Overview of Gas Turbines

Course No: M02-057
Credit: 2 PDH

Elie Tawil, P.E., LEED AP

CHAPTER 6

GAS TURBINES

The gas turbine is an internal combustion engine that uses air as the working fluid. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine. The Navy uses gas turbine engines on ships for the purpose of providing electrical power and as the ship's main propulsion unit.

This chapter will provide you with a basic understanding of the basic gas turbine engine theory, types, construction features, and operating principles.

LEARNING OBJECTIVES

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

1. Identify laws and principles that apply to gas turbine engines.
2. Recognize the methods used to classify gas turbines.
3. Recognize the major components used on gas turbines.
4. Recognize the functions of the starting systems.
5. Recognize the types of ignition aids.
6. Identify the types of gas turbine monitoring systems.

LAWS AND PRINCIPLES

The theory of gas turbine engines is based on the laws and principles of physics discussed in the following paragraphs.

Newton's Laws of Motion

Newton's first law *(Figure 6-1, 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 6-1, 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.

Newton's third law of motion (*Figure 6-1, view C*) states "that for every action there is an equal and opposite reaction". The action reaction is simultaneous and it does not matter which is the action and

which is the reaction; both forces are a part of a single interaction and neither force exists without the other.

Pressure, Temperature, and Volume

Boyle's Law

Charles Boyle, an English scientist, was among the first to experiment with the pressure-volume relationship of gas. Boyle's law states that the volume of any dry gas varies inversely with its absolute pressure, provided the temperature remains constant. This law may also be expressed as:

$$V1\,P1 = V2\,P2$$

Where $V1$ is the original volume of the gas, $P2$ its original absolute pressure, $V2$ the new volume of the gas, and $P2$ its new absolute pressure.

Charles' Law

Jacques Charles, a French physicist, provided much of the foundation for modem kinetic theory of gases. Charles' law states that the volume of a gas is directly proportional to its absolute temperature provided the pressure is kept constant. The equation for this law is:

$$V1\,T2 = V2\,T1$$

The general gas equation combines Boyle's law and Charles' law. It expresses the interrelationship of the volume, the absolute pressure, and the absolute temperature of gases. The general gas law is expressed by:

Figure 6-1 — Newton's laws of motion.

$$\frac{P1\,V1}{T1} = \frac{P2\,V2}{T2}$$

You probably will not find it necessary to use the equations themselves, but you should have a thorough understanding of the following principles they express:

- When temperature is held constant, increasing the pressure on a gas causes a proportional decrease in volume. Decreasing the pressure causes a proportional increase in volume.

