CHAPTER 1

JET ENGINE THEORY AND DESIGN

Every rating or specialty has a language of its own. The Aviation Machinist's Mate (AD) is no different. To be a good technician, we must learn and understand the language (terms and theories) necessary for a thorough understanding of your specialty. With this basic understanding, we will develop the skills to recognize, analyze, and correct problems with jet engines. Without it, you become a "parts changer" unable to recognize possible reasons for the problem and analyze them. This chapter contains the basics necessary for the AD to build a strong foundation. You will learn the theory, terms, types of engines, and major parts of jet engines.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. State the theory of jet propulsion.
2. Identify the different types of engines and their major assemblies.
3. Identify the two types of engine designation standards.
4. Identify the common terms and variables affecting engine performance.

BASIC THEORY OF JET PROPULSION

Jet propulsion is the propelling force generated in the direction opposite to the flow of a mass of gas or liquid under pressure. The mass escapes through a hole or opening called a jet nozzle. A familiar example is the nozzle at the end of a fire hose. The nozzle forms a smaller passageway through which the water must flow. The nozzle increases the velocity of the water, giving the term, "a jet of water." Another example of the theory of jet propulsion is an inflated balloon. With the opening in the balloon closed (*Figure1-1*), there is no action because the pressure of the gas inside the balloon is equal in all directions. When you allow the opening to release the air *(Figure 1-2*), the balloon moves. Its movements appear to be in all directions. However, it is always moving in the opposite direction from the open end where the air is exiting.

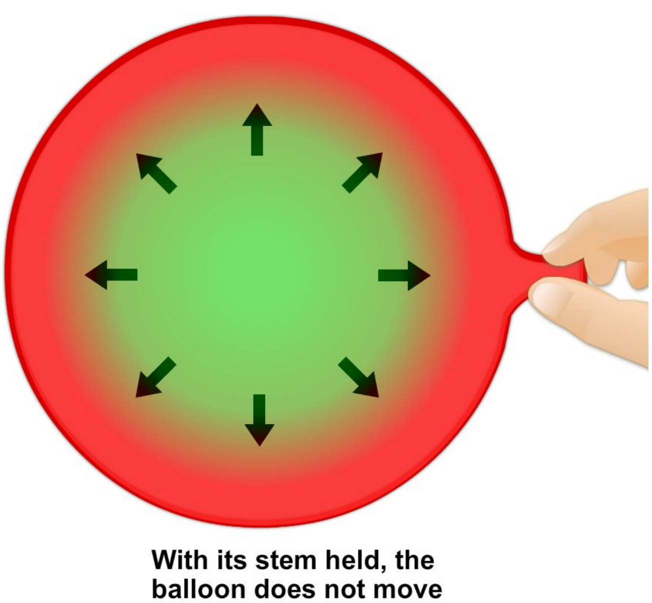


Figure 1-1 — Balloon example of restricting jet propulsion.

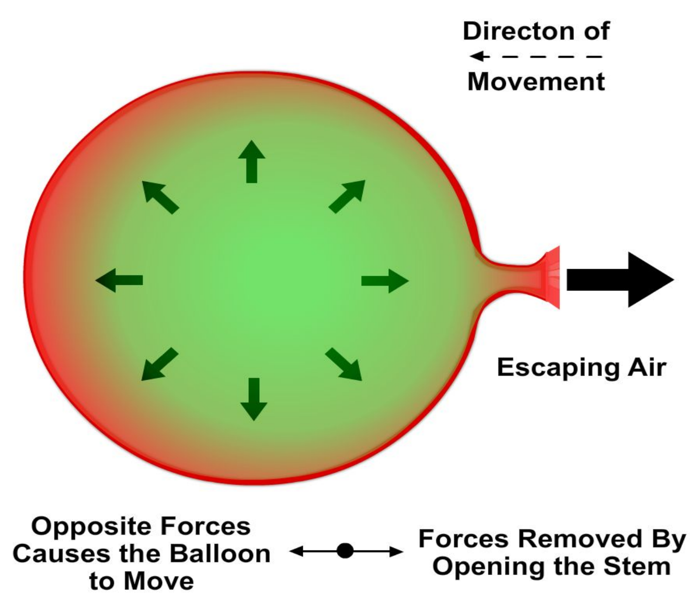


Figure 1-2 — Balloon example of jet propulsion theory.

Interaction Available

Look at the balloon example from the mechanic's point of view. Igniting a hydrocarbon fuel (a compound containing only hydrogen and carbon) and oxygen in a closed container *(Figure 1-3)* releases heat. The burning fuel causes the trapped gases to expand rapidly. The expansion occurs equally in all directions, the force of the pressure is balanced, and the container does not move.

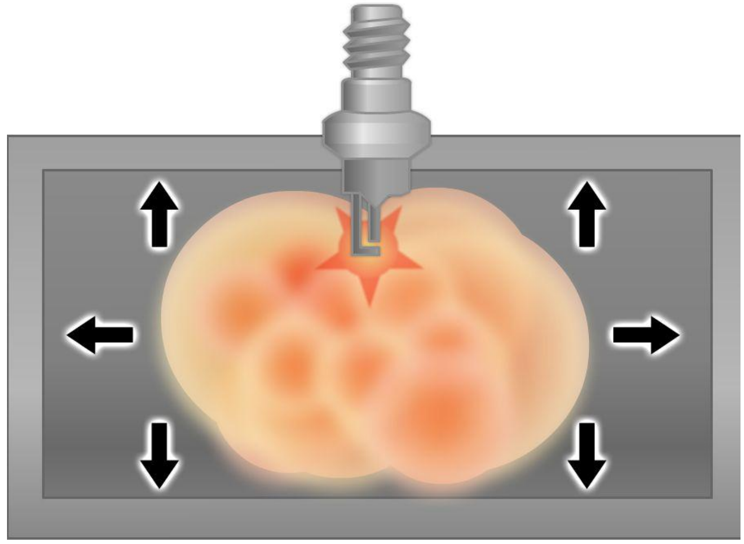


Figure 1-3 — Combustion in a closed vessel.

Rocket

When combustion takes place in an open container, the expanding gases rush out the opening at a high velocity (*Figure 1-4).* The release of internal pressure at the nozzle end of the container leaves an unbalanced pressure at the other end. The released pressure propels the container (a rocket) in the direction opposite of the exhaust gases. Obviously, propulsion depends solely upon internal conditions. The container does not "push against" external air. In fact, a complete vacuum would produce greater force, the basic operating principle for all jets. The rocket (propulsion unit) is one of the four main classes of jet engines. Before we continue on to the physical principles of jet engines, we will review the three other types of jet engines.

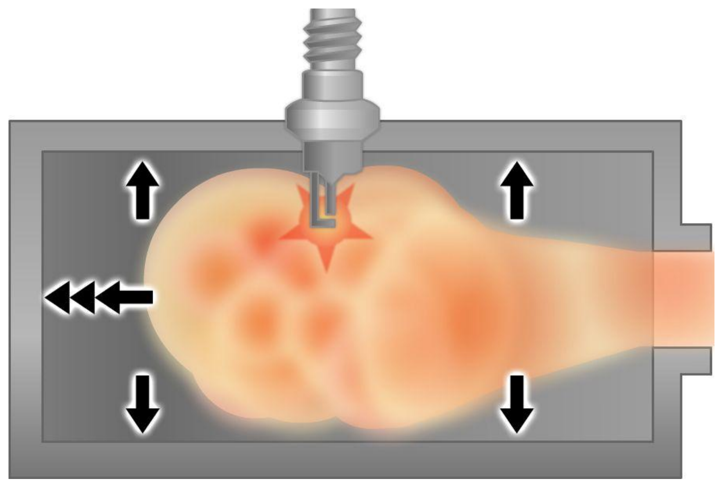


Figure 1-4 — Principles of jet propulsion.

The Ramjet

Suppose you attach a plain cylinder with open ends under the wing of an aircraft flying at high speed. Air enters the front of the duct and leaves at the rear. Nothing increases the force of flow through the duct. There is a loss of energy because of skin friction and airflow disturbances at the entrance and exit. If you add heat energy to the air as it passes through the duct, the air would expand and increase the jet velocity. *(Figure 1-5).* The amount of heat you can add is largely dependent upon the pressure of the air treated. A simple method of raising the pressure is to pass the air through a DIVERGENT entry nozzle. A divergent entry nozzle converts gaseous energy from velocity to pressure and temperature. This also provides a forward pressure wall for the jet to react. A CONVERGENT exit nozzle converts gaseous energy from pressure and temperature to velocity. The simple gas unit *(Figure 1-6)* created has little practical use because of the following:

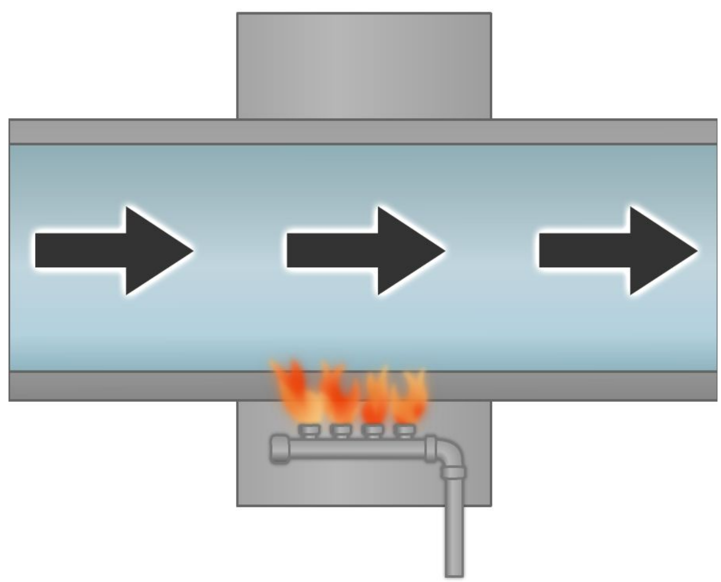


Figure 1-5 — Thermal duct with heat added externally to accelerate the airflow.

Interaction Available

- Air compression depends solely on “ram effect.”
- A limited amount of heat is added.
- Considerable heat is lost by radiation.

The next step is to improve the method of adding heat, through internal combustion. *Figure1-7* shows a divergent-convergent duct. Fuel is injected and burned, releasing heat directly into the airstream. This simple “Aero Thermo Dynamic Duct” (ATHODYD) or RAMJET is used in remotely piloted vehicle (RPV), cruise missiles, and National Aeronautics and Space Administration (NASA) on their X-15 and X-34 projects.

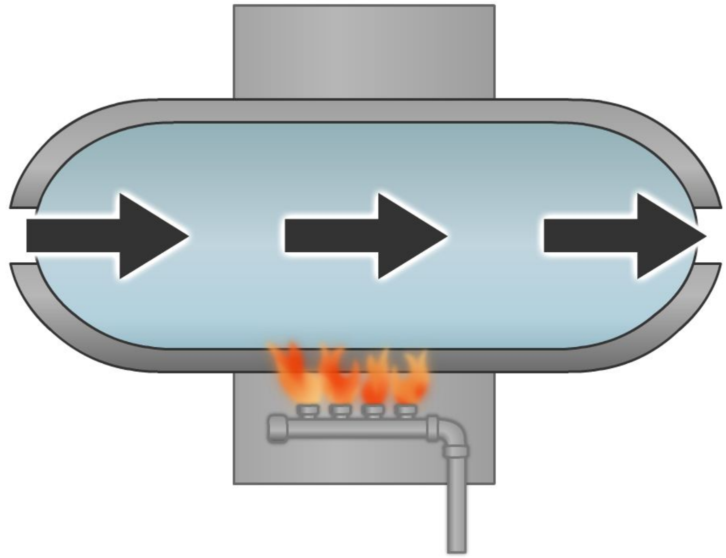


Figure 1-6 — A convergent discharge nozzle.

Interaction Available

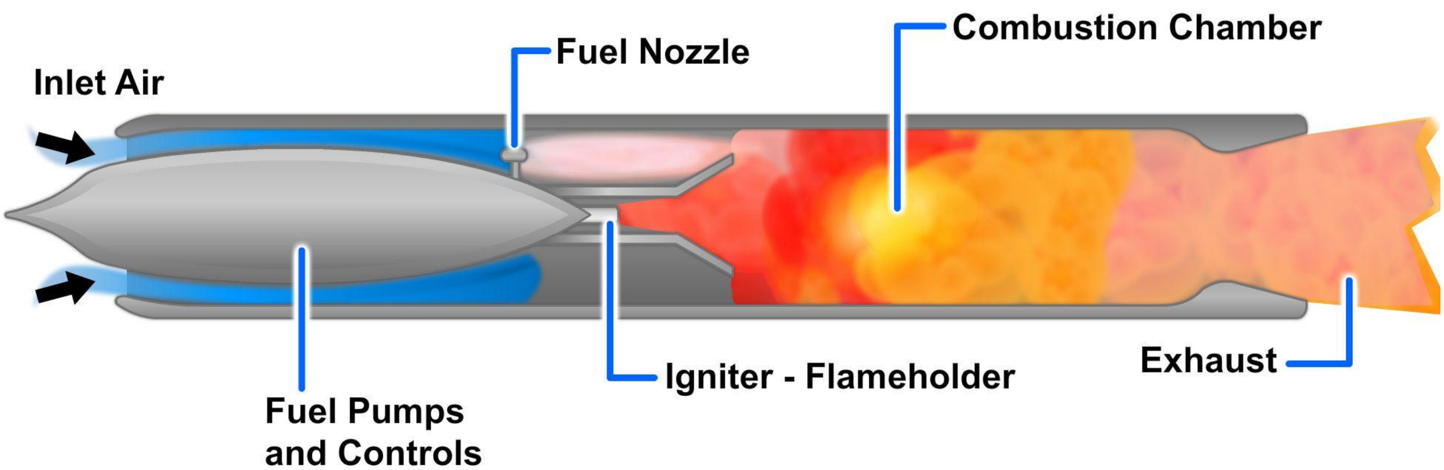


Figure 1-7 — the ramjet engine.

The Pulsejet Engine

The “intermittent impulse” jet engine *(Figure1-8),* known as the aero-pulse or pulsejet, improves compression by sacrificing the principle of continual power generation. The pulsejet is like the ramjet, but with a series of non-return shutter valves. Fuel injection nozzles located just aft of the shutter valves provide fuel. As the engine travels through the air, pressure on the nose opens the valve and rams air into the duct, mixing air with fuel. Igniting the combustible mixture creates a high pressure (from the expanding gases), closing the valves. The violent ejection of the gases forms a relatively low pressure area inside the duct, admitting a fresh charge of air through the flat spring valves. Because of the temperature of the duct and the return of part of the flaming exhaust gases, the rest of the charges burn without an igniter plug. This operating cycle or pulsation creates a loud buzzing

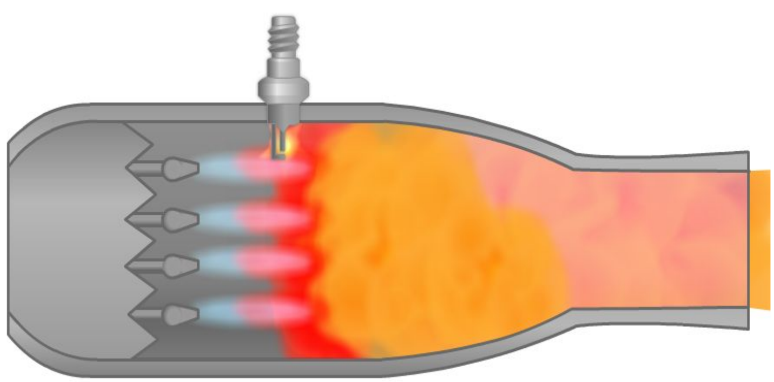


Figure 1-8 — The Aeropulse or pulsejet.

Interaction Available

sound. “Buzz bomb” described an early application of this unit, the German V-1 flying bomb designed for the German Air Ministry in 1933, and more recently used for ultra-light type aircraft.

We learned the basic principle of jet propulsion with the rocket. The ram jet taught us that adding heat would expand the gases and increase velocity. It also showed the amount of heat that is possible to add is dependent upon the amount of air available. The pulsejet proved that the more air an engine could compress the greater the power (thrust) it produced.

Gas Turbine Engine

The compressor is the greatest single reason the gas turbine engine runs and produces the thrust needed by modern aircraft. A basic axial-flow compressors job is to compress gaseous energy while accelerating it straight back along a single axis by means of a shaft with blades attached in rows, called a rotor. When the rotor shaft turns, the blades pull air into the engine. The air is then directed to a set of stationary blades, called stator vanes *(Figure1-9).*

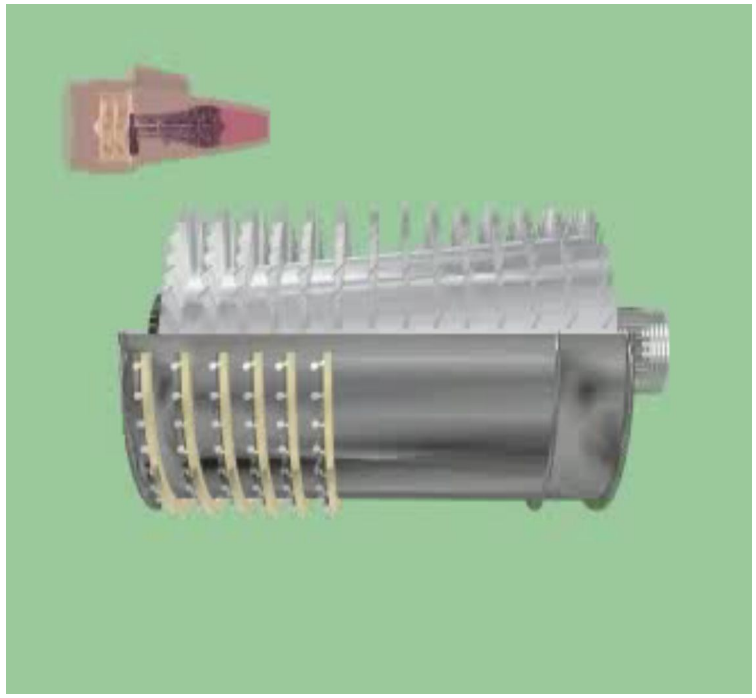


Figure 1-9 — Rotor and stator elements of an axial-flow compressor.

