diverts the flow of air from the diffuser, which is an integral part of the manifold, into the combustion chambers. The manifold has one outlet port for each chamber so that the air is evenly divided. A compressor outlet elbow is bolted to each of the outlet ports. These air outlets are constructed in the form of ducts and are known by a variety of names, such as air outlet ducts, outlet elbows, or combustion chamber inlet ducts. Regardless of the terminology used, these outlet ducts perform a very important part of the diffusion process; that is, they change the radial direction of the airflow to an axial direction, in which the diffusion process is completed after the turn. To help the elbows perform this function in an efficient manner, turning vanes (cascade vanes) are sometimes fitted inside the elbows. These vanes reduce air pressure losses by presenting a smooth, turning surface. [*Figure 1-46B*]

Axial-Flow Compressor

The axial-flow compressor has two main elements: a rotor and a stator. The rotor has blades fixed on a spindle. These blades impel air rearward in the same manner as a propeller because of their angle and airfoil contour. The rotor, turning at high speed, takes in air at the compressor inlet and impels it through a series of stages. From inlet to exit, the air flows along an axial path and is compressed at a ratio of approximately 1.25:1 per stage. The action of the rotor increases the compression of the air at each stage and accelerates it rearward through several stages. With this

increased velocity, energy is transferred from the compressor to the air in the form of velocity energy. The stator blades act as diffusers at each stage, partially converting high velocity to pressure. Each consecutive pair of rotor and stator blades constitutes a pressure stage. The number of rows of blades (stages) is determined by the amount of air and total pressure rise required. Compressor pressure ratio increases with the number of compression stages. Most engines utilize up to 16 stages and more.

The stator has rows of vanes, which are in turn attached inside an enclosing case. The stator vanes, which are stationary, project radially toward the rotor axis and fit closely on either side of each stage of the rotor blades. In some cases, the compressor case, into which the stator vanes are fitted, is horizontally divided into halves. Either the upper or lower half may be removed for inspection or maintenance of rotor and stator blades.

The function of the stator vanes is to receive air from the air inlet duct or from each preceding stage and increase the pressure of the air and deliver it to the next stage at the correct velocity and pressure. They also control the direction of air to each rotor stage to obtain the maximum possible compressor blade efficiency. Shown in *Figure 1-48* are the rotor and stator elements of a typical axial-flow compressor. The first stage rotor blades can be preceded by an inlet guide vane assembly that can be fixed or variable.

The guide vanes direct the airflow into the first stage rotor blades at the proper angle and impart a swirling motion to the air entering the compressor. This preswirl, in the direction of engine rotation, improves the aerodynamic characteristics of the compressor by reducing drag on the first stage rotor blades. The inlet guide vanes are curved steel vanes usually welded to steel inner and outer shrouds.

At the discharge end of the compressor, the stator vanes are constructed to straighten the airflow to eliminate turbulence. These vanes are called straightening vanes or the outlet vane assembly. The casings of axial-flow compressors not only support the stator vanes and provide the outer wall of the axial path the air follows, but they also provide the means for extracting compressor air for various purposes. The stator vanes are usually made of steel with corrosion- and erosion-resistant qualities. Quite frequently, they are shrouded (enclosed) by a band of suitable material to simplify the fastening problem. The vanes are welded into the shrouds, and the outer shroud is secured to the compressor housing inner wall by radial retaining screws.

The rotor blades are usually made of stainless steel with the latter stages being made of titanium. The design of

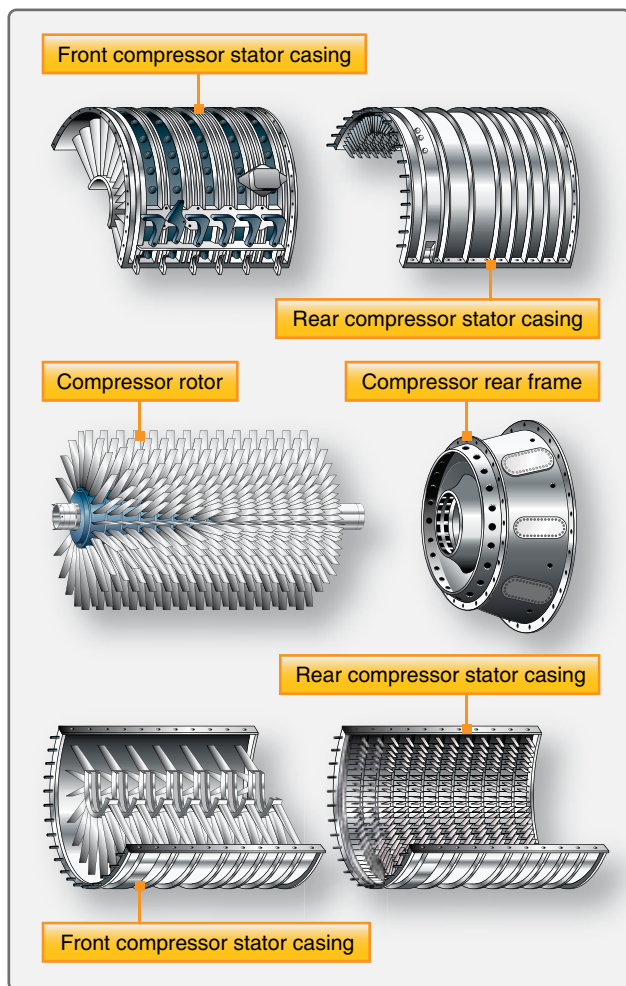


Figure 1-48. Rotor and stator elements of a typical axial-flow compressor.

blade attachment to the rotor disk rims varies, but they are commonly fitted into disks by either bulb-type or fir-tree methods. [Figure 1-49] The blades are then locked into place by differing methods. Compressor blade tips are reduced in thickness by cutouts, referred to as blade profiles. These profiles prevent serious damage to the blade or housing should the blades contact the compressor housing. This condition can occur if rotor blades become excessively loose or if rotor support is reduced by a malfunctioning bearing. Even though blade profiles greatly reduce such possibilities, occasionally a blade may break under stress of rubbing and cause considerable damage to compressor blades and stator vane assemblies. The blades vary in length from entry to discharge because the annular working space (drum to casing) is reduced progressively toward the rear by the decrease in the casing diameter. [Figure 1-50] This feature provides for a fairly constant velocity through the compressor, which helps to keep the flow of air constant.

The rotor features either drum-type or disk-type construction. The drum-type rotor consists of rings that are flanged to fit one against the other, wherein the entire assembly can then be held together by through bolts. This type of construction is satisfactory for low-speed compressors where centrifugal stresses are low. The disk-type rotor consists of a series of disks machined from aluminum forgings, shrunk over a steel shaft, with rotor blades dovetailed into the disk rims. Another method of rotor construction is to machine the disks and shaft from a single aluminum forging, and then to bolt steel stub shafts on the front and rear of the assembly to provide bearing support surfaces and splines for joining the turbine shaft. The drum-type and disk-type rotors are illustrated in Figures 1-50 and 1-51, respectively.