- When pressure is held constant, increasing the temperature of a gas causes a proportional increase in volume. Decreasing the temperature causes a proportional decrease in volume.
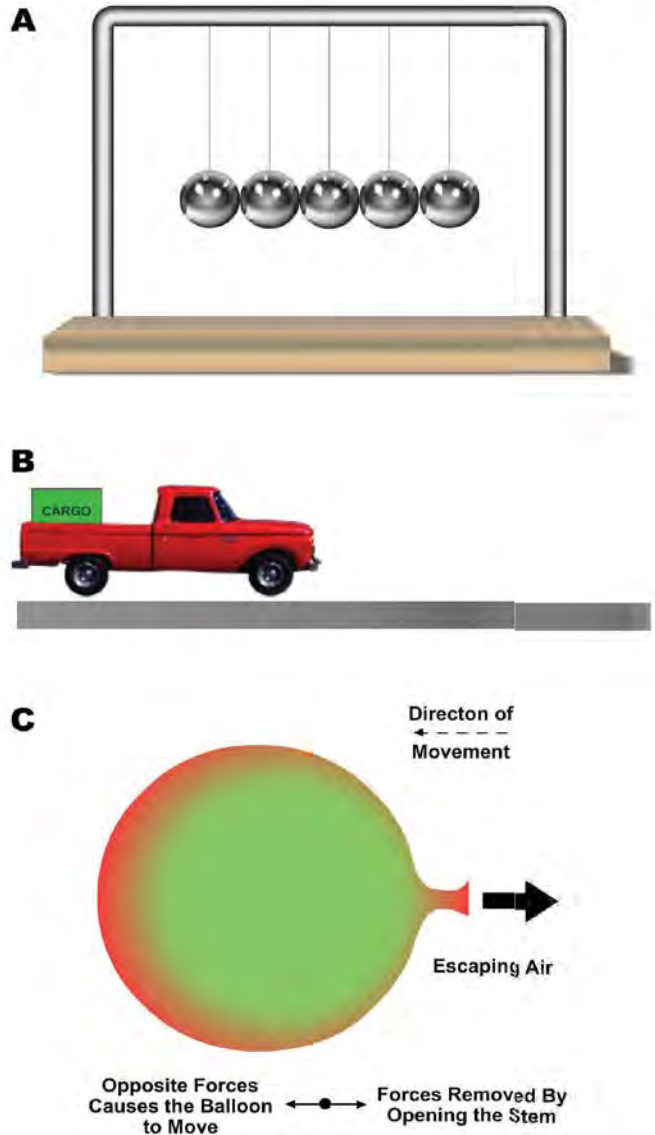
- When the volume is held constant, increasing the temperature of a gas causes a proportional increase in pressure. Decreasing the temperature causes a proportional decrease in pressure.

In this discussion of the effects of pressure on a gas, the volume and the temperature of gas are different after the pressure has been changed. It is important to note, however, that a temperature change normally occurs in a gas while the pressure is being changed. Compressing a gas raises its temperature; allowing a gas to expand lowers its temperature.

Bernoulli's Principle

Bernoulli's principle is about the behavior of a fluid – a gas or a liquid – as it flows through a pipe or tube. According to Bernoulli's principle, if a fluid flowing through a tube reaches a constriction, or narrowing of the tube, the velocity of fluid flowing through the constriction increases and the pressure decreases.

Operating Principles

The gas turbine engine operates like a toy balloon. Newton's third law of motion explains this operation. As stated above, "For every acting force there is an equal and opposite reacting force." Imagine an inflating balloon. The air pressure inside the balloon, which is stretching the skin, is greater than the pressure outside the balloon (*Figure 6-2*). If the stem is tied closed, the inside air pushes in all directions and the balloon will not move.

Place the balloon in a vacuum and release the stem. The escaping air has nothing to push against, but the balloon will move in a direction away from the stem, just as it does in a normal atmosphere.

Releasing the stem removes a section of skin on the side of the balloon against which the air has been pushing. On the side directly opposite the stem, however, the air continues to push on an equal area of skin. The continued push of air on this area causes the balloon to move in the direction away from the stem (*Figure 6-3*).
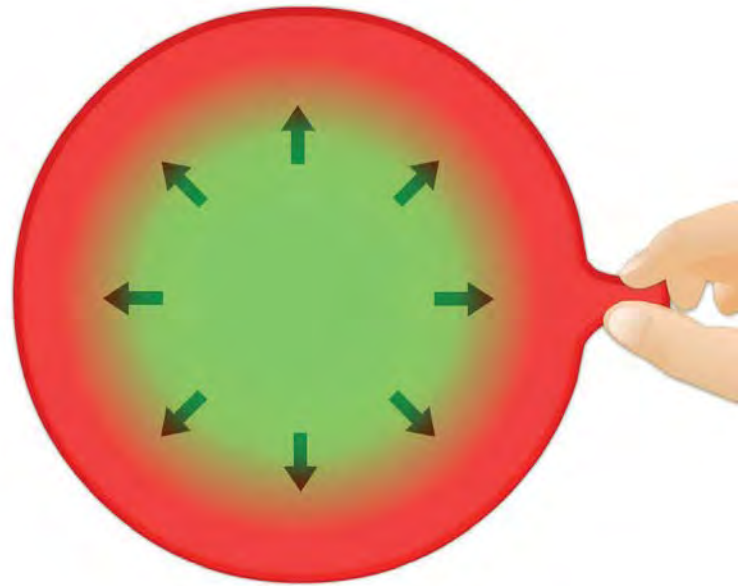
With its stem held, the balloon does not move

Figure 6-2 — Balloon example of restricting jet propulsion.