Interaction Available

The stator vanes direct air into the next set of compressor vanes. Each set of blades and vanes increases the compression of the air used for combustion. A greater number of stages amount to a higher compression ratio. Air from the compressor section goes into the combustion section. This area is where fuel and air are mixed and ignited. The burning of the fuel/air mixture produces hot, expanding gases that rush into the turbine rotors. The turbine rotors attach to the same shaft as the compressor rotors, so the turbine drives the compressor, making the engine self-sustaining. Finally, the exhaust gases exit the engine *(Figure 1-10)* as jet thrust.

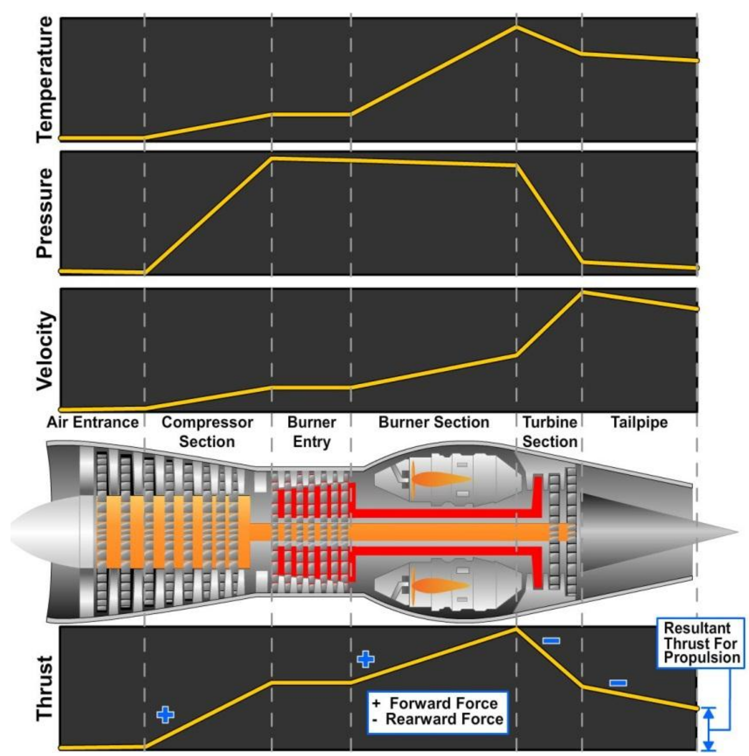


Figure 1-10 — Effects on airflow through an engine.

PHYSICAL PRINCIPLES OF JET PROPULSION

Physical principles govern the action of matter, motion, force, and energy. You study these actions in physics. An English scientist, Sir Isaac Newton, stated three laws of motion explaining jet propulsion. Another scientist, Bernoulli, explained the principle behind the convergent/divergent ducts we discussed earlier. These laws and principles have words or terms with specific meanings.

Understanding the exact meaning of the words is the key to understanding the principles of physics. So we will define some of the basic terms of physics we need for a good understanding of jet propulsion.

DEFINITION OF TERMS

Force is the action or effect on a body that changes the state of motion of the body. A force may move a body at rest, or it could increase/decrease the speed of a body, or change the direction of motion. The application of a force does not necessarily result in a change in motion. Force is any push or pull acting upon a body. Water in a can exerts a force on the sides and bottom of the can. A tugboat exerts a push or pull (force) on a barge. A man leaning against a bulkhead exerts a force on the bulkhead.

Matter is anything that occupies space and has weight.

Mass is the quantity of matter in a body measured in relation to its inertia. Mass and weight are similar terms, and they are often confused with each other. Weight is the common measurement to determine the quantity of matter with the pull of gravity on it. The following example will help you understand the difference between weight and mass. A person weighing 164 pounds on earth weighs 32 pounds on the moon because of the difference in the pull of gravity the mass of the person is the same. A mathematical formula for mass is as follows: Mass is equal to the weight of the object divided by the acceleration because gravity, or

$$M = \frac{W}{g}.$$

Slug is an English measurement of mass. A slug is mass with force and acceleration (due to gravity) taken into consideration. So, a 1-pound slug is the mass accelerated by 32 feet per second per second (32 ft/sec2) when acted upon by a force of 1 pound.

Energy is the capacity for doing work.

Work is done when a force moves a mass through a distance (work = force x distance). For example, if you raise a 100-pound weight 10 feet, 1,000 foot pounds of work was done. The amount of work is the same, regardless of how much time (rate) is involved.

Power is the rate of doing work, or

$$power = \frac{work}{time}.$$

In the above example, if the work were done in 10 seconds, power expended was 100 foot pounds per second. If it took 5 minutes (300 seconds), the rate of power is 3.3 foot pounds per second. We often talk of power in terms of horsepower.

Horsepower is the English measurement for mechanical power and is 33,000 foot pounds per minute, or 550 foot pounds per second. (A foot pound is the energy required to lift a 1-pound weight 1 foot.)

Speed is the distance a body in motion travels per unit of time. It is expressed in terms like *miles per hour* (MPH) and *feet per second.*

Velocity is speed in a given direction. The symbol *V* represents the term *velocity.*

Acceleration (a) is the rate of velocity change. This definition is not based on distance traveled. Acceleration is the gain or loss of velocity with time. Negative acceleration is commonly called deceleration.

$$Acceleration = \frac{final\ velocity\ (V_2) - initial\ velocity\ (V_1)}{time\ (t)}$$

or

$$a = \frac{V_2 - V_1}{t}$$

Acceleration due to gravity is 32.2 feet per second per second (or feet per second squared). This means that a free-falling 1-pound object accelerates at 32.2 feet per second each second that gravity acts on it. We use the lower case *g* to express the acceleration due to gravity.

Standard day is a reference or standard. Standard day shows conditions at sea level: barometric pressure—29.92 inches of mercury (Hg); temperature—59.0 °F. Operation of engines at a temperature above or below this temperature will proportionally affect thrust output by as much as 15 or 20 percent. As the temperature of a slug of air increases, the molecules move faster. They run into each other with more impact, and move further apart. This decreases the density of the air. With the decrease in density, the weight of the air is less, and the thrust produced is proportional to the weight of the slug of air.

Pressure effect is an increase in pressure, resulting in more molecules per cubic foot, which, in turn, increases the weight of the slug of air. The weight of the air affects thrust output.

Ram effect is defined simply as more air arriving at the engine intake than the engine can ingest.

Ram recovery is the airspeed at which ram pressure rise is equal to friction pressure loss. This speed varies with duct design factors. Mach 0.2, or 150 miles per hour, is a representative reference number for the beginning of ram effect.

Now let's apply the terms we learned to the principles of thrust.

NEWTON'S LAWS OF MOTION

Newton's first law *(Figure1-11, view A),* states "A body (mass) at rest tends to remain at rest, and a body in motion tends to move at a constant speed, in a straight line unless acted upon by some external force." Newton's second law *(Figure 1-11, view B),* states "An unbalance of force on a body tends to produce an acceleration in the direction of force, and that acceleration, if any, is directly proportional to the force and inversely proportional to the mass of the body." This law simply stated is "force is proportional to the product of mass and acceleration"

or

$$F = MA$$

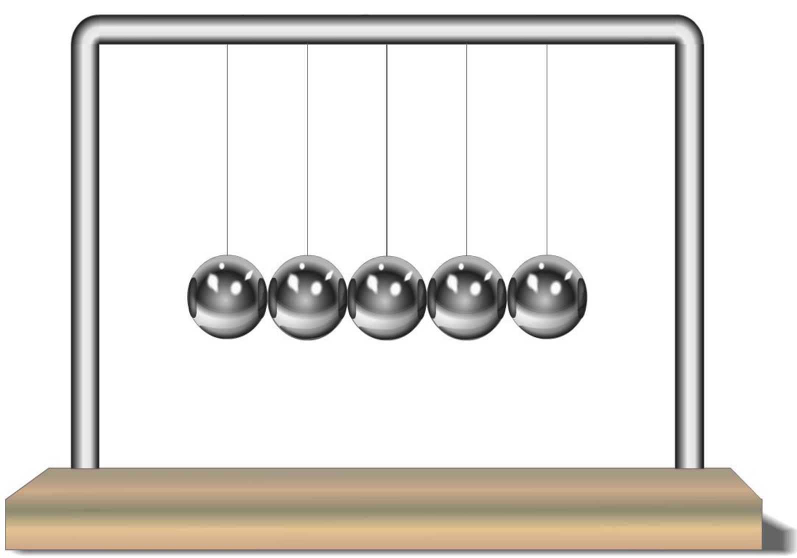
where

F = force, in pounds;

M = mass, in slugs; and

A = acceleration, in feet per second per second.

His third law (*Figure 1-11, view C)* states that "for every acting force (action) there is an equal and opposite reacting force (reaction)."The action reaction is simultaneous and it does not matter which is



Interaction Available

Figure 1-11 — Newton's three laws, view A, B, and C.

the action and which is the reaction, both forces are a part of a single interaction and neither force exists without the other. We learned this principle earlier with the rocket.

JET ENGINE TYPES AND DESIGNATION

We learned the four basic types or classes of jet engines: rocket, pulsejet, ramjet and gas turbine. As an AD, you will work with the gas turbine engines. Under gas turbine engines are four types: turbojet, turboprop, turbofan, and turboshaft.

Turbojet

Turbojet engines are the basis for all other gas turbine engines. We already know their cycle. Air is drawn into the turbojet engine, compressed, mixed with fuel, and burned continuously. The exhaust product of this burning operates the turbine for the compressor, producing thrust which propels the aircraft, such as F-5, T-38, and the Concord passenger aircraft use a Turbojet engine. Adding fans, propellers, or free turbines changes the basic turbojet into a turboshaft, turboprop, or turbofan.

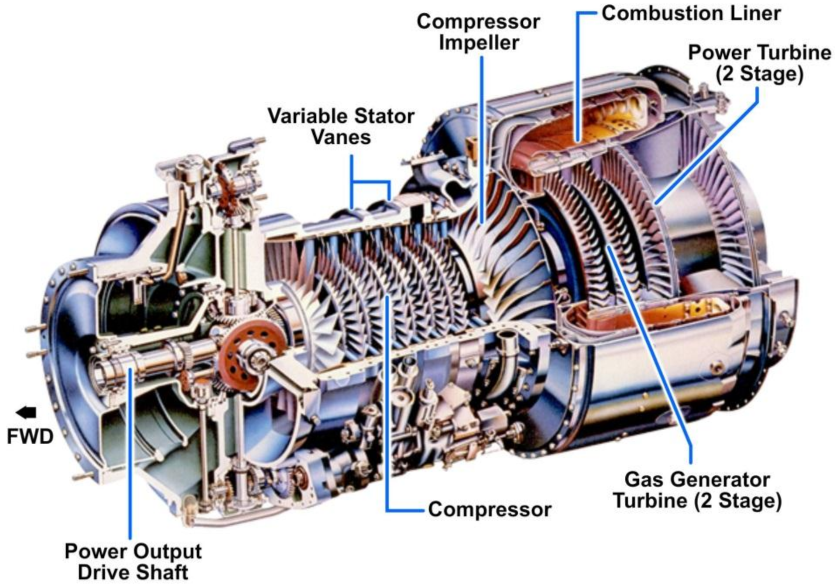


Figure 1-12 — typical turboshaft engine.

Turboshaft

Turboshaft engines use the free turbine principle. The gas generator turbine drives the compressor to sustain engine performance. The power turbine drives the helicopter rotors through driveshaft's and gearboxes. The gas generator is located immediately aft of the combustion section and the power turbine is just aft of the gas generator turbine. Exhaust gases drive the gas generator turbine and a power turbine. *Figure 1-12* shows a cutaway view of a turboshaft engine.

Turboprops

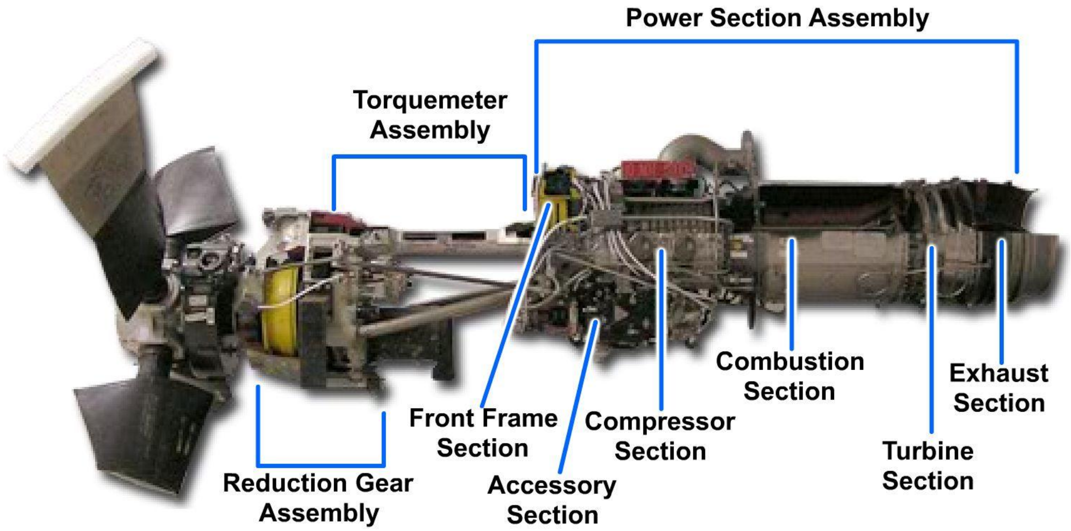


Figure 1-13 — Turboprop engine.

Turboprops have a reduction gear assembly, torquemeter assembly, compressor section, combustion section (or chambers), turbine, and exhaust section, most of which operate in the same manner as their counterparts in the turbojet. The difference is in the turbine. It sends increased power, generated by the exhaust gases passing through additional stages of the turbine, to the torquemeter assembly and then to the reduction gear assembly *(Figure 1-13).* A propeller mounted on the reduction gear assembly provides thrust for the plane.

Turbofan

The turbofan gas turbine engine is the same as a turboprop, except that a duct-enclosed, axial-flow fan (*Figure 1-14*) replaces the reduction gearbox assembly and prop. The fan is either part of the first-stage compressor blades or mounted as a separate set of fan blades. The high pressure turbine drives the high pressure compressor (N2) and the low pressure turbine drives the fan (N1). The fan uses 30 to 60 percent of the available propulsive energy. The propulsive efficiency, thrust, and fuel consumption for the turbofan engine falls somewhere between those of the turbojet and the turboprop engines. Some examples of what the Turbofan engine powers are the F-18, F-110, F-111for military use, and Boeing 787 for commercial use.

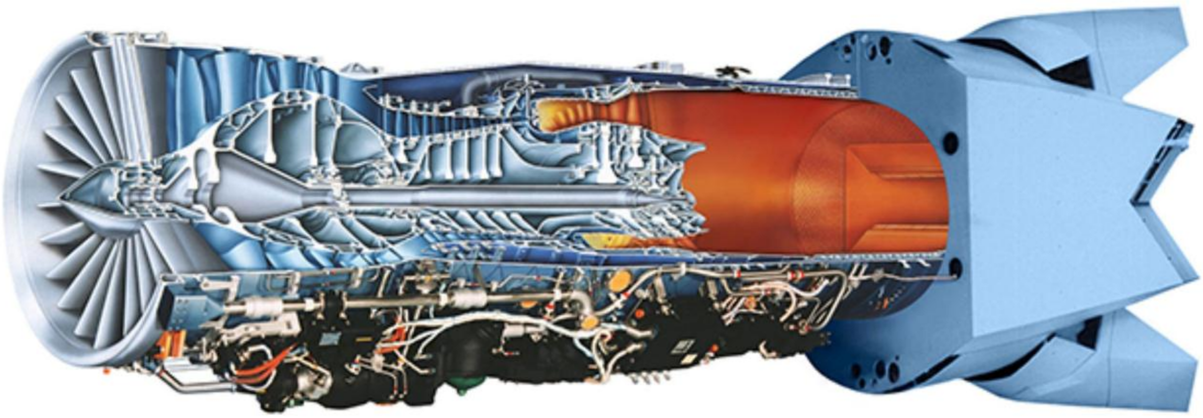


Figure 1-14 — Pratt and Whitney F-119 engine.