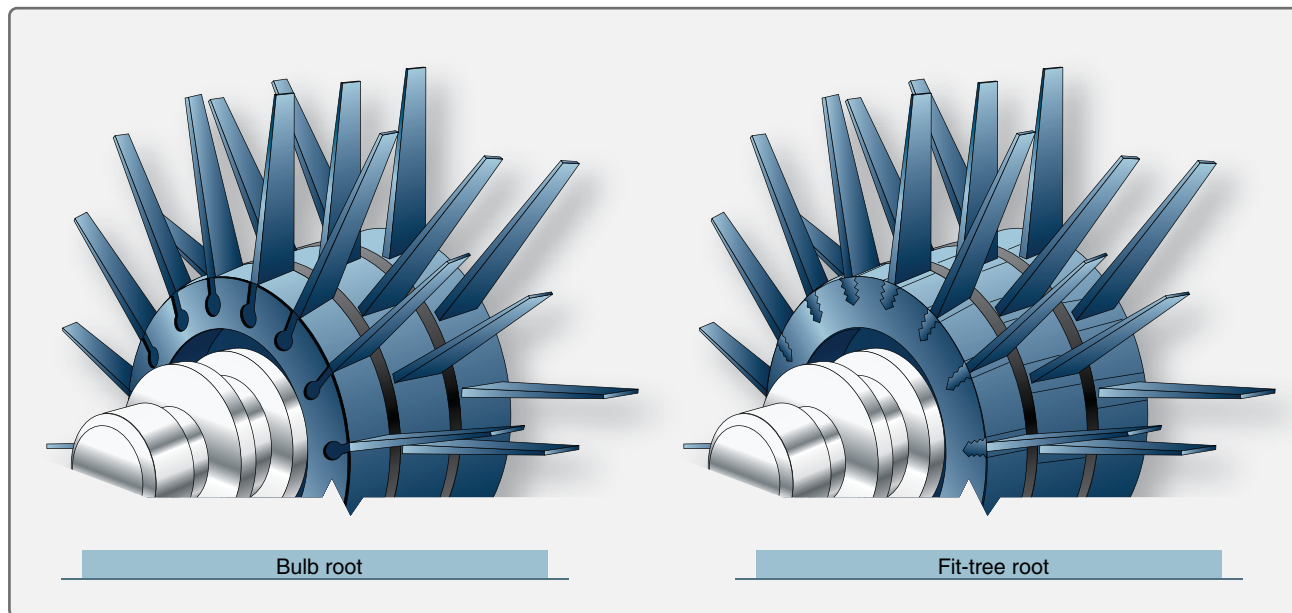


Figure 1-49. Common designs of compressor blade attachment to the rotor disk.

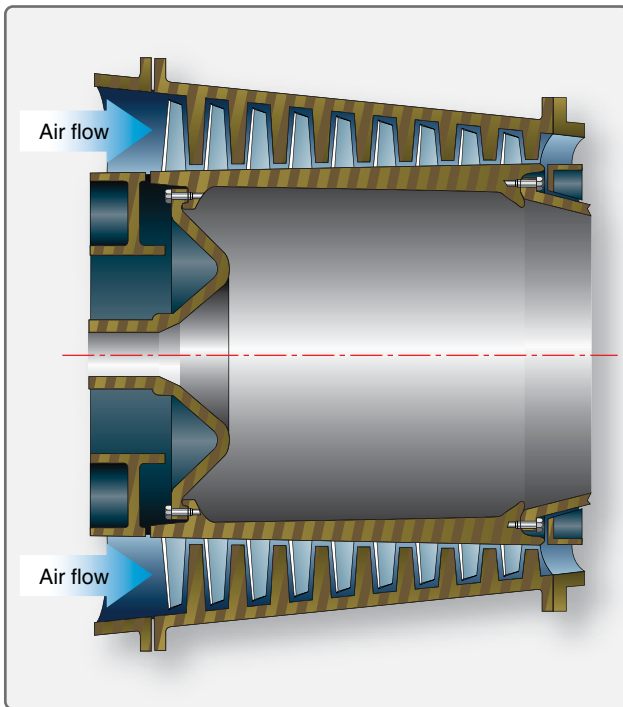


Figure 1-50. *Drum-type compressor rotor.*

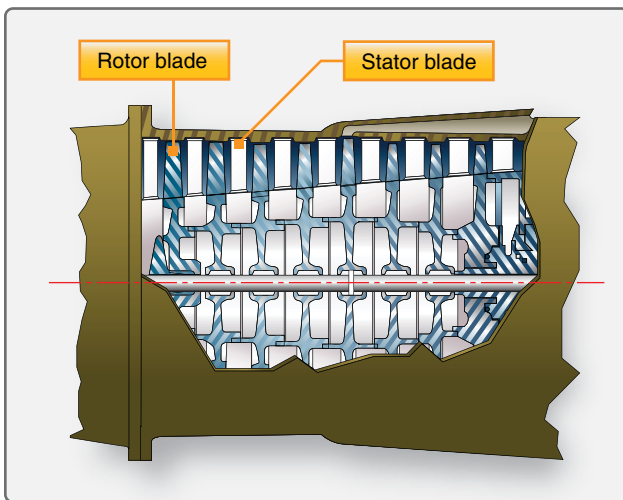


Figure 1-51. *Disk-type compressor rotor.*

The combination of the compressor stages and turbine stages on a common shaft is an engine referred to as an engine spool. The common shaft is provided by joining the turbine and compressor shafts by a suitable method. The engine's spool is supported by bearings, which are seated in suitable bearing housings.

As mentioned earlier, there are two configurations of the axial compressor currently in use: the single rotor/spool and the dual rotor/spool, sometimes referred to as solid spool and split spool (two spool, dual spool).

One version of the solid-spool (one spool) compressor uses variable inlet guide vanes. Also, the first few rows of stator vanes are variable. The main difference between variable inlet guide vane (VIGV) and a variable stator vane (VSV) is their position with regard to the rotor blades. VIGV are in front of the rotor blades, and VSV are behind the rotor blades. The angles of the inlet guide vanes and the first several stages of the stator vanes can be variable. During operation, air enters the front of the engine and is directed into the compressor at the proper angle by the variable inlet guide and directed by the VSV. The air is compressed and forced into the combustion section. A fuel nozzle that extends into each combustion liner atomizes the fuel for combustion. These variables are controlled in direct relation to the amount of power the engine is required to produce by the power lever position.