Direction of Movement

Escaping Air

Opposite Forces Causes the Balloon to Move
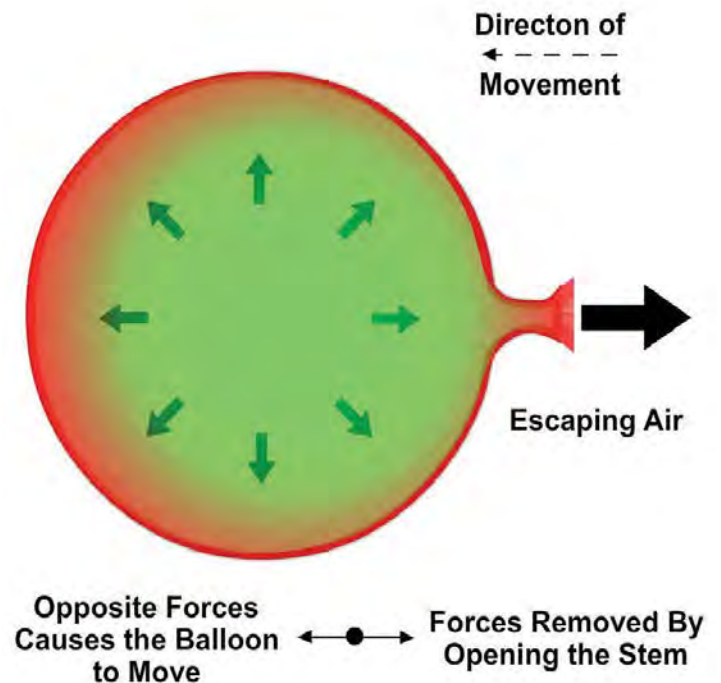
Forces Removed By Opening the Stem

Figure 6-3 — Balloon example of jetpropulsion theory.

If we could keep the balloon full of air (*Figure 6-4, view A*), the balloon would continue to move forward. If a fan or pinwheel is placed in the air stream (*Figure 6-4, view B*), the pressure energy and velocity energy will rotate the fan and it can then be used to do work as shown in *Figure 6-4*.

By replacing the balloon with a stationary tube or container and filling the tube with air from a fan or series of fans, we can use the discharge air to do work by turning a fan at the rear of the tube (*Figure 6-5, view A*).

If fuel is added and combustion occurs, we greatly increase both the volume of air and the velocity that propels it over the fan. This velocity increases the horsepower the fan will produce (*Figure 6-5, view B*). The continuous pressure created by the inlet fan, or compressor, prevents the hot gases from going forward.

Next, if we attach a shaft to the compressor *(Figure 6-5, view B)* and extend it back to a turbine wheel, we have a simple gas turbine. It can supply power to run its own compressor and still provide enough power to do useful work, such as to drive a generator or propel a ship (*Figure 6-5, view A*). By comparing *Figure 6-5, view A* and *Figure 6-5, view B*, you can see that a gas turbine is very similar to our balloon turbine.

Theoretical Cycles

A cycle is a process that begins with certain conditions, progresses through a series of events, and returns to the original conditions.