ENGINE DESIGNATION SYSTEMS

The engine designation systems use standard symbols to represent the type, manufacturer, and model of aircraft engines used in military. Knowing the designation systems gives you basic information about the engine. Two engine designation systems are in use today. The old system is under *Air Force-Navy Aeronautical (ANA) Bulletin* No. 306. The new system is under MIL-HDBK-1812 and includes all newly developed gas turbine engines of the Air Force, Army, and Navy. ANA Bulletin No. 306 will remain in effect until all engines manufactured before the introduction of MIL-HDBK-1812 have had a change to the configuration, the performance, or been dropped from service.

MIL-HDBK-1812

The purpose of this standard is to provide type designation systems and procedures for use by the Department of Defense to standardize the identification of photographic equipment, aerospace vehicle propulsion engines. Aeronautical equipment, support equipment, and electronic material. In addition this standard defines the method for obtaining nomenclatures and type designations.

Type Indicator

The type indicator part of the engine designation shall consist of the appropriate type letter symbol, together with a type numeral. The type numeral used in connection with the type letter shall be assigned consecutively by the services, beginning with number 100 for the Air Force, 400 for the Navy, and 700 for the Army.

J.............Turbojet

T ....Turboshaft, turboprop

F ....Turbofan

O………...Opposing

R………....Radial

P…………Any type not listed

Manufacturer's Symbols

The second part of the designation consists of a dash and a two-letter symbol showing the manufacturer, as follows:

Air Research Division, Garrett Corp ....GA

Allison Division, General Motors Corp ....AD

Bell Aerosystems Co…………………………………………BA

Continental Aviation and Engineering Corp ....CA

General Electric Company..GE

Lockheed Propulsion Co……………………………………LP

Lycoming Division, Avco Corp ....LD

Pratt and Whitney Aircraft Division, United Aircraft Corp...PW

Rolls Royce, Ltd ....RR

United Aircraft of Canada, Ltd. ....CP

Curtiss-Wright Corp ....WA

Special manufacturer symbols show when two manufacturers are jointly producing an engine. In that case, the manufacturer symbol consists of one letter from the symbol for each manufacturer.

NOTE
Manufacturer letter symbols are not the same as manufacturer code symbols. The code symbols are with the federal supply code for manufacturers.

Model Indicator

The model indicator consists of a dash and a model number, or a dash and a model number with a suffix letter you assign, and a model number for each configuration of a given engine. Each service has a block of numbers they use consecutively, just like the type indicator number. The following is the beginning number for each service.

100 .... Air Force

400 .... Navy

700 .... Army

NOTE
Should any service use another's designated engine, the designation remains the same unless there is a model change. In this case, only the model indicator is changed, showing the engine has been modified.

Suffix Indicator

When an engine with an existing designation requires the addition of a suffix letter as a result of minor design changes, the engine shall be reflected by the addition of the suffix letter A or the next consecutive suffix letter for the specific engine, except the letters I, O, and W.

The following are examples of the various designations:

MIL-HDBK-1812

F401-PW-400-A

F = Turbofan

401 = Second Navy turbofan in new designation system

PW = Pratt and Whitney Aircraft Division, United Aircraft Corporation

400 = First Navy model of this particular engine

A= Suffix Indicator

Table 1-1 lists by engine type some of the more common designations and their associated Navy/Marine aircraft. You will notice that included with the turboprop and turbofans are two civilian engines, which have the manufacturer's designations.

Table 1-1 — Navy Aircraft and Associated Engines

ENGINE TYPE	DESIGNATION	AIRCRAFT
TURBOJET	J60-P-3 JT8D-9A J52-P-408	T-39, C-9 EA-6B
TURBOFAN	F404-GE-402 F414-GE-400 F119-PW-100 F402-RR-404 F405-RR-401 CFM-56-2A-2 CFM-56-7B27	F/A- 18C F/A-18 E/F, EA-18G F-35 AV-8A T-45 E-6,C-40 P8-A
TURBOPROP	T56-A-14 T56-A-16 T56-A-426 T56-A-427 PT6A-68 PT6A-34B	P-3C KC-130 C-2 E2C T-6 A/B T-44
TURBOSHAFT	T700-GE-401C T64-GE-419 250-C20J	SH B/R/MH/HH-60 H-53 TH-57 B/C

JET TURBINE ENGINE MAJOR ASSEMBLIES

There are many different models of jet engines in the Navy today. Developments over the years have produced a more efficient engine, both from a performance and maintenance point of view. These modern engines are more complex, but they still operate according to the same basic principles. This section discusses the major parts found in various gas turbine engines, their name (nomenclature), construction, purpose, and operating characteristics. Major components of all gas turbine engines are basically the same. The nomenclature of the various engines in current use, however, may vary slightly because of differences in manufacturers' terminology. Through experience and reading the many and varied publications, the mechanic recognizes the engine components, regardless of the terminology used.

A turbojet engine consists of the following sections and systems:

- Air intake section
- Compressor section
- Combustion section
- Turbine section
- Exhaust section
- Accessory section
- Systems necessary for starting, lubrication, fuel supply, and auxiliary purposes, such as anti-icing, cooling, and afterburning

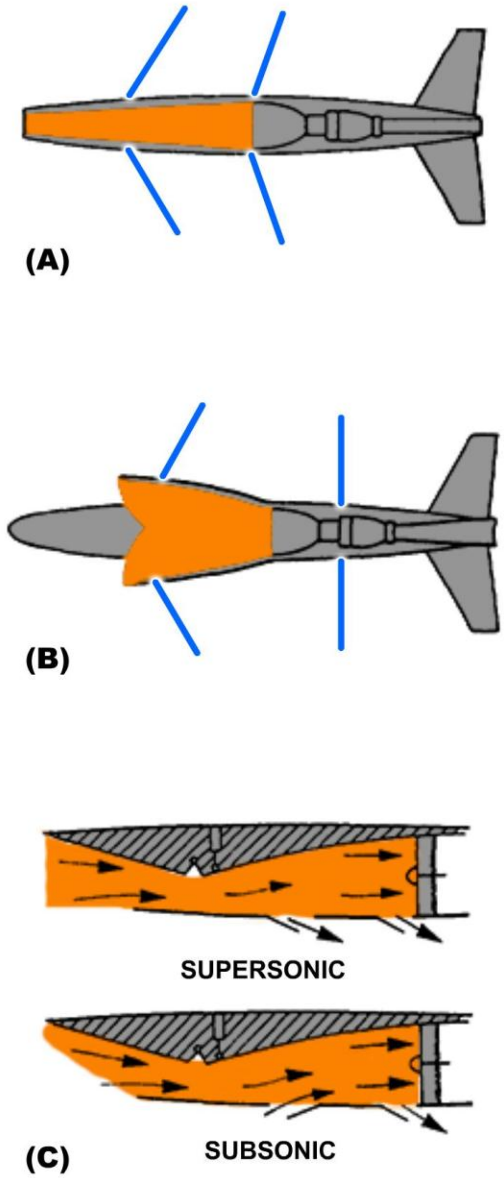


Figure 1-15 — Air entrance designs. (A) Single entrance; (B) dual. entrance; (C) variable entrance.

AIR INTAKE SECTION

The air intake section directs incoming air to the compressor entrance with a minimum of energy loss. Additionally, it must deliver this air under all flight conditions with as little turbulence and pressure variation as possible. Normally, the engine inlet is part of the airframe. Because of its importance in engine performance we include it here. Proper duct design contributes to aircraft performance by increasing ram recovery and limiting pressure drops. Divergent inlet designs changes ram air velocity into high static pressure at the compressor inlet. Friction due to air passing over the duct surfaces and through bends in the duct causes pressure drops and differences. Performance achieved through proper duct design is only half the story. Careful construction and maintenance is essential to maintain designed performance. Small amounts of airflow distortion result in loss of engine efficiency and unexplainable compressor surges. This is caused by poor sheet metal work, protruding rivet heads, or poor welds. Engine inlet ducts take a variety of shapes, depending on the position of the engine and purpose of the aircraft.

Two methods of classifying inlet ducts are as follows:

- Single entrance and divided entrance
- Subsonic and supersonic ducts

Single Entrance/Divided Entrance

The simplest type of air ducts are on engines mounted in pods under the wing. The single entrance (*Figure 1-15, view A*) gets maximum ram pressure through the straight flow. It’s used where an unobstructed entrance lends itself readily to a single, short, straight duct. Some aircraft, because of fuselage design or internal parts, have to use a dual or divided entrance, as shown in *Figure 1-15, view B*. These dual entrances are in the wing root, or in scoops on the side of the fuselage. Either placement presents more problems to the aircraft and engine designers than the single entrance. Problems are caused by boundary layer airflow and the difficulty in obtaining enough entrance area without creating too much drag.

Subsonic/Supersonic Ducts

Modern Navy aircraft capable of supersonic flight pose another problem to aircraft designers because the airframe can withstand supersonic velocity air, but the engine cannot. There are two methods commonly used to diffuse the intake air and slow its flow to subsonic speeds during supersonic flight. One is to create a shock wave in the intake airstream, which will disrupt the flow and cause a decrease in velocity. The other method is to vary the area, or geometry, of the intake duct. The F/A 18 A-D uses the airframe intake ducting as a fixed opening/channel to the engine inlet and the air is slowed down during supersonic flight due to the divergent design and a 'Vortex Generator" located in the inlet, or incorporating movable ramps as shown in *Figure 1-15, view C*, to change the area and shape of the intake duct.

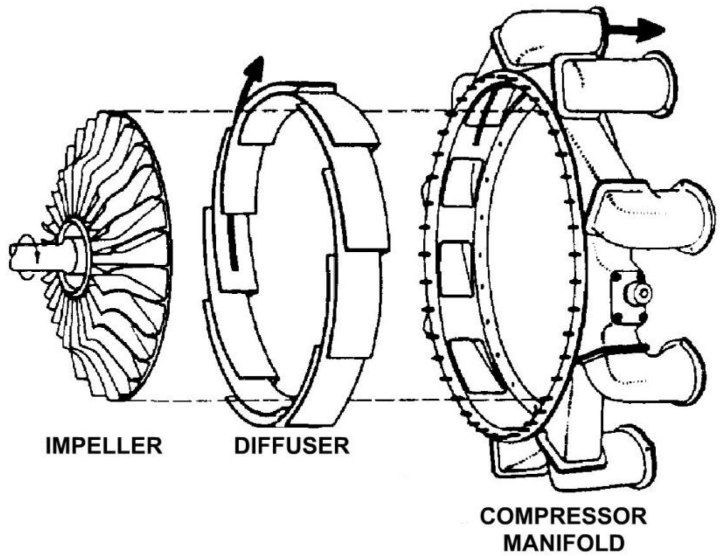


Figure 1-16 — Elements of the centrifugal compressor.

COMPRESSOR SECTION

The primary function of the compressor is to supply air in enough quantity to satisfy the requirements of the combustion burners. Specifically, the compressor increases the air mass received from the air inlet duct and directs it to the burners in the quantity and at the pressures required. A secondary function is to supply compressor bleed air for various purposes in the engine and aircraft. The compressor provides space for mounting accessories and engine parts. There are two basic types of compressors. The compressor type is also the engine type, so a centrifugal-flow compressor is in a centrifugal engine. Centrifugal-flow compressors have a compression ratio of 5:1. Present-day axial flow compressors have compression ratios approaching 15:1 and airflows up to 350 lb. The addition of a fan raises these values to 25:1 and 1,000 lb. /sec.

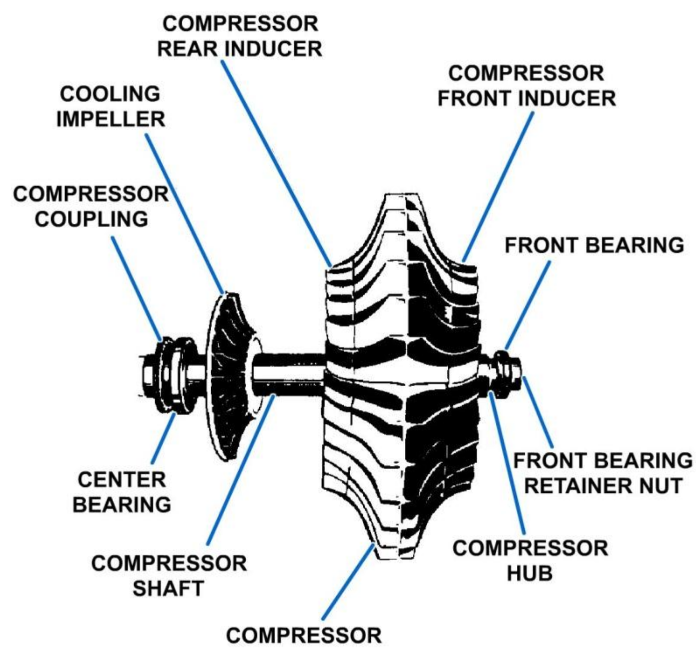


Figure 1-17— Double entry centrifugal-flow compressor.

Centrifugal-Flow Compressors

The single entry centrifugal-flow compressor *(Figure 1-16)* consists of an impeller (rotor element), a diffuser (stator element), and a manifold. The impeller picks up and accelerates air outward to the diffuser. The diffuser directs air into the manifold. The manifold distributes air into the combustion section.

Double entry centrifugal-flow compressors *(Figure 1-17)* handle the same airflow with a smaller diameter. Small multi-stage centrifugal-flow engines used in aircraft *(Figure 1-18),* or as Auxiliary Power Units (APUs) that take advantage of this feature.

Axial-Flow Compressors

The term *axial flow* applies to the axial (straight-line) flow of air through the compressor section of the engine. The axial-flow compressor has two main elements—a rotor and a stator. Each consecutive pair of rotor and stator blades makes a pressure stage. The rotor is a shaft with blades attached to it. These blades impel air rearward in the same manner as a propeller, by reason 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. The action of the rotor increases the compression of the air. At each stage it accelerates rearward. The stator blades act as diffusers, partially converting high velocity to pressure. Maintaining high efficiency requires small changes in the rate of diffusion at each stage. The number of stages depends on the amount of air and total pressure rise required. A greater number of stages means a higher compression ratio. Most present day engines use from 10 to 16 stages.

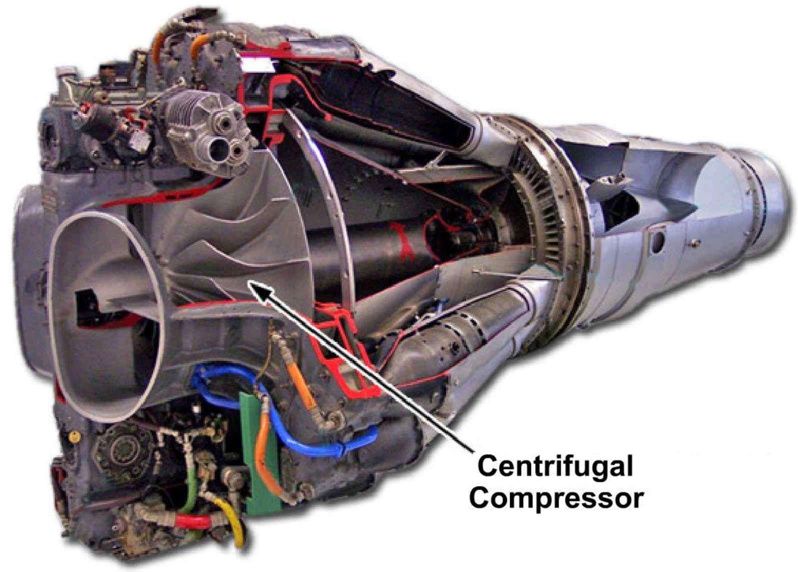


Figure 1-18 — Centrifugal-flow engine.

An axial-flow compressor follows the same rules and has the same limitations as an aircraft wing. The concept is more complicated than a single airfoil, because the blades are close together. Each trailing edge blade affects the next leading edge. This cascade effect is of prime importance in determining blade design and placement. The axial-flow compressor has its disadvantages, the most important of which is the stall problem. If, for some reason, the angle of attack—the angle at which the airflow strikes the rotor blades—becomes too low, the pressure zones, shown in *Figure 1-19*, will be of low value, and the airflow and compression will be low. If the angle of attack is high, the pressure zones will be high, and the airflow and compression ratio will be high. If the angle of attack is too high, the compressor will stall.

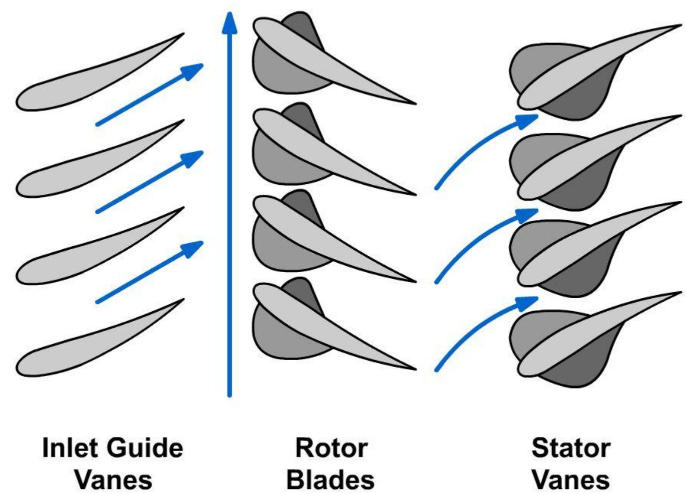


Figure 1-19 — The cascade effect.