Most turbofan engines are of the split-spool compressor type. Most large turbofan engines use a large fan with a few stages of compression called the low-pressure spool. These turbofans incorporate two compressors with their respective turbines and interconnecting shafts, which form two physically independent rotor systems. Many dual rotor systems have rotors turning in opposite directions and with no mechanical connection to each other. The second spool, referred to as the high-pressure spool and is the compressor for the gas generator and core of the engine, supplies air to the combustion section of the engine.

The advantages and disadvantages of both types of compressors are included in the following list. Even though each type has advantages and disadvantages, each has its use by type and size of engine.

The centrifugal-flow compressor's advantages are:

- High pressure rise per stage,
- Efficiency over wide rotational speed range,
- Simplicity of manufacture and low cost,
- Low weight, and
- Low starting power requirements.

The centrifugal-flow compressor's disadvantages are:

- Its large frontal area for a given airflow and
- Losses in turns between stages.

The axial-flow compressor's advantages are:

- High peak efficiencies;
- Small frontal area for given airflow;
- Straight-through flow, allowing high ram efficiency; and
- Increased pressure rise by increasing number of stages, with negligible losses.

The axial-flow compressor's disadvantages are:

- Good efficiencies over only narrow rotational speed range,
- Difficulty of manufacture and high cost,
- Relatively high weight, and
- High starting power requirements (partially overcome by split compressors).

Diffuser

The diffuser is the divergent section of the engine after the compressor and before the combustion section. It has the all-important function of reducing high-velocity compressor discharge air to increased pressure at a slower velocity. This prepares the air for entry into the flame burning area of the combustion section at a lower velocity so that the flame of combustion can burn continuously. If the air passed through the flame area at a high velocity, it could extinguish the flame.

Combustion Section

The combustion section houses the combustion process, which raises the temperature of the air passing through the engine. This process releases energy contained in the air/fuel mixture. The major part of this energy is required at the turbine or turbine stages to drive the compressor. About $\frac{2}{3}$ of the energy is used to drive the gas generator compressor. The remaining energy passes through the remaining turbine stages that absorb more of the energy to drive the fan, output shaft, or propeller. Only the pure turbojet allows the air to create all the thrust or propulsion by exiting the rear of the engine in the form of a high-velocity jet. These other engine types have some jet velocity out the rear of the engine but most of the thrust or power is generated by the additional turbine stages driving a large fan, propeller, or helicopter rotor blades.

The primary function of the combustion section is, of course, to burn the fuel/air mixture, thereby adding heat energy to the air. To do this efficiently, the combustion chamber must:

- Provide the means for proper mixing of the fuel and air to assure good combustion,
- Burn this mixture efficiently,
- Cool the hot combustion products to a temperature that the turbine inlet guide vanes/blades can withstand under operating conditions, and
- Deliver the hot gases to the turbine section.

The location of the combustion section is directly between the compressor and the turbine sections. The combustion chambers are always arranged coaxially with the compressor and turbine regardless of type, since the chambers must be in a through-flow position to function efficiently. All combustion chambers contain the same basic elements:

1. Casing
2. Perforated inner liner
3. Fuel injection system
4. Some means for initial ignition
5. Fuel drainage system to drain off unburned fuel after engine shutdown

There are currently three basic types of combustion chambers, variations within type being in detail only. These types are:

1. Can type
2. Can-annular type
3. Annular type

The can-type combustion chamber is typical of the type used on turboshaft and APUs. [Figure 1-52] Each of the can-type combustion chambers consists of an outer case or housing, within which there is a perforated stainless steel (highly heat resistant) combustion chamber liner or inner liner. [Figure 1-53] The outer case is removed to facilitate liner replacement.



Figure 1-52. Can-type combustion chamber.

Older engines with several combustion cans had each can with interconnector (flame propagation) tube, which was a necessary part of the can-type combustion chambers. Since each can is a separate burner operating independently of the other cans, there must be some way to spread combustion during the initial starting operation. This is accomplished by interconnecting all the chambers. As the flame is started by the spark igniter plugs in two of the lower chambers, it passes through the tubes and ignites the combustible mixture



Figure 1-53. Inside view of a combustion chamber liner.

in the adjacent chamber, and continues until all the chambers are burning.

The flame tubes vary in construction details from one engine to another, although the basic components are almost identical. [Figure 1-54] The spark igniters previously mentioned are normally two in number, and are located in two of the can-type combustion chambers.

Another very important requirement in the construction of combustion chambers is providing the means for draining unburned fuel. This drainage prevents gum deposits in the fuel manifold, nozzles, and combustion chambers. These deposits are caused by the residue left when the fuel evaporates. Probably most important is the danger of afterfire if the fuel is allowed to accumulate after shutdown. If the fuel is not

drained, a great possibility exists that, at the next starting attempt, the excess fuel in the combustion chamber will ignite and exhaust gas temperature will exceed safe operating limits.

The liners of the can-type combustors have perforations of various sizes and shapes, each hole having a specific purpose and effect on flame propagation within the liner. [Figure 1-52] The air entering the combustion chamber is divided by the proper holes, louvers, and slots into two main streams—primary and secondary air. The primary or combustion air is directed inside the liner at the front end, where it mixes with the fuel and is burned. Secondary or cooling air passes between the outer casing and the liner and joins the combustion gases through larger holes toward the rear of the liner, cooling the combustion gases from about 3,500 °F to near 1,500 °F. To aid in atomization of the fuel, holes are provided around the fuel nozzle in the dome or inlet end of the can-type combustor liner. Louvers are also provided along the axial length of the liners to direct a cooling layer of air along the inside wall of the liner. This layer of air also tends to control the flame pattern by keeping it centered in the liner, thereby preventing burning of the liner walls. Figure 1-55 illustrates the flow of air through the louvers in the annular combustion chamber.

Some provision is always made in the combustion chamber case for installation of a fuel nozzle. The fuel nozzle delivers the fuel into the liner in a finely atomized spray. The more the spray is atomized, the more rapid and efficient the burning process is.

Two types of fuel nozzle currently being used in the various types of combustion chambers are the simplex nozzle and the duplex nozzle. The construction features of these nozzles are covered in greater detail in Chapter 3, Engine Fuel and Fuel Metering Systems.