The airflow over the upper foil surface will become turbulent and destroy the pressure zones. This will decrease the compression airflow. The angle of attack will vary with engine rpm, compressor-inlet temperature, and compressor discharge or burner pressure. Any action that decreases airflow relative to engine speed will increase the angle of attack and increase the tendency to stall.

The decrease in airflow may result from a too-high compressor-discharge pressure. During ground operation of the engine, the prime action that causes a stall is choking. If there is a decrease in the engine speed, the compression ratio will decrease with the lower rotor velocities. With a decrease in compression, the volume of air in the rear of the compressor will be greater. This excess volume of air causes a choking action in the rear of the compressor with a decrease in airflow. This, in turn, decreases the air velocity in the front of the compressor and increases the tendency to stall. If no corrective action is taken, the front of the compressor will stall at low engine speeds.

Another reason for engine stall is high compressor inlet air temperatures. High-speed aircraft may experience an inlet air temperature of 250°F because of ram effect. Another reason for engine stall is high compressor inlet air temperatures. These high temperatures cause low compression ratios (due to air density changes) and will also cause choking in the rear of the compressor. This choking-stall condition is the same stall condition caused by low engine revolutions per minute (RPM). Each stage of a compressor should develop the same pressure ratio as all other stages. When the engine slows down or the compressor inlet air temperature climbs, the front stages supply too much air for the rear stages to handle, and the rear stages will choke.

There are five basic ways manufacturers can correct this front-end, low-speed, high temperature stall:

1. Lowering the angle of attack on the front stages so the high angles at low engine speed are not stall angles.
2. Installing a bleed valve in the middle or rear of the compressor to bleed air and increase airflow in the front of the compressor at low engine speeds.
3. Splitting the compressor into two rotors and designing the front rotor rpm to decrease more than the rear rotor at low speeds, so low front-rotor speed will equal the low choked airflow.
4. Installing variable inlet-guide vanes and variable stators in the front of the first series of compressor stages so the angle of attack is changed at low engine speed.
5. Using a variable-area exhaust nozzle to unload the compressor during acceleration.

NOTE
A combination of any of the above may be used.

The stator has rows of blades or vanes dovetailed into split rings and attached inside an enclosing case. The stator vanes project radially toward the rotor axis and fit closely on either side of each stage of the rotor. The compressor case, into which the stator vanes fit, is horizontally divided into halves. Either the upper or lower half is removed for inspection or maintenance of the rotor and stator blade. The function of the vanes is twofold.

They receive air from the air inlet duct or from each preceding stage of the compressor. It is delivered to the next stage or to the burners at a workable velocity and pressure.

They also control the direction of air to each rotor stage to get the maximum compressor blade efficiency. The rotor blades are in front of the inlet guide vane assembly. The guide vanes impart a swirling motion to the air entering the compressor in the direction of engine rotation. This motion improves the aerodynamic characteristics of the compressor by reducing the drag on the first-stage rotor blades. The inlet guide vanes are curved and airfoil shaped.

The vanes are made of steel alloy, many with a protective coating to prevent erosion. They are welded to steel inner and outer shrouds. The variable inlet-guide vanes are fitted and pinned to spherical bearings that are retained in the compressor front frame. At the discharge end of the compressor, the stator vanes straighten the airflow to cut turbulence. These are straightening vanes or the exit guide vanes. The casings of axial-flow compressors support the stator vanes and provide the outer wall of the axial path the air follows. They also tap off compressor air for various purposes, such as cockpit pressurization and heating, or fuel tank pressurization. There are outlet ports for bleeding off compressor air at different stages, depending on the pressure or temperature desired. (The temperature rises proportionately with pressure increase.)

The stator vanes are made of steel with corrosion- and erosion-resistant qualities. Frequently they are enclosed by a band of suitable material to simplify the fastening problem. The vanes are welded into the shrouds; then, the outer shroud is secured to the compressor housing inner wall by radial retaining screws. The rotor blades are made of stainless or semi-stainless steel. Methods of attaching the blades in the rotor disc rims vary in different designs. They commonly fit into discs by either bulb *(Figure 1-20)* or fir-tree *(Figure 1-21)* type roots.

The blades then lock by grub screws, peening, locking wires, pins, or keys. The stator has rows of blades or vanes dovetailed into split rings and attached inside an enclosing case. The stator vanes project radially toward the rotor axis and fit closely on either side of each stage of the rotor. Compressor blade tips reduce in thickness by cutouts, and are referred to as blade “profiles.” These profiles allow rubbing when rotor blades come into contact with the compressor housing or shroud without serious damage. This condition may occur if rotor blades become excessively loose or by reduction of rotor support by a malfunctioning bearing. Even though blade profiles reduce such chances, occasionally a blade may break under duress of rubbing and cause considerable damage to compressor blades and stator vane assemblies.

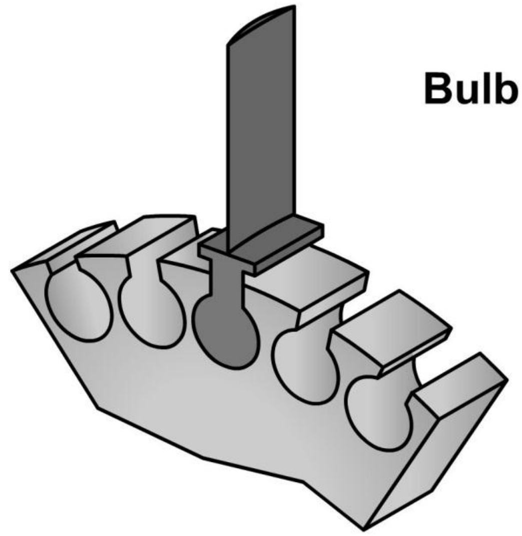


Figure 1-20 — Bulb root-type rotor blades.

The blades vary in length from entry to discharge. The annular working space (drum to casing) reduces progressively toward the rear by the increase in the rotor drum diameter. The rotor may feature either drum-type or disc-type construction. The entire assembly is held together by through-bolts, tie-bolts, or bolted individually to one another. The drum-type rotor *(Figure 1-22)* is machined from a single aluminum alloy forging. Dovetail grooves are machined around the circumference of the drum for blade retention. Provisions for bearing supports and splined drive shafts are on the front and rear faces of the drum. The disc-type rotor consists of separately machined discs and spacers flanged to fit one against the other in sequence.

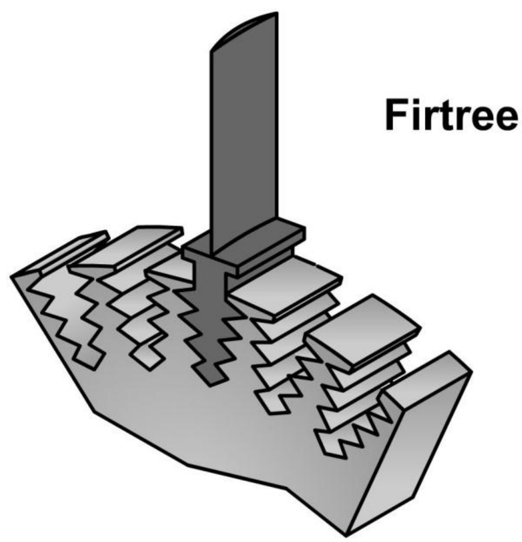


Figure 1-21 — Fir-tree root-type rotor blades.

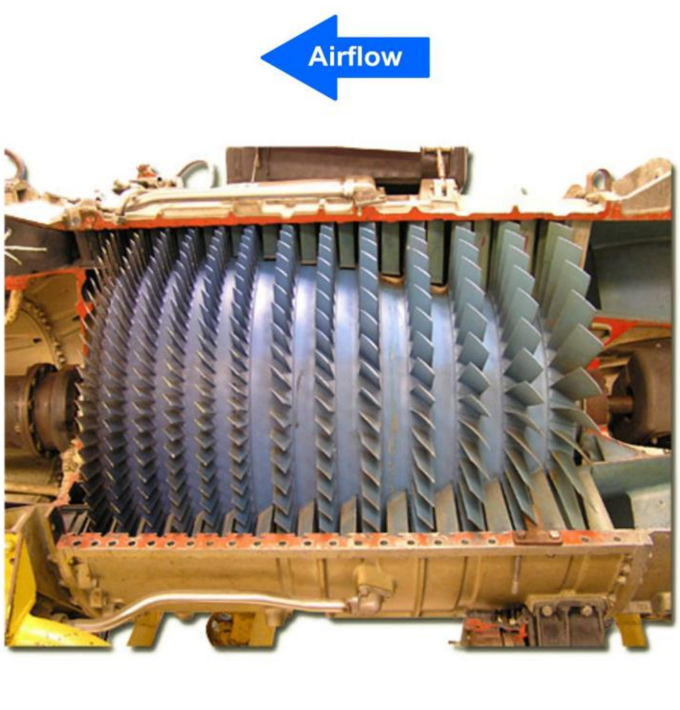


Figure 1-22 — Drum-type compressor rotor.

Blades may be attached to the disc rim by the dovetail or bulb design. Similar provisions to those on the drum-type assembly are made for bearing supports and splined drive shafts. Another method of rotor construction is to machine the discs individually, and shrink fit the discs over a steel drive shaft (heating the disc and freezing the shaft to assemble the rotor). However, this type of compressor construction is only satisfactory for compressors where rotor and centrifugal stresses are relatively low. The drum and disc-type rotor assemblies (*Figures 1-22 and 1-23).*

Many engine designs now use combination disc and drum compressor rotor assemblies due to their split spool design concept. The F404-GE-402 and the F414-GE-400 are examples of the combination compressor rotor assembly. The coverage of axial-flow compressors up to this point has dealt solely with the conventional single-rotor type. Actually, there are two configurations of the axial compressor now in use, the single rotor and the dual rotor, sometimes referred to as solid spool *(Figure 1-24)* and split spool *(Figure 1-25).*

One version of the solid-spool compressor uses variable inlet guide vanes. This is the arrangement found on the J79-GE-10 engine. The engine has a 17-stage compressor. The angles of the inlet guide vanes and the first six stages of the stator vanes are variable. During operation, air enters the front of the engine. Air is directed into the compressor at the proper angle by the variable inlet guide and variable stator vanes. The air is compressed and forced into the combustion section. A fuel nozzle extending into each combustion liner atomizes the fuel for combustion. These variables are controlled in direct relation with the amount of power the engine requires to produce the pilot's power lever position.

One version of the split-spool compressor is in General Electric's F404 engine. It uses two compressors with their respective turbines and interconnecting shafts that form two independent rotor systems. The axial-flow type of engine has definite advantages. The advent of the split-spool axial compressor made these advantages even more positive by offering greater starting flexibility and improved high-altitude performance.

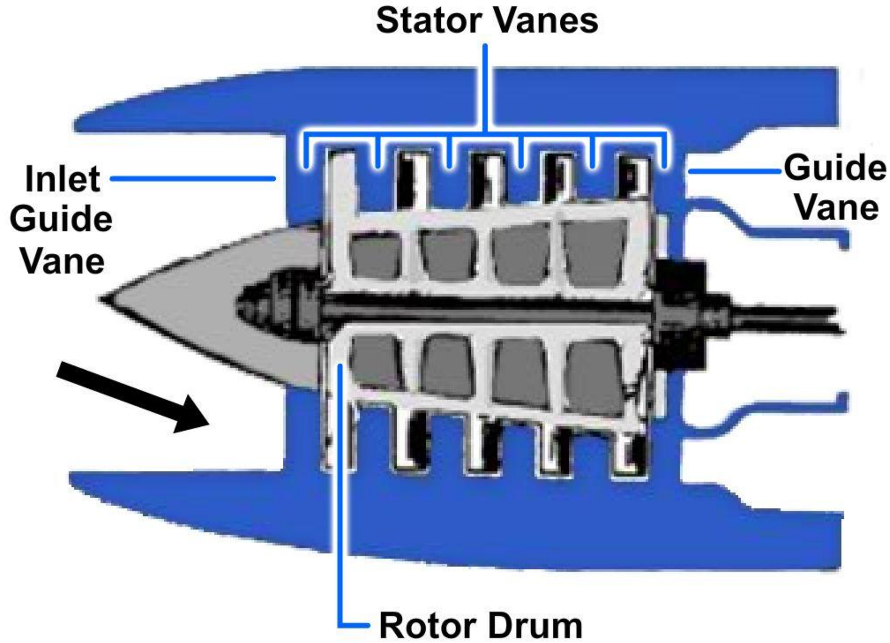


Figure 1-23 — disc type compressor rotor.

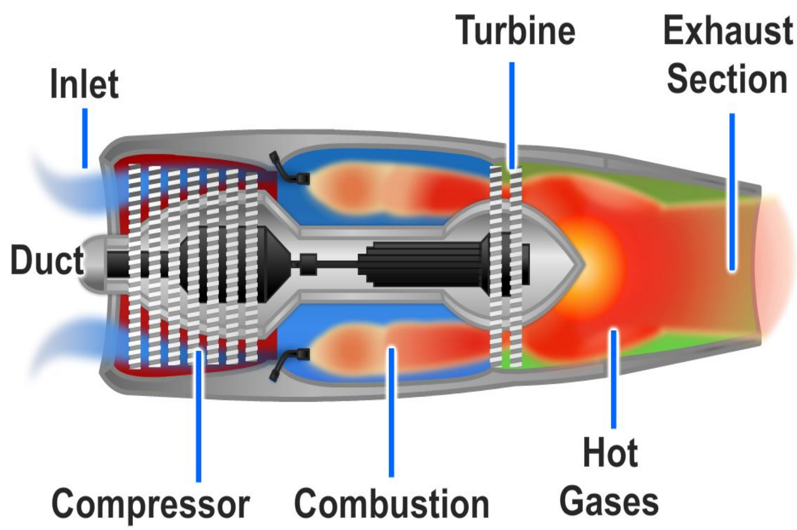


Figure 1-24 — Solid-spool compressor—single rotor turbine.

Figure 1-25 — Split-spool compressor- dual rotor turbine.

Interaction Available

The advantages of the axial-flow compressor are as follows:

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

The disadvantages of the axial-flow compressor are as follows:

- Good efficiencies are possible over narrow rotational-speed range only.
- Difficulty of manufacture and high cost.
- High starting-power requirements.

Because of its similarity to compressors, the fan of a turbofan engine should be mentioned now. The fan accelerates a large mass of air rearward. It requires relatively low drive power, and has a pressure ratio of 2 to 1 or less. It can be thought of as a pre-compressor, as air enters the compressor inlet at a pressure about 1.5-2.0 to 1 atmosphere.

COMBUSTION SECTION

The combustion section provides the means for and houses the combustion process. Its function is to raise the temperature of the air passing through the engine. This process releases energy contained in the air and fuel. The major part of this energy drives the compressor. The remaining energy creates the reaction (or propulsion) and passes out the rear of the engine in the form of a high-velocity jet.

The primary considerations in burning the fuel-air mixture include:

- Providing the means for proper mixing of the fuel and air to assure good combustion.
- Burning this mixture efficiently.
- Cooling the hot combustion products to a temperature that the turbine blades can withstand under operating conditions.
- Directing 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 arranged coaxially with the compressor and turbines. The chambers must be in a through-flow position to function efficiently. About one-fourth of the air entering the combustion chamber area mixes with the fuel for combustion.

This is primary air. The remaining air (secondary air) serves as flame control. Keeping the temperature of the heated gases down to a level at which the liners, turbine nozzles, or blades will not burn. These basic requirements apply to all combustion sections. Another general requirement of combustion chambers is air pollution emission reduction.

Pollution emissions are particles of matter, such as smoke, carbon monoxide, partially burned hydrocarbons, and nitric oxides. In general, exhaust smoke becomes a problem when combustors operate at pressure greater than 10 atmospheres and when the fuel-air ratio in the primary zone of the combustor is rich. For example, in the idle range of operation, both smoke particles and partially burned hydrocarbons emit. During the combustion process, emission levels of nitric oxide increase with temperature increases to about 2,600 °F. At this temperature, these emission levels begin to taper off. There is research being conducted to correct problems, but many new factors may influence the solution of the pollution problem. All combustion chambers contain the same basic elements: a casing, a perforated inner liner, a fuel injection system, some means for initial ignition, and a fuel drainage system to drain off unburned fuel after engine shutdown.

The three basic types of combustion chambers are as follows:

- The multiple chamber, or can.
- The annular, or basket.
- The can-annular.

Can Type

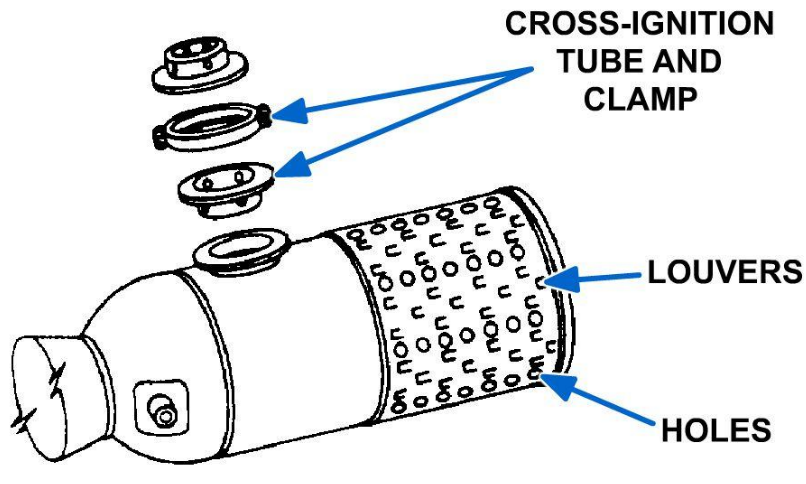


Figure 1-26 — Can-type combustion liner.

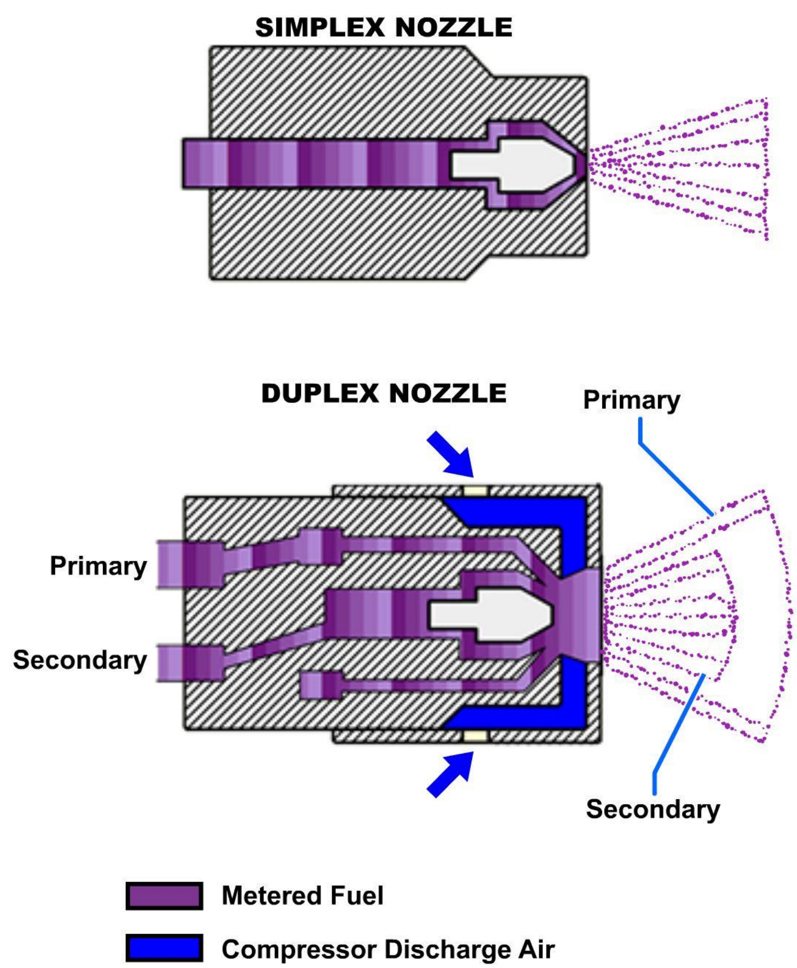


Figure 1-27 — simplex/duplex spray nozzles.

The can-type combustion chamber is typical of the type used on axial-flow engines. Can-type combustion chambers are arranged radially around the axis of the engine. The amount of chambers will vary in number. In the past (or development years) as few as 2 and as many as 16 chambers have been used. The present trend shows the use of about 8 or 10 combustion chambers. *Figure 1-26* shows the liner of a can-type combustion chamber. These chambers are numbered in a clockwise direction. As you face the rear of the engine and look forward, the number 1 chamber is at the top. Some provision is made in the combustion chamber case or in the compressor air outlet elbow for the installation of a fuel nozzle. The fuel nozzle delivers the fuel into the liner in a finely atomized spray. The finer the spray, the more rapid and efficient the burning process becomes. The two types of fuel nozzles being used in the various types of combustion chambers are the simplex nozzle and the duplex nozzle. The fuel nozzles are constructed so they can be installed in various ways. The two methods used most frequently are external mounting and internal mounting.

In external mounting, a mounting pad is provided for attachment of the nozzle to the case or the inlet air elbow, with the nozzle tip projecting into the chamber liner, usually near the dome.

When internal mounting at the liner dome, the chamber cover is removed for replacement or maintenance of the nozzle. The simplex nozzle *(Figure 1-27),* with its single orifice, does not provide a satisfactory spray over a wide range of operating conditions. Therefore, its use on current models of jet engines is limited. The duplex nozzle *(Figure 1-27)* has good spray characteristics. Its use does require a pressurizing valve (flow-divider) to divide flow to the primary and main fuel manifolds. During starting and idling, the small primary orifice of the duplex nozzle provides a high degree of atomization under low pressures. As sufficient pressure builds, the pressurizing valve opens the main line; the larger orifice supplies increased fuel in an atomized form.

Newer engines use single-or multiple-unit duplex nozzles for satisfactory sprays under various operating conditions. The cross-ignition tubes are a necessary part of the can-type combustion chambers. Since each of the cans is in reality a separate burner, each operates independently of the other. Combustion is spread during the initial starting operation by simply interconnecting all the chambers. As the flame is started by the spark igniter plugs in the two lower chambers, it passes through the tubes and ignites the combustible mixture in the adjacent chambers. This process, similar to the action of a pilot light on a gas stove, continues until all the chambers are ignited. Actually, only a few seconds are needed for this process. Then the two spark igniters are no longer needed, and they cut off automatically.

Another very important requirement in the construction of combustion chambers is providing the means for draining unburned fuel. The Fuel Drain Valve, A drain valve that is pressurized to keep closed on startup, then at shutdown depressurizes and opens allowing fuel to drain overboard. The drainage requirement involves many factors, such as the prevention of residual fuel deposits after evaporation in the fuel manifold, nozzles, and combustion chambers. Also, if fuel is allowed to accumulate after shutdown, an after fire could occur, or the excess fuel in the combustion chamber could ignite at the next starting attempt (hot start). Tailpipe temperature could go beyond safe operating limits.

The liners of the can-type combustors have the usual perforations of various sizes and shapes. Each hole has a specific purpose and effect on the flame propagation within the liner. The air entering the combustion chamber is divided by the proper holes. Louvers and slots divide the main streams into 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. Combustion gases are cooled from about3,500 °F to about 1,500 °F forward of the turbine. Holes are provided to aid in atomization of the fuel. These holes are located around the fuel nozzle in the dome or inlet end of the 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 controls the flame pattern by keeping it centered in the liner. This air layer prevents the 3,000 °F temperatures of the combusting gases from burning the liner walls. *Figure 1-28* shows the flow of air through the louvers in the can-annular type of combustion chambers.

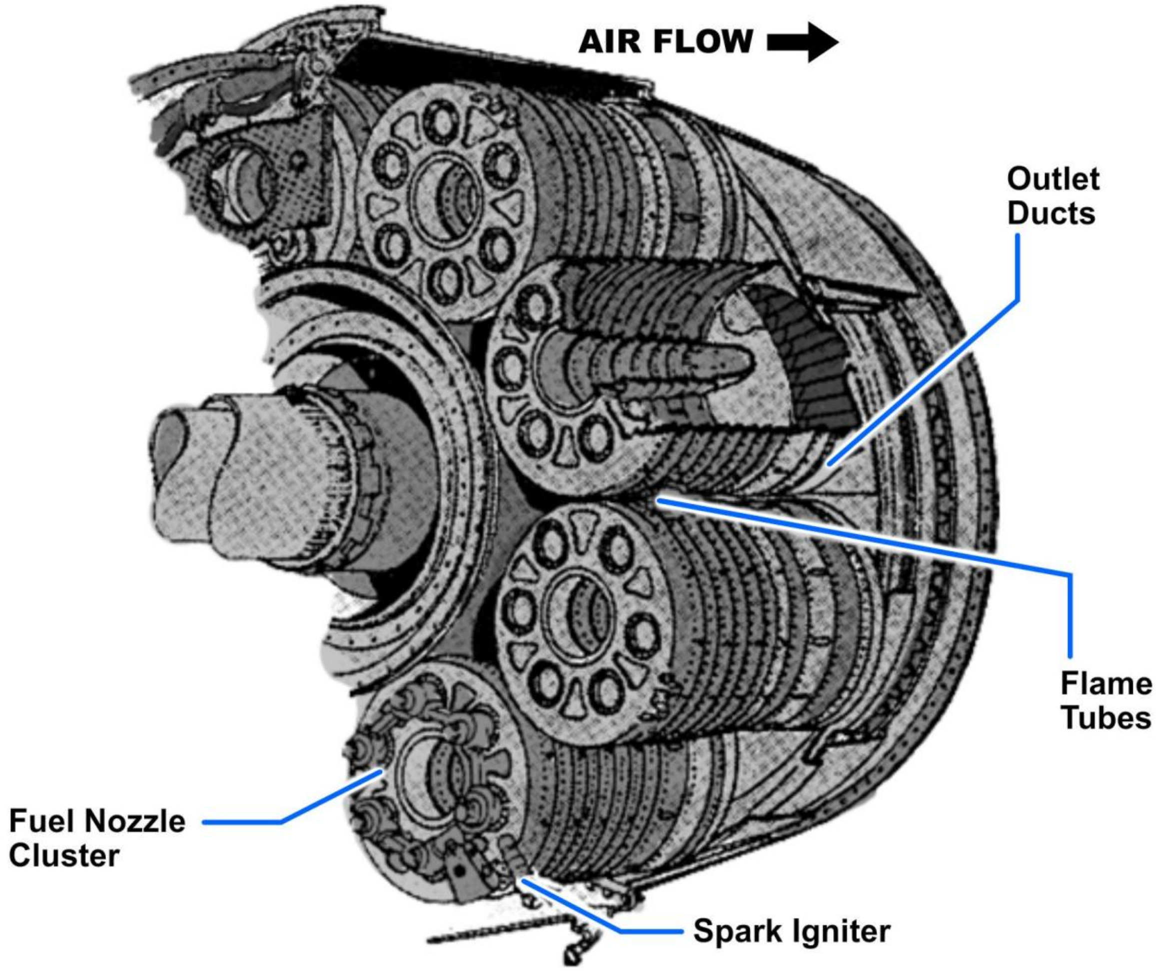


Figure 1-28 — Components and airflow of a can annular combustion chamber.

Annular or Basket Type

The annular combustion chamber, the type usually found in axial-flow engines, consists basically of a housing and a liner, similar to the can type. The difference lies in the construction details of the liner. The liner consists of an undivided circular shroud extending all the way around the outside of the turbine shaft housing see *Figure 1-29.*

The chamber is constructed of one or more baskets. If two or more chambers are used, they are placed one outside of the other in the same radial plane. The double-annular chamber is shown in *Figure 1-29.* The combustion chamber housing is made in three sections. These sections are the inlet, center, and rear sections. The inlet section receives the air from the axial flow compressor. This section is a diffuser. It slows the velocity of the air by providing a larger area just before the liner area, thus raising air pressure. Also present is a coarse wire screen, whose function is to increase turbulence to aid in fuel atomization.

Figure 1-29 — Double annular combustion chambers.

The center section of the chamber housing surrounds the liner, providing an outer wall for the axial path of the air. The center section provides the mounting pads for the installation of fuel drain valves. The drain valves drain residual or accumulated fuel out of the combustion chamber after engine shutdown. This action prevents after fires or excessive starting temperatures during the next start. Located on the bottom of the housing are the spring-loaded combustion chamber drain valves. These valves drain automatically whenever internal chamber pressures approach atmospheric pressure. This fuel is drained to an overboard drain compartment in the airframe. The rear section converges to form a narrow annulus.

This type of construction speeds up airflow before it enters the turbine section. Fuel is introduced through a series of nozzles at the upstream end of the liner. The fuel nozzles are screwed into fuel manifolds, located within two concentric fairings. If the chamber liner is of double-annular construction, there are two fuel manifolds. Only one manifold would be required if it were of single-annular construction. The two concentric fairings that support the fuel manifolds also perform the function of dividing the entering airflow into three concentric annular streams.

The outer stream is delivered to the space between the combustion chamber liner and the chamber housing.

The middle stream is delivered to the space between the inner and outer sections of the liner. The inner stream is delivered to the space between the liner and the rotor shaft housing. The two concentric fairings are supported by radial struts in the diffuser section.

The rotor shaft housing, shown in *Figure 1-30,* provides the inner wall for the axial path of the air. This housing unit is attached to the rear face of the inner ring of the diffuser section. The housing is supported in the rear by components of the turbine section. The spark igniter plugs of the annular combustion chamber are the same basic type used in the can combustion chambers. There are usually two plugs mounted on the boss provided on each of the chamber housings. The plugs must be long enough to protrude from the housing into the outer annulus of the double-annular combustion chamber.

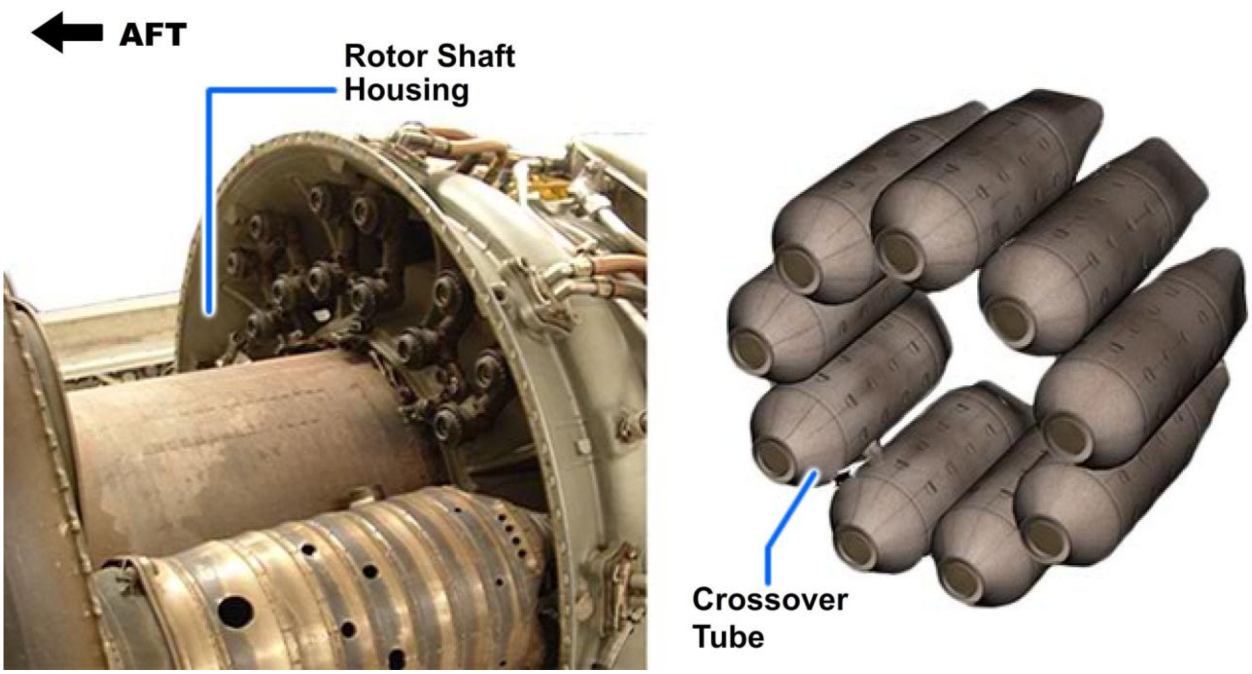


Figure 1-30 — Can annular combustion chamber and components.

Can-Annular Type

The can-annular type combustion chamber is a development by Pratt and Whitney for use in their J57 axial-flow turbojet engine. Since this engine features the split-spool compressor, it requires combustion chambers capable of meeting the stringent requirements of maximum strength, limited length, and high overall efficiency. These attributes are necessary because of the high air pressures and velocities present in a split-spool compressor, along with the shaft length limitations. The split-spool compressor requires two concentric shafts joining the turbine stages to their respective compressors.

The front compressor, joined to the rear turbine stages, requires the longest shaft. This shaft is inside the other. A limitation of diameter is imposed, so that the distance between the front compressor and the rear turbine must be limited if critical shaft lengths are to be avoided. (High torque is present if there is a long shaft of small diameter.) Since the compressor and turbine are not susceptible to shortening, this shaft length limitation is addressed by developing a new type of burner, a design that would give the desired performance in much less relative linear distance.

The can-annular combustion chambers are arranged radially around the axis of the engine; the axis in this instance being the rotor shaft housing. The combustion chambers are enclosed by a removable steel shroud, which covers the entire burner section. This feature makes the burners readily available for any required maintenance. The burners are interconnected by projecting flame tubes, which help the engine-starting process in the can-type combustion chamber. These flame tubes perform a function identical with those previously discussed, the only difference being in construction details. *Figure 1-30* also reveals that each of the combustion chambers contains a central bullet-shaped perforated liner.

The size and shape of the perforations are predetermined to admit the correct quantity of air at the velocity and angle required to control the flame pattern. Cutouts are provided in two of the bottom chambers for installation of the spark igniters. *Figure 1-30* shows how the forward face of the chambers presents apertures that align with the six fuel nozzles of the corresponding fuel nozzle cluster. As in the can-type combustion chamber, these nozzles are the dual-orifice (duplex) type that requires the use of a flow-divider (pressurizing valve). Pre-swirl vanes are located around each of the nozzles for imparting a swirling motion to the fuel spray. This results in better atomization of the fuel, thus better burning and efficiency.

The swirl vanes perform two important functions imperative to proper flame propagation:

- High flame speed, providing better mixing of air and fuel, ensuring spontaneous burning.
- Swirling, preventing the flame from moving rapidly rearward.