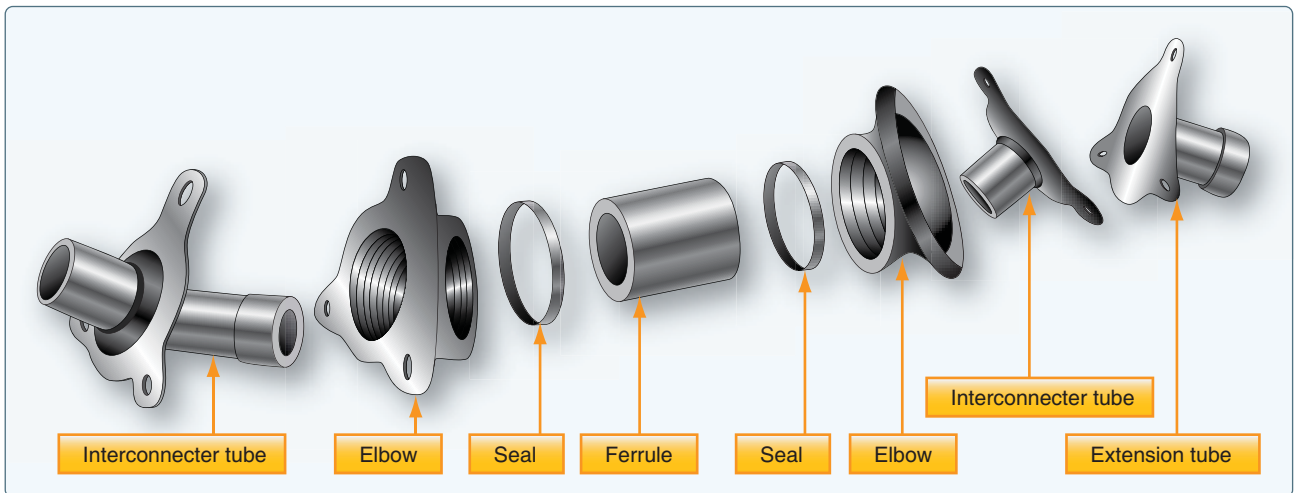


Figure 1-54. Interconnecting flame tubes for can-type combustion chambers.



Figure 1-55. Annular combustion chamber liner.

The spark igniter plugs of the annular combustion chamber are the same basic type used in the can-type combustion chambers, although construction details may vary. There are usually two igniters mounted on the boss provided on each of the chamber housings. The igniters must be long enough to protrude from the housing into the combustion chamber.

The burners are interconnected by projecting flame tubes which facilitate the engine-starting process as mentioned previously in the can-type combustion chamber familiarization. The flame tubes function identically to those previously discussed, differing only in construction details.

This type of combustion chamber is not used in modern engines. The forward face of each chamber presents six apertures, which align with the six fuel nozzles of the corresponding fuel nozzle cluster. [Figure 1-56] These nozzles are the dual-orifice (duplex) type requiring the use of a flow-divider (pressurizing valve), as mentioned in the can-type combustion chamber discussion. Around each nozzle are preswirl vanes for imparting a swirling motion to the fuel spray, which results in better atomization of the fuel, better burning, and efficiency. The swirl vanes function to provide two effects imperative to proper flame propagation:

- 1 High flame speed—better mixing of air and fuel, ensuring spontaneous burning.
- 2 Low air velocity axially—swirling eliminates overly rapid flame movement axially.

The swirl vanes greatly aid flame propagation, since a high degree of turbulence in the early combustion and cooling stages is desirable. The vigorous mechanical mixing of the fuel vapor with the primary air is necessary, since mixing by diffusion alone is too slow. This same mechanical mixing is also established by other means, such as placing coarse screens in the diffuser outlet, as is the case in most axial-flow engines.

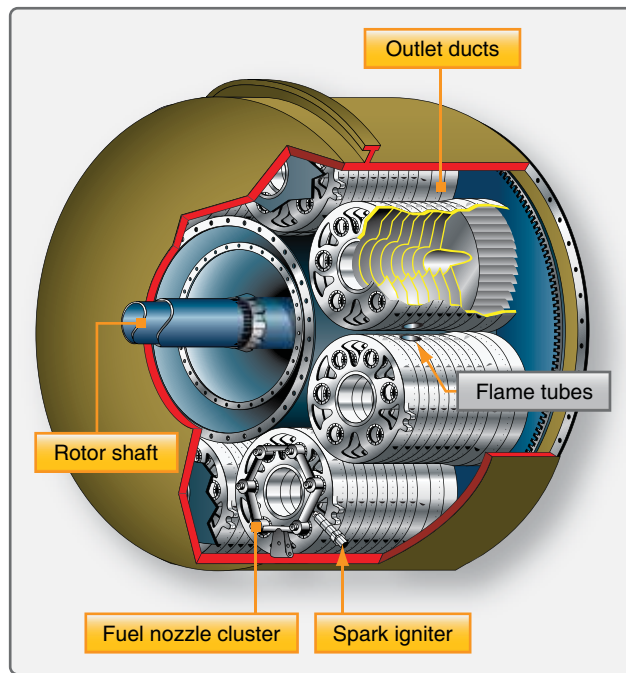


Figure 1-56. Can-annular combustion chamber components and arrangement.

The can-annular combustion chambers also must have the required fuel drain valves located in two or more of the bottom chambers, assuring proper drainage and elimination of residual fuel burning at the next start.

The flow of air through the holes and louvers of the can-annular chambers, is almost identical with the flow through other types of burners. [Figure 1-56] Special baffling is used to swirl the combustion air and to give it turbulence. Figure 1-57 shows the flow of combustion air, metal cooling air, and the diluent or gas cooling air. The air flow direction is indicated by the arrows.

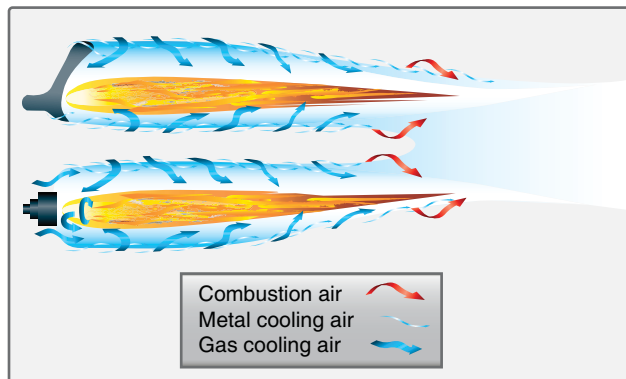


Figure 1-57. Airflow through a can-annular combustion chamber.

The basic components of an annular combustion chamber are a housing and a liner, as in the can type. The liner

consists of an undivided circular shroud extending all the way around the outside of the turbine shaft housing. The chamber may be constructed of heat-resistant materials, which are sometimes coated with thermal barrier materials, such as ceramic materials. The annular combustion chamber is illustrated in *Figure 1-58*. Modern turbine engines usually have an annular combustion chamber. As can be seen in *Figure 1-59*, the annular combustion chamber also uses louvers and holes to prevent the flame from contacting the side of the combustion chamber.



Figure 1-58. Annular combustion with chamber ceramic coating.