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. The can-annular combustion chambers also must have the required fuel drain valves, located in two or more of the bottom chambers, thereby assuring proper drainage and

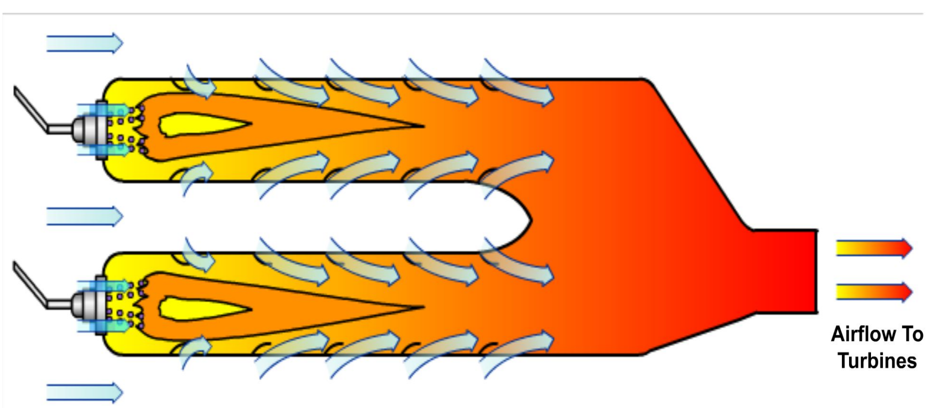


Figure 1-31 — Airflow through a can-annular chamber.

Interaction Available

eliminating the possibility of residual fuel burning during the next start cycle. The flow of air through the holes and louvers of the can-annular chambers is the same as the flow through other types of burners. *Figure 1-31* shows the flow of combustion air, metal-cooling air, and the diluent or gas-cooling air. Pay particular attention to the direction of airflow, indicated by the arrows.

TURBINE SECTION

The turbine transforms a portion of the kinetic (velocity) energy of the exhaust gases into mechanical energy to drive the compressor and necessary accessories. This is the sole purpose of the turbine. This function absorbs about 60 to 80 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. The compressor size, type, accessories, and a propeller and its reduction gears if the engine is a turbo-propeller type, also affect absorption. The turbine section of a turbojet engine is located aft, or downstream, of the combustion chamber section. Specifically, it is directly behind the combustion chamber outlet. The turbine assembly consists of two basic elements, the stator and the rotor, as does the compressor unit. These two elements are shown in *Figures 1-32 and 1-33.* The stator element is known by a variety of names. Turbine nozzle vanes, turbine inlet guide vanes, and nozzle diaphragm are three of the most commonly used. The turbine nozzle vanes are located directly aft of the combustion chambers and immediately forward of the turbine wheel.

Figure 1-32 — Stator element of the turbine assembly.

The function of the turbine nozzle is twofold. First, after the combustion chamber has introduced the heat energy into the mass airflow and delivered it evenly to the turbine nozzle, it becomes the job of the nozzle to prepare the mass flow for harnessing of power through the turbine rotor. The stationary vanes of the turbine nozzle are contoured and set at such an angle that they form small nozzles. They discharge the gas as extremely high-speed jets. Thus, the nozzle converts a varying portion of the heat and pressure energy to velocity energy. It can then be converted to mechanical energy through the rotor blades.

The second purpose of the turbine 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 the turbine is still rotating, it is essential to aim the gas in the general direction of turbine rotation.

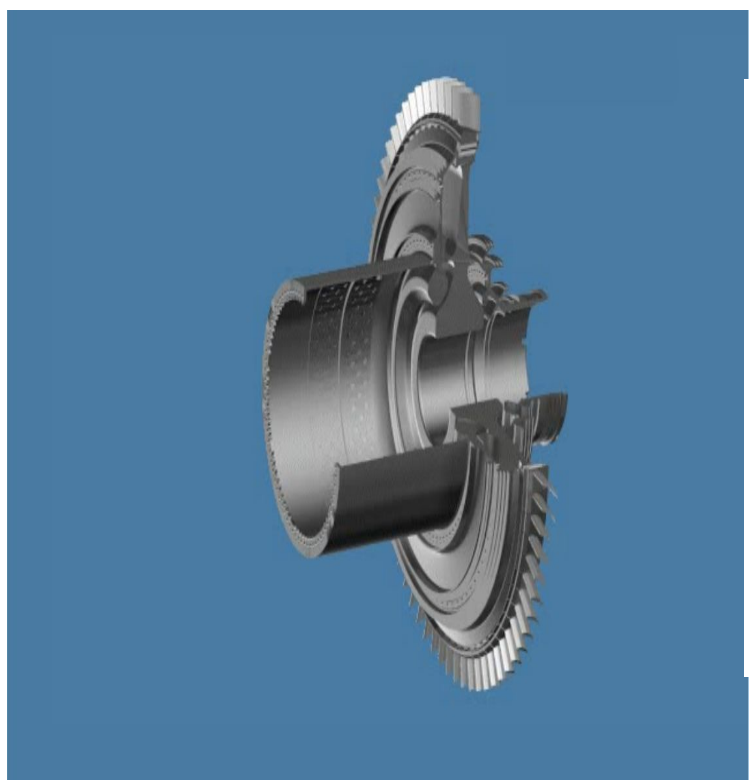


Figure 1-33 — Rotor element of the turbine assembly.

Interaction Available

The elements of the turbine nozzle assembly consist of an inner shroud and an outer shroud, between the nozzle vanes. The number of vanes employed varies with different types and sizes of engines. *Figure 1-34, views A and B* show typical turbine nozzles featuring loose and welded vane fits, respectively.

The vanes of the turbine nozzle are assembled between the outer and inner shrouds or rings in a variety of ways. Although the actual elements may vary slightly in their configuration and construction features, there is one characteristic peculiar to all turbine nozzles; that is, the nozzle vanes are constructed to allow for thermal expansion. Otherwise there would be severe distortion or warping of the metal parts because of rapid temperature variances. The expansion feature of the turbine nozzle is accomplished by one of several methods. One method has the vanes assembled loosely in the supporting inner and outer shrouds shown in *Figure 1-34, view A.*

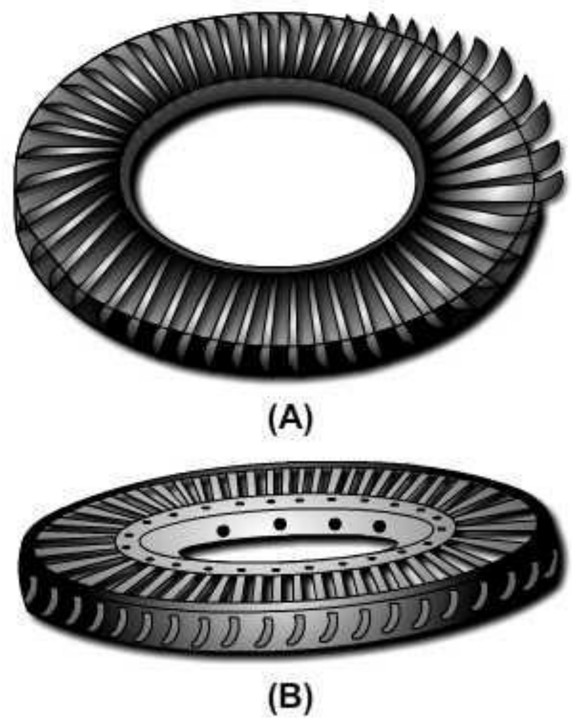


Figure 1-34 — Turbine nozzle vane assembly. (A) with loose fitting vanes; (B) with welded vanes.

Each of the vanes fits into a contoured slot in the shrouds. They conform to the airfoil shape of the vanes. These slots are slightly larger than the vanes to give a loose fit. The inner and outer shrouds are encased by an inner and outer support ring, which give increased strength and rigidity. These supports also help with removing the nozzle vanes as a unit. Otherwise, the vanes could fall out of the shrouds as the shrouds are removed. Another method of thermal expansion construction is to fit the vanes into inner and outer shrouds.

However, this method welds or rivets the vanes into position as shown in *Figure 1-34, view B.* Some means must be provided for the inevitable thermal expansion; therefore, either the inner or the outer shroud ring is cut into segments. These saw cuts dividing the segments will allow enough 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 1-33).*

The following brief discussion of impulse and reaction turbines should help clarify their function.

The turbine blades are of two basic types—impulse and reaction. Most aircraft engines use a blade with both impulse and reaction sections. The impulse is usually at the base of the blade. The impulse turbine can be defined as a turbine that derives its rotation from the weight and velocity of the air striking its blades. The reaction turbine derives its rotation from the air pressure across its blades, as in an airfoil *(Figure 1-35).*

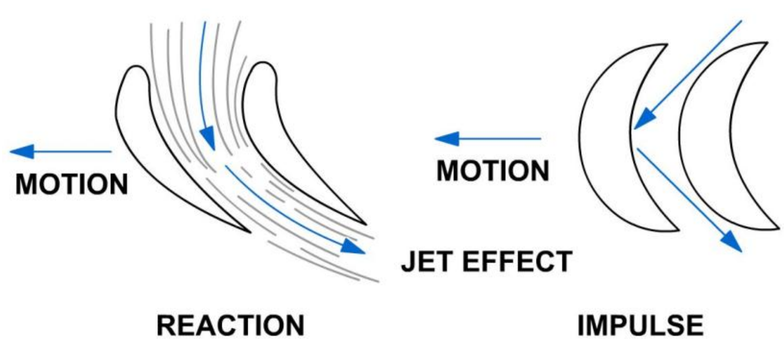


Figure 1-35 — Impulse and reaction blades.

The impulse-reaction turbine combines the rotational forces described in the two previous turbines. It derives its rotation from the weight of air striking the turbine blades and the airfoil reaction of air passing over the blade’s surface.

The turbine wheel is a dynamically balanced unit with blades attached to a rotating disc. The disc is attached to the main power-transmitting shaft of the engine. The jet gases leaving the turbine nozzle vanes act on the blades of the turbine wheel, causing the assembly to rotate at a very high speed. The high rotational speed causes heavy centrifugal loads on the turbine wheel. The elevated temperatures result in a lowering of the strength of the material. The engine speed and temperature must be controlled to keep turbine operation within safe limits.

The part of the turbine wheel without blades is known as a turbine disc. The disc acts as an anchoring part for the turbine blades. Since the disc is attached to the rotor shaft, the exhaust gas energy extracted by the blades is imparted to the shaft. The disc 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 buckets by conduction. Hence, disc rim temperature slopes are quite high and well above the temperatures of the more remote inner portion of the disc. As a result of these temperature slopes, thermal stresses are added to the stresses due to rotation.

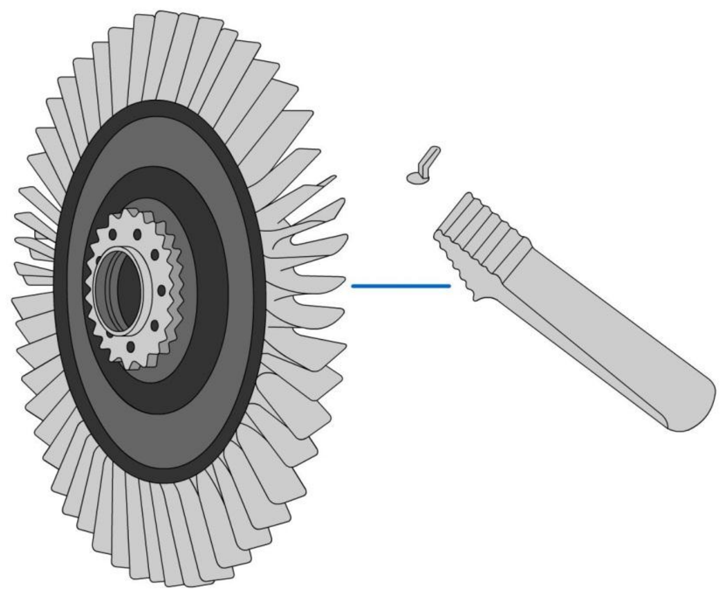


Figure 1-36 —Turbine blade with fir-tree design root and tab lock method retention.

There are various methods provided to relieve, at least partially, these stresses. One such method is the incorporation of an auxiliary fan somewhere ahead of the disc. Usually rotor-shaft driven, it forces cooling air back into the face of the disc. Another method of relieving the thermal stresses of the disc follows as incidental to blade installation. The disc rims are notched to conform to the blade root design. The disc is made adaptable for retaining the turbine blades. At the same time, space is provided by the notches for thermal expansion of the disc.

The turbine shaft is made from low-alloy steel. It must be capable of absorbing high torque loads, such as when a heavy axial-flow compressor is started. The methods of connecting the shaft to the turbine disc vary. One method used is welding. The shaft is welded to the disc, 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 matches a machined surface on the disc face. The bolts are then inserted through holes in the shaft hub and anchored in tapped holes in the disc. Of the two methods, bolting is more common.

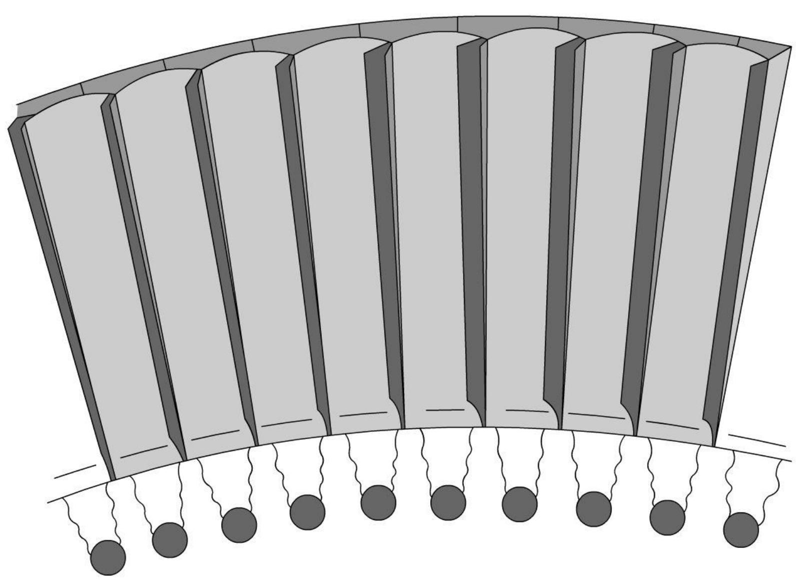


Figure 1-37 —Riveting method of turbine blade retention.

To join the turbine shaft to the compressor rotor hub, a splined cut is made 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. The axial compressor engine may use either of these methods. There are various ways of attaching turbine blades or buckets, some similar to compressor blade attachment. The most satisfactory method used is the fir-tree design, shown in *Figure 1-36.* The blades are retained in their respective grooves by a variety of methods; some of the more common ones are peening, welding, locking tabs, and riveting.

Figure 1-37 shows a typical turbine wheel using riveting for blade retention. A method of blade retention used quite frequently is peening, and it applies in various ways. Two of the most common applications of peening are described in the following paragraphs

One method of peening requires that a small notch be ground in the edge of the blade fir-tree root before blade installation. The blade inserts into the disc. The notch is filled with the disc metal, which is “flowed” into it through a small punch mark made in the disc, adjacent to the notch. The tool used for this job is similar to a center punch, and is usually manufactured locally.

Another method of peening is to construct the blade’s root in such a way as to contain all the elements necessary for its retention. This method is shown in *Figure 1-38*. The blade root has a stop on one end, while on the opposite end of the blade is a tang. The blade is inserted and moves in one direction only. The tang is peened over to secure the blade in the rotor disc.

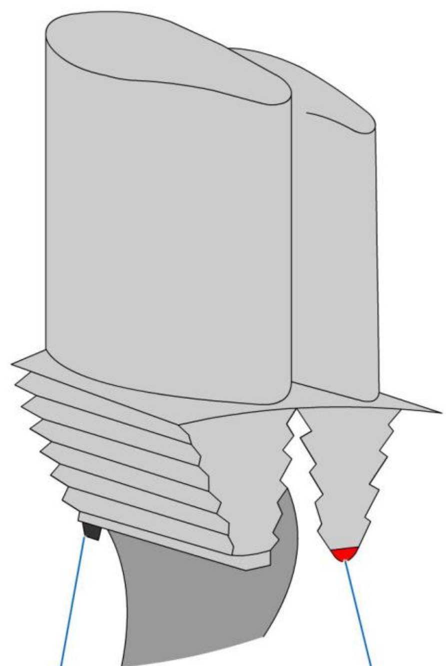


Figure 1-38 — Turbine bucket, featuring peening method of blade retention.

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. Most turbines in use are open at the outer perimeter of the blades; however, there is a second type called the shrouded turbine. 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 shown in *Figure 1-39.* In turbine rotor construction, it may be necessary to use turbines of more than one stage. A single turbine wheel often cannot absorb enough power from the exhaust gases to drive the parts dependent on the turbine for its kinetic energy. In a turbojet engine, these parts are the compressor and engine-driven accessories. In the turboprop engine, these parts are the propeller and the reduction gear assembly. A turbine stage consists of a row of stationary vanes or nozzles, followed by a row of rotating blades. Some models of turboprop engines use as many as five turbine stages. You should remember that regardless of the number of wheels necessary for driving engine parts, there is always a turbine nozzle in front of each wheel. The occasional use of more than one turbine wheel is necessary in cases of heavy

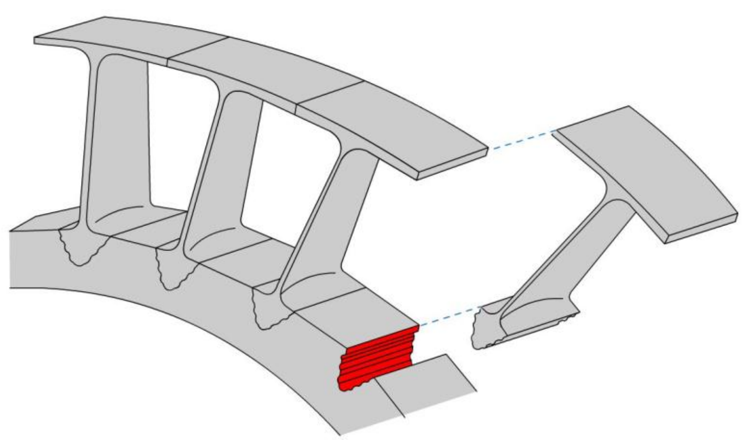


Figure 1-39 — Shrouded turbine blades.

rotational loads. Heavy loads that require multiple-stage turbine wheels often make it advantageous to use multiple rotors. Shafts are bolted to the appropriate turbine on one end and at the other end to the unit requiring the kinetic energy. Typical examples of this situation are split compressors or propellers, or a gas generator for helicopters. In each of these situations, the turbine for each of the rotors may have one or more stages.

In the single-rotor turbine, the power is developed by one rotor. All engine-driven parts are driven by this single wheel; this arrangement uses engines where the need for low weight and compactness predominates. The single-rotor turbine may be either single or multiple stages. In the multiple-rotor turbine, the power is developed by two or more rotors. It is possible for each turbine rotor to drive a separate part of the engine. For example, a triple-rotor turbine may be so arranged that the first turbine drives the rear half of the compressor and the accessories. The second turbine drives the front half of the compressor, and the third turbine furnishes power to a propeller shown in *Figure 1-40.* The turbine rotor arrangement for a dual rotor turbine, such as required for a split-spool compressor, is similar to the arrangement shown in *Figure 1-40.* The difference is in the use of the third turbine for a propeller. The remaining element of the turbine is the turbine casing or housing. The turbine casing encloses the turbine wheel and the nozzle vane assembly. It gives either direct or indirect support to the stator elements of the turbine section. It always has flanges to provide for the front and rear bolting of the assembly to the combustion chamber housing and the exhaust cone assembly, respectively. *Figure1-41* shows a turbine casing.

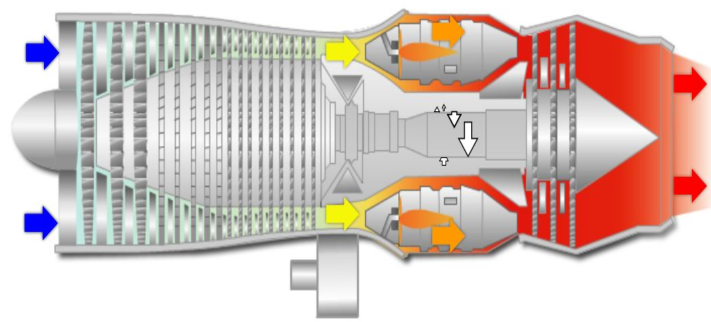


Figure 1-40 — Triple-rotor turbine arrangement.

Interaction Available

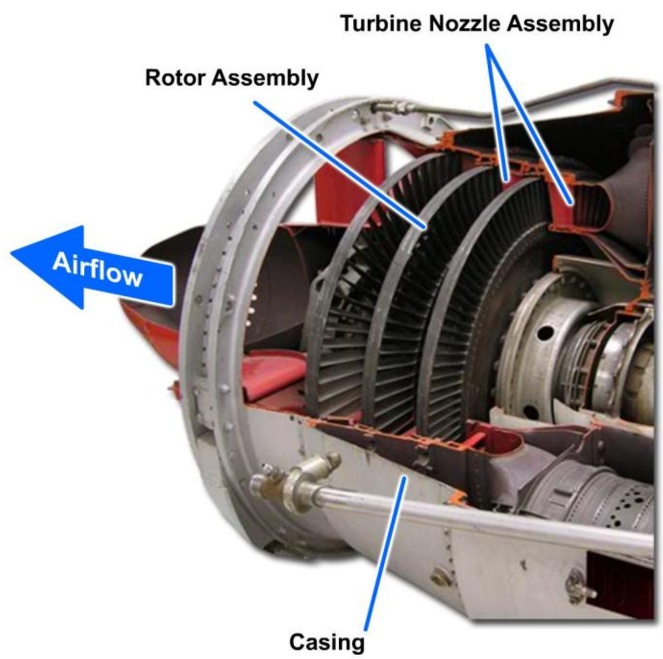


Figure 1-41 — Turbine casing assembly.

EXHAUST SECTION

The exhaust section of the turbojet engine is made up of several parts, each of which has its individual functions. Although the parts 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, while causing a high final or exit velocity to the gases.

In performing the various functions, each of the parts affects the flow of gases in different ways, as described in the following paragraphs. The exhaust section is directly behind the turbine section. It ends with the ejection of gas at the rear in the form of a high-velocity jet. The parts of the exhaust section include the exhaust cone, tailpipe (if required), and the exhaust, or jet nozzle. Each of these parts is discussed individually so the exhaust section will be quite familiar to you. The exhaust cone collects the exhaust gases discharged from the turbine assembly and gradually converts them into a solid jet. During this operation, the velocity of the gases will decrease slightly, and the pressure will increase. This is caused by the diverging passage between the outer duct and the inner cone. The annular area between the two unit’s increases rearward as shown *Figure 1-42.*

Interaction Available

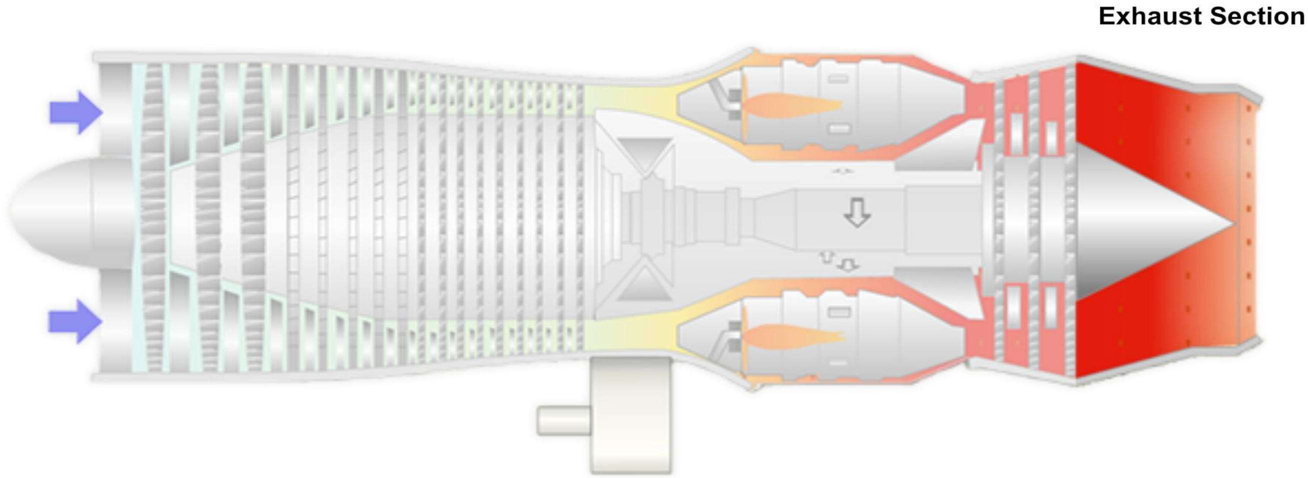


Figure 1-42 — Exhaust cycle.

The elements of the exhaust cone assembly consist of an outer shell or duct, an inner cone, and three or four radial hollow struts or fins. Tie rods aid the struts in supporting the inner cone from the outer duct. The outer shell or duct, made of stainless steel, is attached to the rear flange of the turbine case. This element collects and delivers the exhaust gases. The gases flow either directly or through a tailpipe to the jet nozzle, depending on whether or not a tailpipe is required.

There is no need for a tailpipe in some engines. For instance, the required engine-installation space in wing roots, pods, or wings is short and requires very little tailpipe. In which case the exhaust duct and exhaust nozzle will suffice.

The construction of the duct includes such features as a predetermined number of thermocouple bosses for installing exhaust gas temperature thermocouples. Also, there must be insertion holes for the supporting tie rods. In some cases, there are no requirements for tie rods for supporting the inner cone from the outer duct shown in *Figure 1-43*. 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.

The radial struts actually have a twofold function. They not only support the inner cone in the exhaust duct, they also perform the important function of straightening the swirling exhaust gases, which otherwise would leave the turbine at an angle of about 45 degrees.

If tie rods are required for inner cone support, these struts also form fairings around the rods.

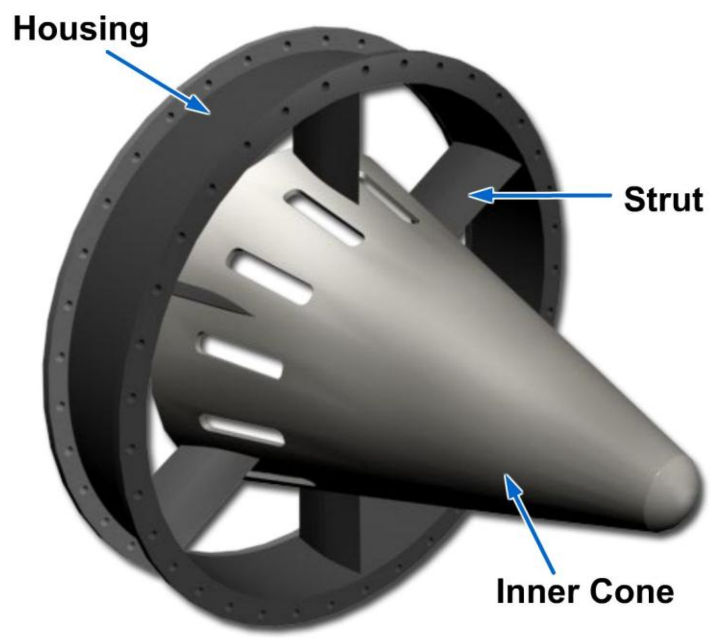


Figure 1-43 — Exhaust collector and welded support status.

The centrally located inner cone fits rather closely against the rear face of the turbine disc. This fit prevents turbulence of the gases as they leave the turbine wheel. The cone is supported by the radial struts, which are usually vertical and horizontal in relation to the normal position of the engine.

In some configurations, there is a small hole located in the exit tip of the cone shown in *Figure 1-43.* This hole allows cooling air to circulate from the exit end of the cone. The pressure of the gases is relatively high in the interior of the cone and 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 for cooling the turbine wheel return to the path of flow by passing through the clearance between the disc and the cone. The clearance between the turbine disc and the inner cone must be checked periodically since the higher pressures aft tend to push the inner cone against the turbine wheel. The exhaust cone assembly is the terminating part of the basic engine. The remaining parts such as the tailpipe and jet nozzle *(Figure 1-44)* are usually considered airframe parts. The tailpipe pipes the exhaust gases out of the airframe. Actually, the tailpipe imposes a penalty on the operating efficiency of the engine in the form of heat and duct (friction) losses. These losses materially affect the final velocity of the exhaust gases and, hence, the thrust.

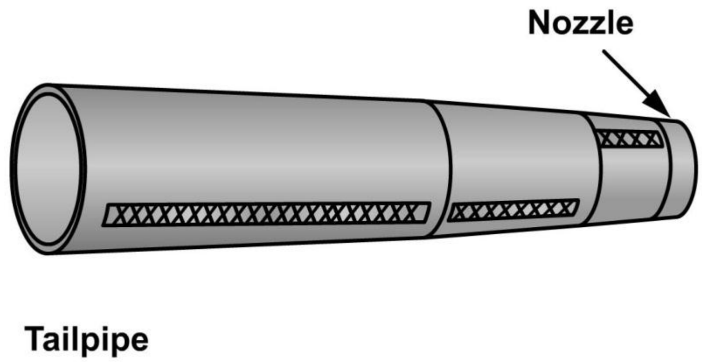


Figure 1-44 — Exhaust nozzle and tailpipe.

The tailpipe ends in a jet nozzle, located just forward of the end of the fuselage. Most installations employ a single direct exhaust to get the advantages of low weight, simplicity, and minimum duct losses. The construction of the tailpipe is semi-flexible. Again, the need for this feature is dependent on its length. On an extremely long tailpipe, a bellows arrangement allows movement both in installation and maintenance and in thermal expansion. This cuts stress and warping, which would otherwise be present. The heat radiation from the exhaust cone and tailpipe could conceivably injure the airframe parts surrounding these units. For this reason some means of insulation had to be devised.

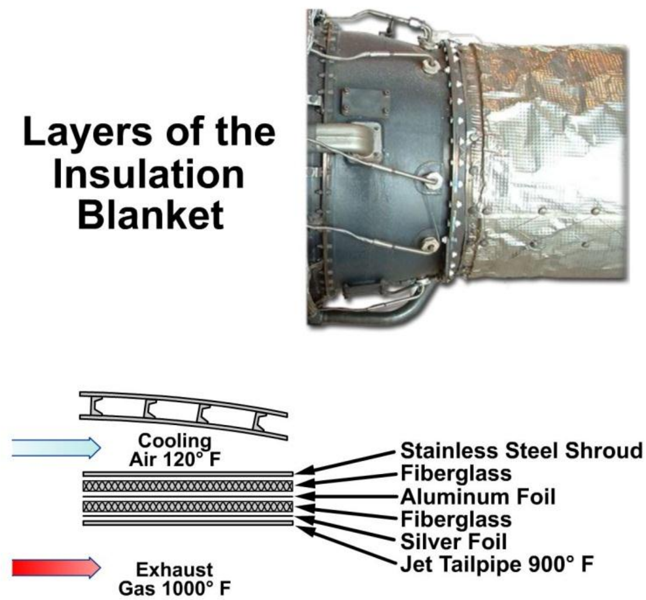


Figure 1-45 — Insulation blanket, with temperatures that would be obtained at the various locations.

There are several suitable methods for protection of the fuselage structure; two of the most common are insulation blankets and shrouds. An insulation blanket type of configuration, shown in *Figures 1-45,* consists of several layers of aluminum foil, each separated by a layer of bronze screening or some other suitable material. Although these blankets protect the fuselage from heat radiation, they primarily reduce heat losses from the exhaust system. Since engine temperature limits are of little concern after the gases pass the turbine, the reduction of heat losses improves engine performance by retaining the maximum permissible temperatures, resulting in maximum velocity in the jet. A typical insulation blanket and the temperatures at the various locations in the exhaust section are shown in *Figure 1-45*. This

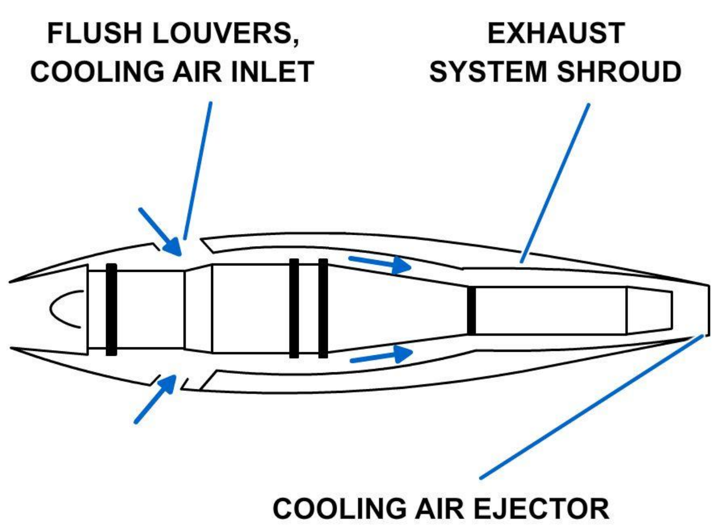


Figure 1-46 — Exhaust system shroud.

blanket contains fiberglass as the low-conductance material and aluminum foil as the radiation shield. The blanket is covered to prevent its becoming soaked with oil. The heat shroud type of configuration consists of a stainless steel envelope enclosing the exhaust system *(Figure 1-46).*

There are two types of jet nozzle design. They are the converging design, used on most freed-area nozzles for subsonic velocities, and the converging/diverging design, for supersonic gas velocities.

The fixed-area type is the simpler of the two jet nozzles, since there are no moving parts. It is attached to either a tailpipe or exhaust cone, and any adjustment in nozzle area is mechanical.

Adjustments in a fixed-area nozzle are sometimes necessary because the size of the exit orifice will directly affect the operating temperature of the engine. There are several ways to adjust a fixed-area nozzle. One method is to trim or cut away strips from the conical section of the exhaust nozzle, provided, of course, the temperature was too high. If the inlet temperature is too low, a nozzle of less area is used to replace the inadequate one.

Another method of reducing the nozzle area is to use inserts. The inserts fit inside a joggled retainer held in place by two screws. Usually a set of 10 inserts of various curvatures is provided with each aircraft.

NOTE

All advanced-technology engines now used by the Navy have state-of the-art electronic parts that eliminate the need for physically changing the exhaust nozzle area.