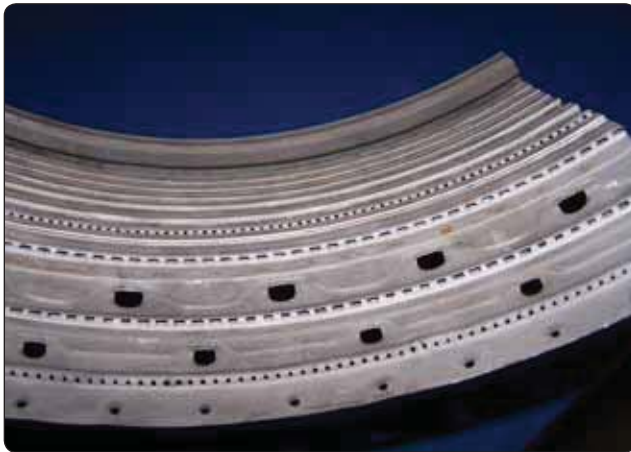


Figure 1-59. Combustion chamber louvers and holes.

Turbine Section

The turbine transforms a portion of the kinetic (velocity) energy of the exhaust gases into mechanical energy to drive the gas generator compressor and accessories. The sole purpose of the gas generator turbine is to absorb approximately 60 to 70 percent of the total pressure energy from the exhaust gases. The exact amount of energy absorption at the turbine is determined by the load the turbine is driving (i.e., compressor size and type, number of accessories, and the load applied by

the other turbine stages). These turbine stages can be used to drive a low-pressure compressor (fan), propeller, and shaft. The turbine section of a gas turbine engine is located aft, or downstream, of the combustion chamber. Specifically, it is directly behind the combustion chamber outlet.

The turbine assembly consists of two basic elements: turbine inlet guide vanes and turbine blades. [*Figures 1-60 and 1-61*] The stator element is known by a variety of names, of which turbine inlet nozzle vanes, turbine inlet guide vanes, and nozzle diaphragm are three of the most commonly used. The turbine inlet nozzle vanes are located directly aft of the combustion chambers and immediately forward of the turbine wheel. This is the highest or hottest temperature that comes in contact with metal components in the engine. The turbine inlet temperature must be controlled or damage will occur to the turbine inlet vanes.



Figure 1-60. Turbine inlet guide vanes.



Figure 1-61. Turbine blades.

After the combustion chamber has introduced the heat energy into the mass airflow and delivered it evenly to the turbine inlet nozzles, the nozzles must prepare the mass air flow to drive the turbine rotor. The stationary vanes of the turbine

inlet nozzles are contoured and set at such an angle that they form a number of small nozzles discharging gas at extremely high speed; thus, the nozzle converts a varying portion of the heat and pressure energy to velocity energy that can then be converted to mechanical energy through the turbine blades.

The second purpose of the turbine inlet nozzle is to deflect the gases to a specific angle in the direction of turbine wheel rotation. Since the gas flow from the nozzle must enter the turbine blade passageway while it is still rotating, it is essential to aim the gas in the general direction of turbine rotation.

The turbine inlet nozzle assembly consists of an inner shroud and an outer shroud between which the nozzle vanes are fixed. The number and size of inlet vanes employed vary with different types and sizes of engines. *Figure 1-62* illustrates typical turbine inlet nozzles featuring loose and welded vanes. The vanes of the turbine inlet nozzle may be assembled between the outer and inner shrouds or rings in a variety of ways. Although the actual elements may vary slightly in configuration and construction features, there is one characteristic peculiar to all turbine inlet nozzles: the nozzle vanes must be constructed to allow thermal expansion. Otherwise, there would be severe distortion or warping of the metal components because of rapid temperature changes. The thermal expansion of turbine nozzles is accomplished by one of several methods. One method necessitates loose assembly of the supporting inner and outer vane shrouds. [*Figure 1-62A*]

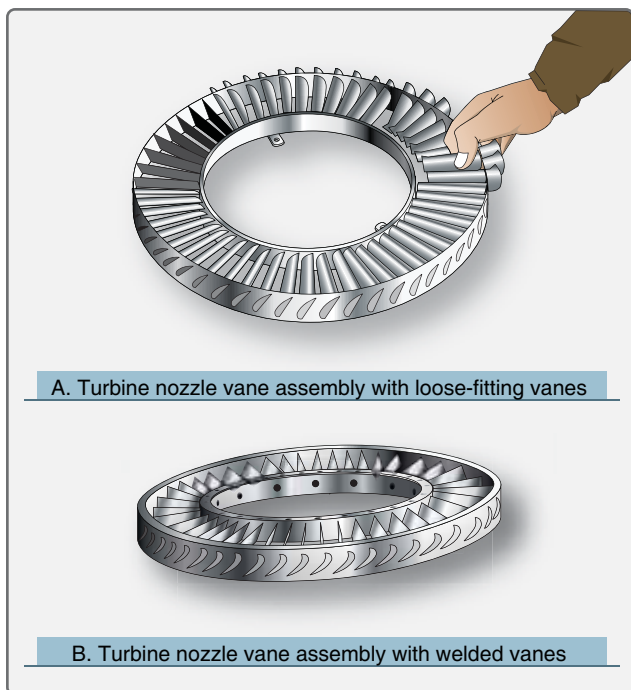


Figure 1-62. Typical turbine nozzle vane assemblies.

Each vane fits into a contoured slot in the shrouds, which conforms to the airfoil shape of the vane. These slots are slightly larger than the vanes to give a loose fit. For further support, the inner and outer shrouds are encased by inner and outer support rings, which provide increased strength and rigidity. These support rings also facilitate removal of the nozzle vanes as a unit. Without the rings, the vanes could fall out as the shrouds were removed.

Another method of thermal expansion construction is to fit the vanes into inner and outer shrouds; however, in this method the vanes are welded or riveted into position. [*Figure 1-62B*] Some means must be provided to allow thermal expansion; therefore, either the inner or the outer shroud ring is cut into segments. The saw cuts separating the segments allow sufficient expansion to prevent stress and warping of the vanes.

The rotor element of the turbine section consists essentially of a shaft and a wheel. [*Figure 1-63*] The turbine wheel is a dynamically balanced unit consisting of blades attached to a rotating disk. The disk, in turn, is attached to the main power-transmitting shaft of the engine. The exhaust gases leaving the turbine inlet nozzle vanes act on the blades of the turbine wheel, causing the assembly to rotate at a very high rate of speed. The high rotational speed imposes severe centrifugal loads on the turbine wheel, and at the same time the elevated temperatures result in a lowering of the strength of the material. Consequently, the engine speed and temperature must be controlled to keep turbine operation within safe limits.



Figure 1-63. Rotor elements of the turbine assembly.

The turbine disk is referred to as such without blades. When the turbine blades are installed, the disk then becomes the turbine wheel. The disk acts as an anchoring component for

the turbine blades. Since the disk is bolted or welded to the shaft, the blades can transmit to the rotor shaft the energy they extract from the exhaust gases.

The disk rim is exposed to the hot gases passing through the blades and absorbs considerable heat from these gases. In addition, the rim also absorbs heat from the turbine blades by conduction. Hence, disk rim temperatures are normally high and well above the temperatures of the more remote inner portion of the disk. As a result of these temperature gradients, thermal stresses are added to the rotational stresses. There are various methods to relieve, at least partially, the aforementioned stresses. One such method is to bleed cooling air back onto the face of the disk.

Another method of relieving the thermal stresses of the disk is incidental to blade installation. A series of grooves or notches, conforming to the blade root design, are broached in the rim of the disk; at the same time, space is provided by the notches for thermal expansion of the disk. Sufficient clearance exists between the blade root and the notch to permit movement of the turbine blade when the disk is cold. During engine operation, expansion of the disk decreases the clearance. This causes the blade root to fit tightly in the disk rim.

The turbine shaft is usually fabricated from alloy steel. [Figure 1-63] It must be capable of absorbing the high torque loads that are exerted on it.

The methods of connecting the shaft to the turbine disk vary. In one method, the shaft is welded to the disk, which has a butt or protrusion provided for the joint. Another method is by bolting. This method requires that the shaft have a hub that fits a machined surface on the disk face. Then, the bolts are inserted through holes in the shaft hub and anchored in tapped holes in the disk. Of the two connection methods, bolting is more common.

The turbine shaft must have some means for attachment to the compressor rotor hub. This is usually accomplished by a spline cut on the forward end of the shaft. The spline fits into a coupling device between the compressor and turbine shafts. If a coupling is not used, the splined end of the turbine shaft may fit into a splined recess in the compressor rotor hub. This splined coupling arrangement is used almost exclusively with centrifugal compressor engines, while axial compressor engines may use either of these described methods.

There are various ways of attaching turbine blades, some similar to compressor blade attachment. The most satisfactory method utilizes the fir-tree design. [Figure 1-64]

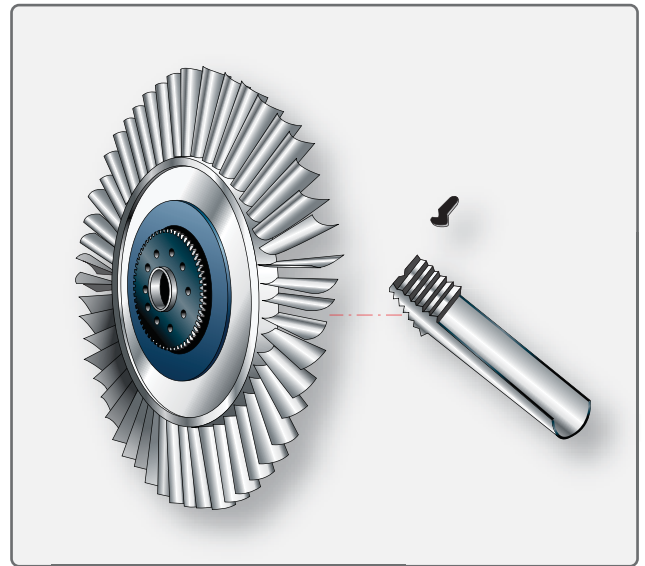


Figure 1-64. Turbine blade with fir-tree design and lock-tab method of blade retention.

The blades are retained in their respective grooves by a variety of methods, the more common of which are peening, welding, lock tabs, and riveting. Figure 1-65 shows a typical turbine wheel using rivets for blade retention.

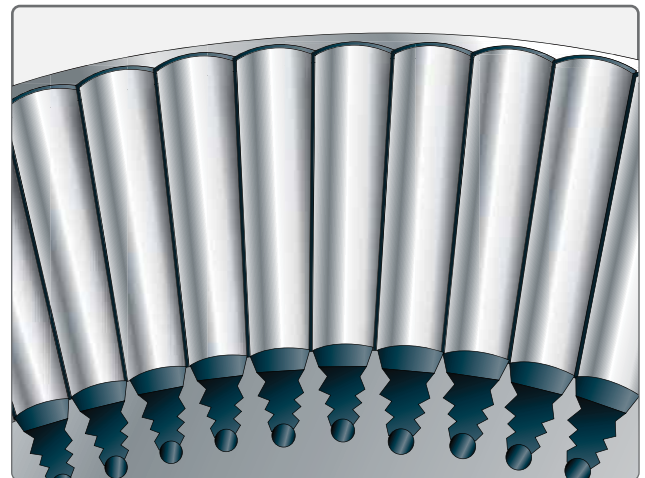


Figure 1-65. Rivet method of turbine blade retention.

The peening method of blade retention is used frequently in various ways. One of the most common applications of peening requires a small notch to be ground in the edge of the blade fir-tree root prior to the blade installation. After the blade is inserted into the disk, the notch is filled by the disk metal, which is “flowed” into it by a small punch-mark made in the disk adjacent to the notch. The tool used for this job is similar to a center punch.

Another method of blade retention is to construct the root of the blade so that it contains all the elements necessary for its retention. This method uses the blade root as a stop made on one end of the root so that the blade can be inserted and removed in one direction only, while on the opposite end is a tang. This tang is bent to secure the blade in the disk.

Turbine blades may be either forged or cast, depending on the composition of the alloys. Most blades are precision cast and finish ground to the desired shape. Many turbine blades are cast as a single crystal, which gives the blades better strength and heat properties. Heat barrier coating, such as ceramic coating, and air flow cooling help keep the turbine blades and inlet nozzles cooler. This allows the exhaust temperature to be raised, increasing the efficiency of the engine. *Figure 1-66* shows a turbine blade with air holes for cooling purposes.

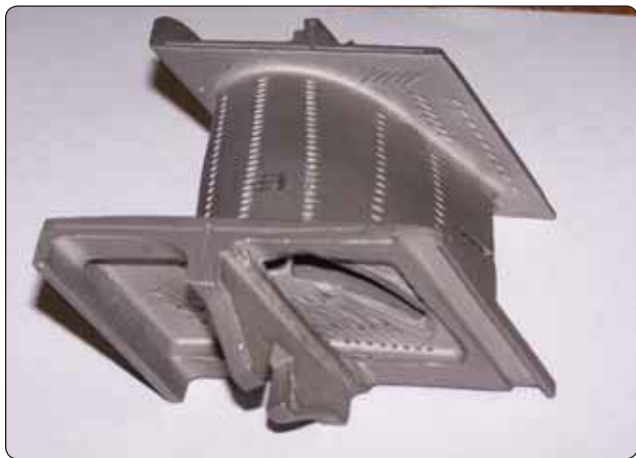


Figure 1-66. Turbine blade with cooling holes.