NOTE

The exhaust or jet nozzle gives to the exhaust gases the all-important final boost in velocity. The jet nozzle, like the tailpipe, is not a part of the basic power plant, but is supplied as a part of the airframe. The nozzle attaches to the rear of the tailpipe if there is a need. It is attached to the rear flange of the exhaust duct if a tailpipe is not necessary. There are basically two types of jet nozzles—fixed-area and variable-area.

The different size inserts allow a total change of 10 square inches in nozzle area in 1-inch increments. Thus, with experience, a mechanic can run the engine at maximum speed with one combination of inserts, check the temperature, and substitute another combination to make up a temperature deficiency or remedy an excess temperature situation. The variable-area nozzle at the exhaust exit is automatic. A very important use of this type of nozzle is to increase the exit area during afterburning. The segment-type nozzle area opens and closes by individual overlapping sliding segments See *Figure 1-47.* Some engines use the inner and outer-flap variable nozzle assembly, shown in *Figure 1-48*. The assembly has an internal primary nozzle with sectional flaps and an external secondary nozzle with sectional flaps. The flaps of the primary nozzle are hinged to the rear of the tailpipe. The secondary nozzle is secured by a stationary supporting shroud, on which the pivot points for the flap-operated mechanisms are located. The flaps are slotted to permit thermal expansion and are mounted onto the tailpipe. The flaps are controlled by four synchronized hydraulic actuators.

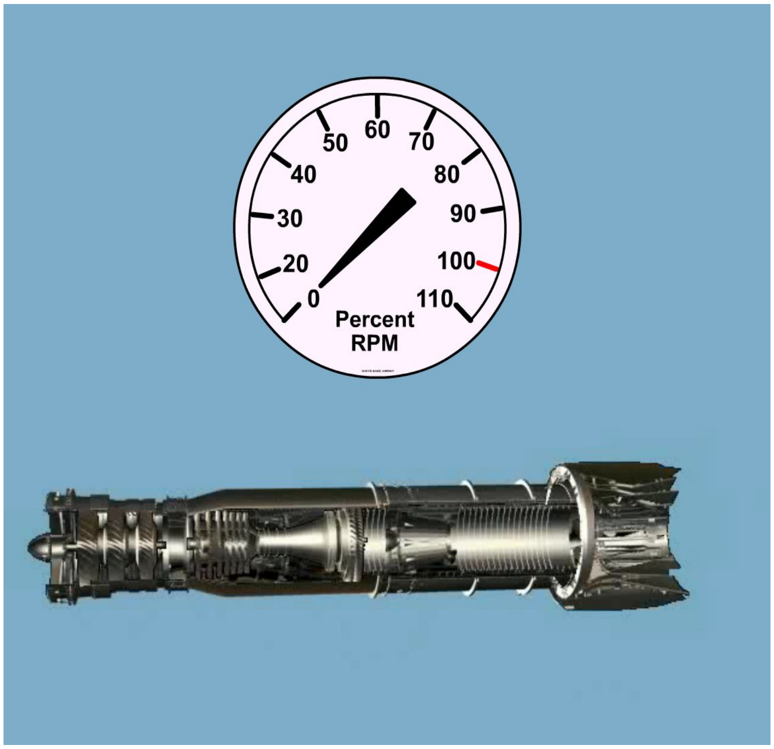


Figure 1-47 — Segment-type nozzle assembly.

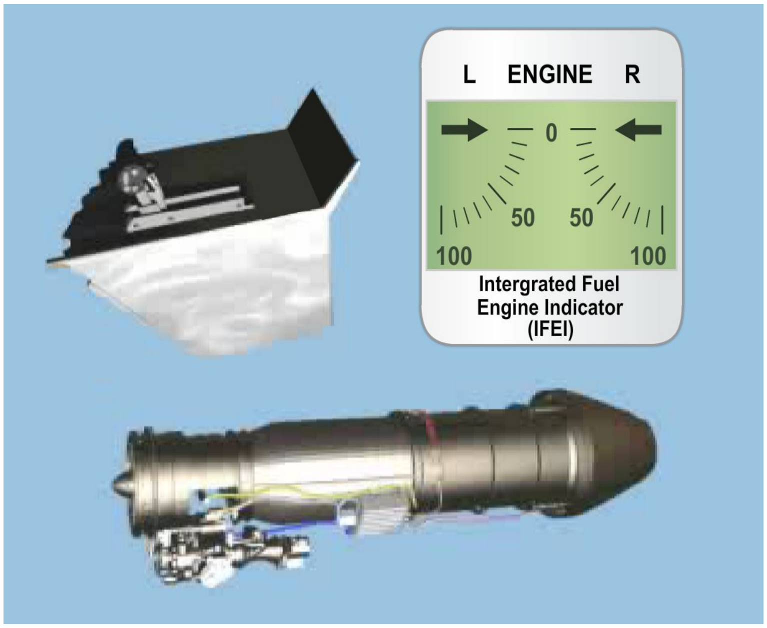


Figure 1-48 — Variable exhaust nozzle assembly.

Interaction Available

ACCESSORY SECTION

The accessory section of the turbojet engine has various functions. The primary function is to provide space for the mounting of accessories necessary for the operation and control of the engine. It also includes accessories concerned with the aircraft, such as electric generators and fluid power pumps. The secondary purpose includes acting as an oil reservoir, oil sump, and providing for and housing of accessory drive gears and reduction gears. The arrangement and driving of accessories have always been major problems on gas turbine engines. Driven accessories are mounted on common pads either ahead of or next to the compressor section as shown in *Figure 1-49.*

The parts of an axial-flow engine accessory section are the accessory gearbox and a power takeoff assembly. These units contain the necessary drive shafts and reduction gears. *Figure 1-50, views A and B* show the location of the accessory gearbox. The accessory gearbox and the power takeoff are located near each other.

There are two factors that affect the location of gearboxes in general. These factors are engine diameter and engine installation. Designers strive to reduce engine diameter to make the engine more streamlined, thereby increasing performance by reducing drag.

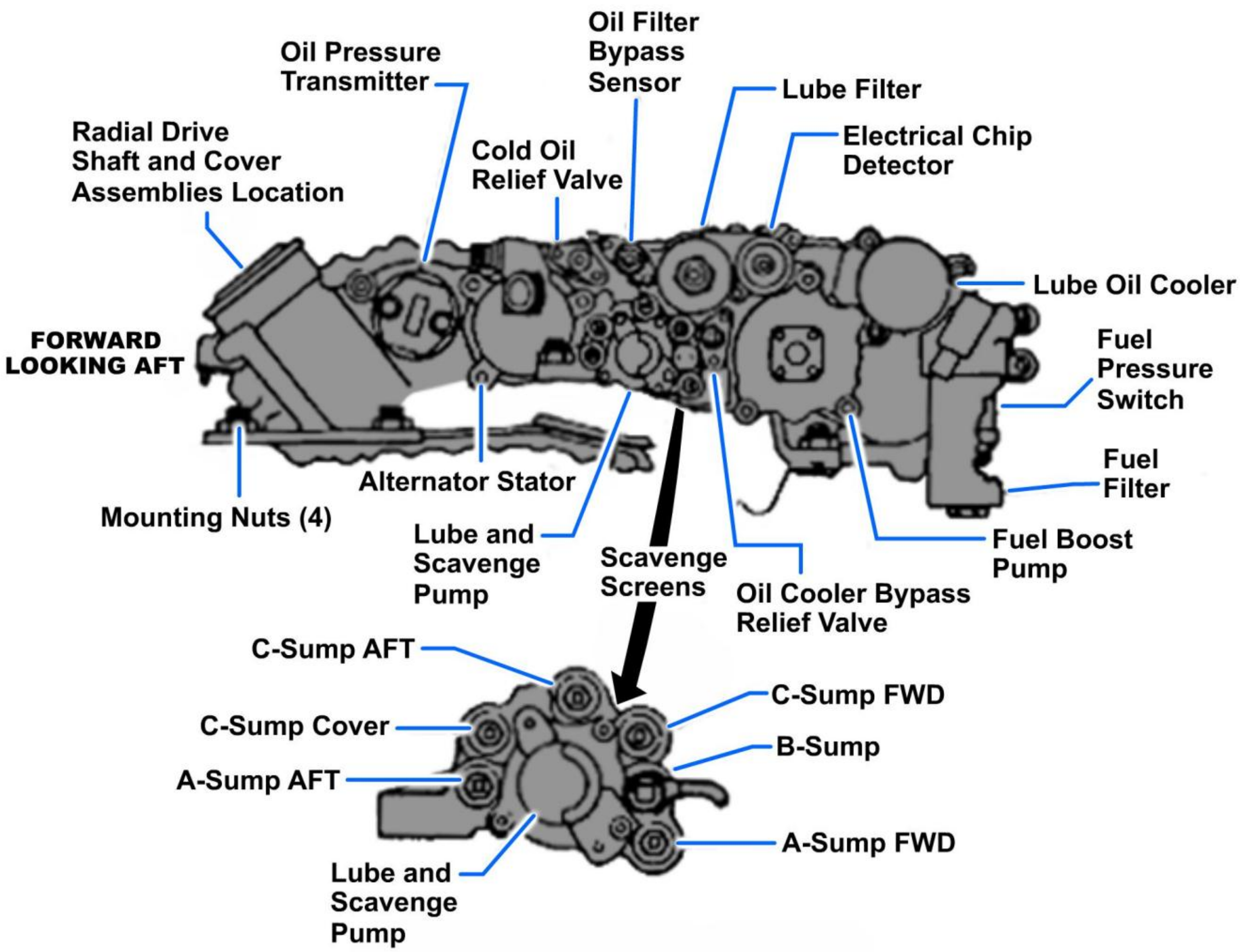


Figure 1-49 — the accessory section arrangement of a turboshaft engine.

Also, engine installation in a particular aircraft may dictate the location or rearrangement of the accessory gearboxes (*Figure 1-50 view A and B*).

The accessories on engines are the fuel control with its governing device, the high-pressure fuel pump(s), and a breather screen or other means for venting the oil system. Other parts are the oil sump, oil pressure and scavenge pumps, auxiliary fuel pump, starting fuel pump, and other accessories, including starter, generator, and tachometer.

Although these accessories are essential, the particular combination of engine driven accessories depends upon the use for which the engine is designed. The accessories mentioned above (except starters) are of the engine-driven type. There are also the non-driven-type accessories such as booster coils or ignition exciters, fuel and oil filters, barometric units, drip valves, compressor bleed valves, and relief valves.

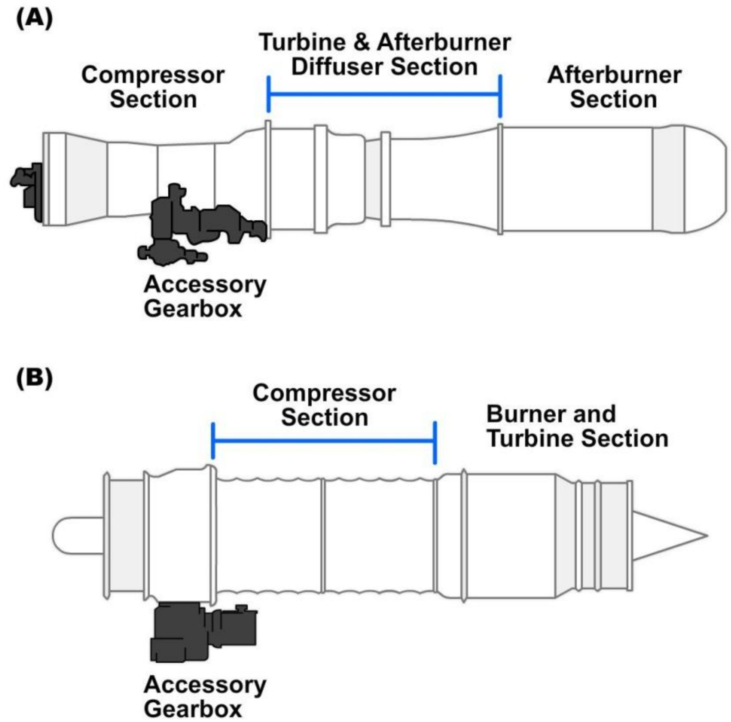


Figure 1-50 — Accessory gearbox. (A) Mounted beneath the compressor; (B) mounted beneath the front bearing support.

AFTERBURNER SECTION

The afterburner increases or boosts the normal thrust rating of a gas turbine engine. There are times when the maximum normal thrust of an engine is not enough.

For instance, it is conceivable that although the in-flight requirements are met satisfactorily by an engine of moderate size, the aircraft still may not have good takeoff performance. With afterburning, maximum thrust is obtained without sacrificing the economy of the small basic gas turbine. Increased thrust is required for takeoff, emergencies, and combat conditions.

The afterburner duct replaces the usual aircraft tailpipe. Actually, it is more like a converted tailpipe. It functions as the engine tailpipe during non-afterburning (cold) operation and is also the main working element of the afterburner. The entire afterburner is projected from the engine. It is supported only at the exhaust end where it is bolted to the engine. The essential working element of the afterburner is an afterburner duct. A flame-holder or diffuser and a variable-area exhaust nozzle are the other parts *(Figure. 1-46).*

The afterburner duct is the main working element of the afterburner. It’s designed so that the normal pressure relationship between the air entering the main engine turbine and the air leaving the turbine is not upset.

Since the duct acts as a burner, the inlet air velocity must be sufficiently low to support stable combustion and to avoid excessive pressure losses. For these purposes a diffuser is located between the turbine outlet and the tailpipe burner inlet. Thus, the burner section of the duct can reduce gas velocities so they do not exceed the flame propagation rate. Otherwise, the flame could not get a foothold, because the onrushing turbine exhaust would simply push the burning mixture right out the exhaust nozzle.

In addition to the diffuser, some mechanical mixing of the fuel and air is necessary.

Mixing by diffusion is too slow a process to be an aid in forming a combustible mixture. The flame-holders provide local turbulence and reduce velocity, which aids combustion stability. The flame-holders are located downstream from the fuel-injection nozzles, thereby allowing time for proper mixing of the fuel and air before reaching the burner area. The flame-holders are circular, concentrically mounted, and supported in position by tie rods that project through the wall of the duct. Two of the tie rods are in a horizontal position, and the remaining two are vertical.

The afterburner, tailpipe burner, or re-heaters get their names because the air going through the engine is subjected to additional burning after the basic cycle is completed. The unburned oxygen in the air used for cooling the exhaust gases is the afterburner air supply. Since no cooling is required past the turbine assembly, any or all of this air may be burned for augmentation. Additional energy is given to the exhaust gases by burning additional fuel sprayed in the exhaust stream aft of the turbine.

END OF CHAPTER 1

JET ENGINE THEORY AND DESIGN

Review Questions

1-1. What is an English measurement of mass?

A. Force
B. Energy
C. Slug
D. Work

1-2. Name one of the four main classes of jet engines.

A. Rocket
B. Chevy
C. Turbine
D. Ram effect

1-3. What is considered a Standard day reference?

A. 60 °F, barometric pressure 30.2 inches of mercury(Hg)
B. 59 °F, barometric pressure 29.92 inches of mercury(Hg)
C. None needed
D. 70 °F, barometric pressure 29.0 inches of mercury(Hg)

1-4. What is the definition of Newton's third law (motion)?

A. "For every action there is an equal and opposite reaction."
B. "A body at rest tends to remain at rest; a body in motion tends to move at a constant speed unless acted upon by an outside force."
C. "Speed in a given direction."
D. "More air arriving at the engine intake than the engine can digest."

1-5. What is the primary function of the compressor section?

A. To compress air as it enters the section
B. To provide a means of properly mixing the fuel and air
C. To transform a portion of kinetic energy of exhaust gasses into power
D. To supply air in enough quantity to satisfy the requirements of the combustion burner

1-6. What is the ram effect?

A. More air arriving at the engine compressor than the engine can ingest
B. The airspeed at which ram pressure rise equals friction pressure loss
C. More air arriving at the engine intake than the engine can ingest
D. The airspeed at which ram/pressure decrease equals friction pressure loss

1-7. Which of the following groups of jet engines will you, as an AD, be associated with most?

A. Rocket, pulsejet, ramjet, and jet turbine
B. Turboshaft, turboprop, pulse, and turbojet
C. Turbojet, turboprop, turboshaft, and ramjet
D. Turbofan, turbojet, turboprop, and turboshaft

1-8. What are two common forms of blade roots?

A. Fir-tree and bulb
B. Grub and bulb
C. Fir–tree and key
D. Grub and key

1-9. What is the primary function of the combustion section?

A. To provide ignition
B. To drive the turbine
C. To drive the compressor
D. To burn the fuel-air mixture

1-10. Approximately what percent of air entering the combustion chamber is mixed with fuel for combustion?

A. 40%
B. 35%
C. 25%
D. 20%

1-11. What total number of engine designation systems is presently in use?

A. Two
B. Three
C. Four
D. Five

1-12. Power is the rate of doing work, or…….

A. Power=work/time.
B. Power=distance/time.
C. Power=weight/gravity.
D. Power=distance/slug.

1-13. What components does the centrifugal compressor consist of?

A. Turbine, shield, magnaflux
B. Impeller, diffuser, turbine
C. Impeller, diffuser, manifold
D. Manifold, diffuser, intake

1-14. How many main elements are in the axial flow compressor?

A. 2
B. 5
C. 6
D. 12

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