Most turbines are open at the outer perimeter of the blades; however, a second type called the shrouded turbine is sometimes used. The shrouded turbine blades, in effect, form a band around the outer perimeter of the turbine wheel. This improves efficiency and vibration characteristics, and permits lighter stage weights. On the other hand, it limits turbine speed and requires more blades. [*Figure 1-67*]

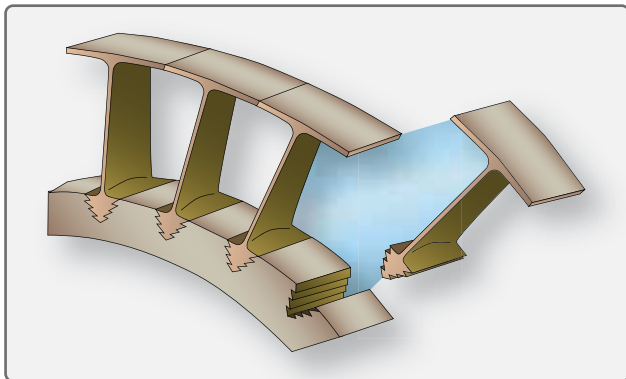


Figure 1-67. Shrouded turbine blades.

In turbine rotor construction, it occasionally becomes necessary to utilize turbines of more than one stage. A single turbine wheel often cannot absorb enough power from the exhaust gases to drive the components dependent on the turbine for rotative power; thus, it is necessary to add additional turbine stages.

A turbine stage consists of a row of stationary vanes or nozzles, followed by a row of rotating blades. In some models of turboprop engine, as many as five turbine stages have been utilized successfully. It should be remembered that, regardless of the number of wheels necessary for driving engine components, there is always a turbine nozzle preceding each wheel.

As was brought out in the preceding discussion of turbine stages, the occasional use of more than one turbine wheel is warranted in cases of heavy rotational loads. It should also be pointed out that the same loads that necessitate multistage turbines often make it advantageous to incorporate multiple compressor rotors.

In the single-stage rotor turbine, the power is developed by one turbine rotor, and all engine-driven parts are driven by this single wheel. [*Figure 1-68*] This arrangement is used on engines where the need for low weight and compactness predominates. This is the simplest version of the pure turbojet engine. A multistage turbine is shown in *Figure 1-69*.

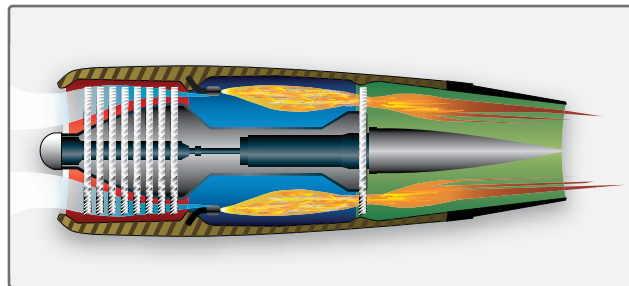


Figure 1-68. Single-stage rotor turbine.

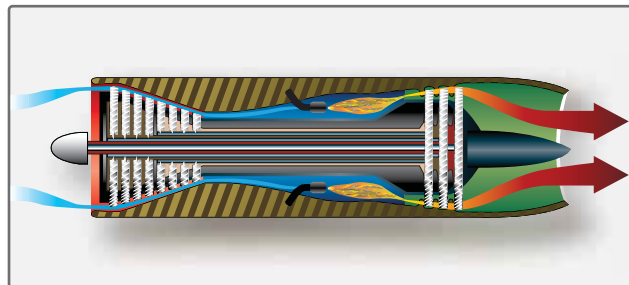


Figure 1-69. Multirotor turbine.

In multiple spool engines, each spool has its own set of turbine stages. Each set of turbine stages turns the compressor

attached to it. Most turbofan engines have two spools: low pressure (fan shaft a few stages of compression and the turbine to drive it) and high pressure (high pressure compressor shaft and high pressure turbine). [Figure 1-70]

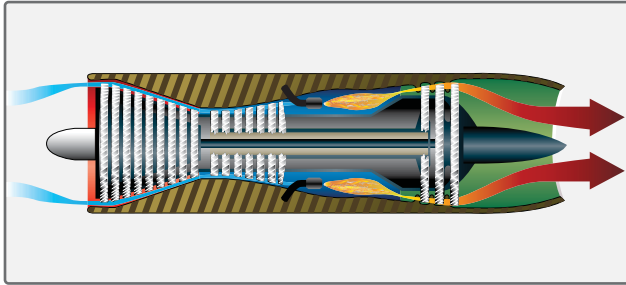


Figure 1-70. Dual-rotor turbine for split-spool compressor.

The remaining element to be discussed concerning turbine familiarization is the turbine casing or housing. The turbine casing encloses the turbine wheel and the nozzle vane assembly, and at the same time gives either direct or indirect support to the stator elements of the turbine section. It always has flanges provided front and rear for bolting the assembly to the combustion chamber housing and the exhaust cone assembly, respectively. A turbine casing is illustrated in Figure 1-71.

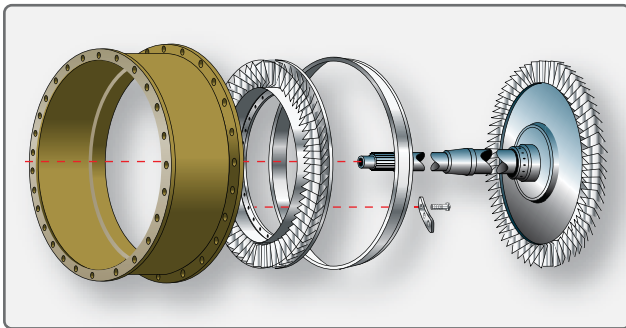


Figure 1-71. Turbine casing assembly.

Exhaust Section

The exhaust section of the gas turbine engine consists of several components. Although the components have individual purposes, they also have one common function: they must direct the flow of hot gases rearward in such a manner as to prevent turbulence and, at the same time, impart a high final or exit velocity to the gases. In performing the various functions, each of the components affects the flow of gases in different ways. The exhaust section is located directly behind the turbine section and ends when the gases are ejected at the rear in the form of a high-velocity exhaust gases. The components of the exhaust section include the exhaust cone, tailpipe (if required), and the exhaust nozzle. The exhaust cone collects the exhaust gases discharged from the turbine section and gradually converts them into a solid

flow of gases. In performing this, the velocity of the gases is decreased slightly and the pressure increased. This is due to the diverging passage between the outer duct and the inner cone; that is, the annular area between the two units increases rearward. The exhaust cone assembly consists of an outer shell or duct, an inner cone, three or four radial hollow struts or fins, and the necessary number of tie rods to aid the struts in supporting the inner cone from the outer duct.

The outer shell or duct is usually made of stainless steel and is attached to the rear flange of the turbine case. This element collects the exhaust gases and delivers them directly to the exhaust nozzle. The duct must be constructed to include such features as a predetermined number of thermocouple bosses for installing exhaust temperature thermocouples, and there must also be insertion holes for the supporting tie rods. In some cases, tie rods are not used for supporting the inner cone. If such is the case, the hollow struts provide the sole support of the inner cone, the struts being spot-welded in position to the inside surface of the duct and to the inner cone, respectively. [Figure 1-72] The radial struts actually have a twofold function. They not only support the inner cone in the exhaust duct, but they also perform the important function of straightening the swirling exhaust gases that would otherwise leave the turbine at an angle of approximately 45°.

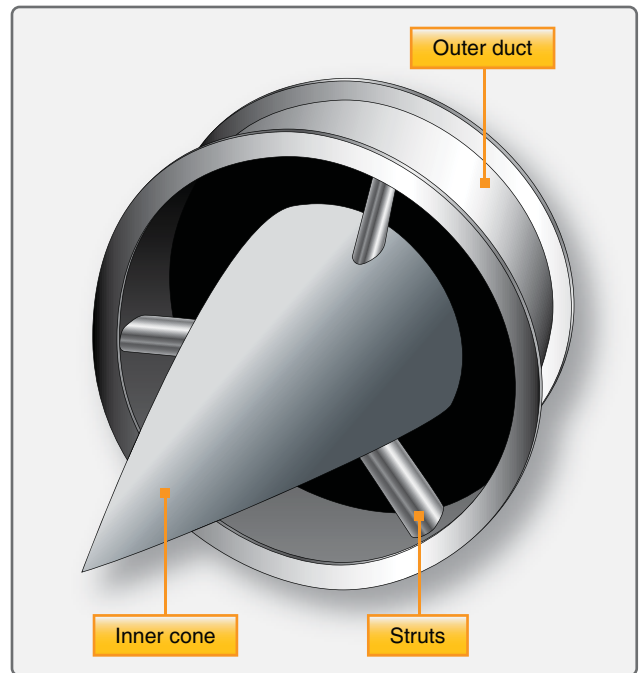


Figure 1-72. Exhaust collector with welded support struts.

The centrally located inner cone fits rather closely against the rear face of the turbine disk, preventing turbulence of the gases as they leave the turbine wheel. The cone is supported by the radial struts. In some configurations, a small hole is

located in the exit tip of the cone. This hole allows cooling air to be circulated from the aft end of the cone, where the pressure of the gases is relatively high, into the interior of the cone and consequently against the face of the turbine wheel. The flow of air is positive, since the air pressure at the turbine wheel is relatively low due to rotation of the wheel; thus air circulation is assured. The gases used for cooling the turbine wheel return to the main path of flow by passing through the clearance between the turbine disk and the inner cone. The exhaust cone assembly is the terminating component of the basic engine. The remaining component (the exhaust nozzle) is usually considered an airframe component.

The tailpipe is usually constructed so that it is semiflexible. On some tailpipes, a bellows arrangement is incorporated in its construction, allowing movement in installation, maintenance, and in thermal expansion. This eliminates stress and warping which would otherwise be present.

The heat radiation from the exhaust cone and tailpipe could damage the airframe components surrounding these units. For this reason, some means of insulation had to be devised. There are several suitable methods of protecting the fuselage structure; two of the most common are insulation blankets and shrouds.

The insulation blanket, illustrated in *Figures 1-73 and 1-74*, consists of several layers of aluminum foil, each separated by a layer of fiberglass or some other suitable material. Although these blankets protect the fuselage from heat radiation, they are used primarily to reduce heat loss from the exhaust system. The reduction of heat loss improves engine performance.

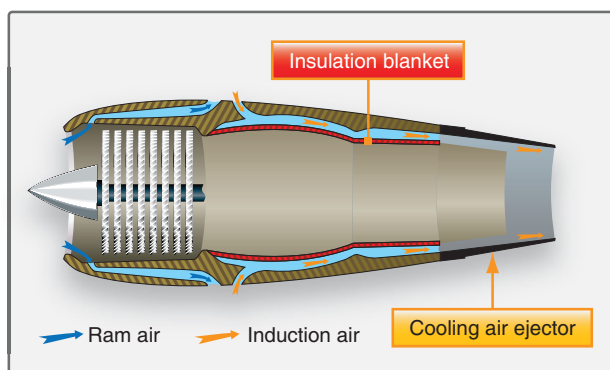


Figure 1-73. Exhaust system insulation blanket.

There are two types of exhaust nozzle designs: the converging design for subsonic gas velocities and the converging-diverging design for supersonic gas velocities. These exhaust nozzle designs are discussed in greater detail in Chapter 2, Induction and Exhaust Systems.

The exhaust nozzle opening may be of either fixed or variable area. The fixed-area type is the simpler of the two exhaust nozzles since there are no moving parts. The outlet area of the fixed exhaust nozzle is very critical to engine performance. If the nozzle area is too large, thrust is wasted; if the area is too small, the engine could choke or stall. A variable-area exhaust nozzle is used when an augmentor or afterburner is used due to the increased mass of flow when the afterburner is activated. It must increase its open area when the afterburner is selected. When the afterburner is off, the exhaust nozzle closes to a smaller area of opening.

Gas Turbine Engine Bearings and Seals

The main bearings have the critical function of supporting the main engine rotor. The number of bearings necessary for proper engine support is, for the most part, determined by the length and weight of the engine rotor. The length and weight are directly affected by the type of compressor used in the engine. Naturally, a two-spool compressor requires more bearing support. The minimum number of bearings required to support one shaft is one deep groove ball bearing (thrust and radial loads) and one straight roller bearing (radial load only). Sometimes, it is necessary to use more than one roller bearing if the shaft is subject to vibration or its length is excessive. The gas turbine rotors are supported by ball and roller bearings, which are antifriction bearings. [Figure 1-75] Many newer engines use hydraulic bearings, in which the outside race is surrounded by a thin film of oil. This reduces vibrations transmitted to the engine.

In general, antifriction bearings are preferred largely because they:

- Offer little rotational resistance,
- Facilitate precision alignment of rotating elements,
- Are relatively inexpensive,
- Are easily replaced,
- Withstand high momentary overloads,
- Are simple to cool, lubricate, and maintain,
- Accommodate both radial and axial loads, and
- Are relatively resistant to elevated temperatures.