As an introduction to gas turbine operation, consider first the reciprocating engine, which operates on the Otto cycle (*Figure 6-6, view A*). The Otto cycle consists of four basic events that occur at different times but in the same place, inside a cylinder of the engine. The events are (1) intake, where a mixture of air and fuel is drawn into the cylinder; (2) compression, where the mixture is squeezed into a much smaller volume; (3) power (or combustion), where the mixture is burned; and (4) exhaust, where the burned fuel/air mixture is forced from the cylinder. Now consider the gas turbine engine.
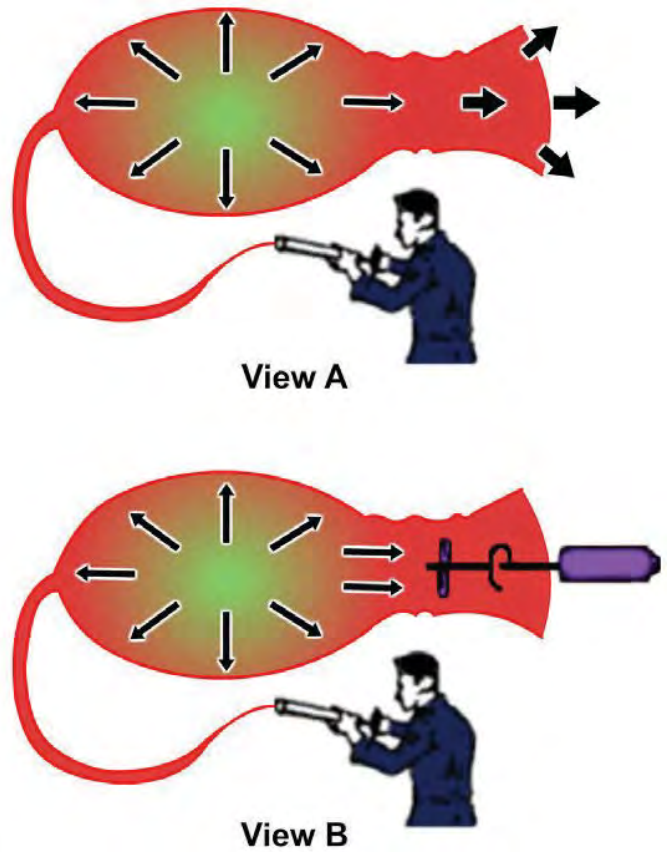

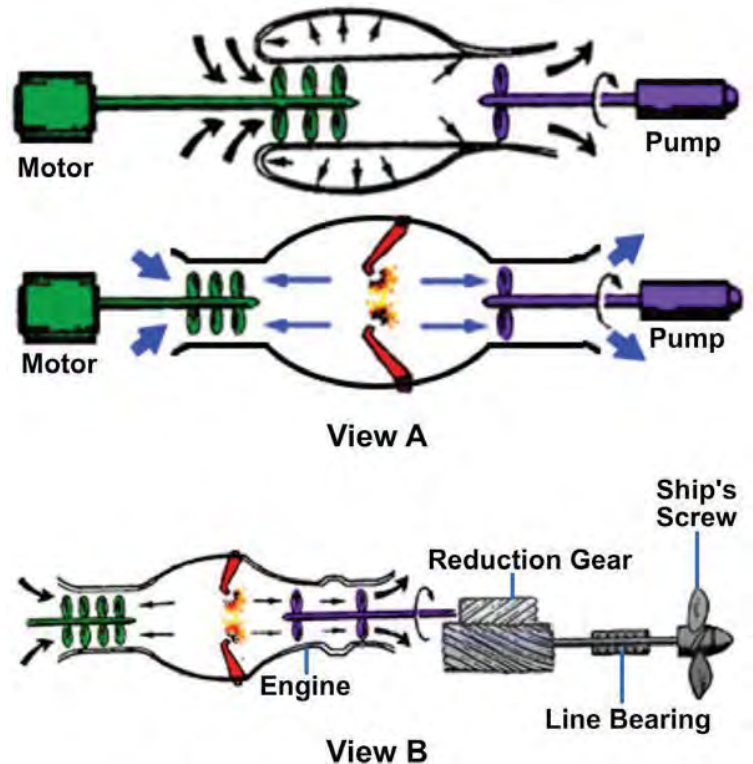
View A

View B

Figure 6-4 — Turbine operating theory.

View A

View B

Figure 6-5 — Turbine operating theory.
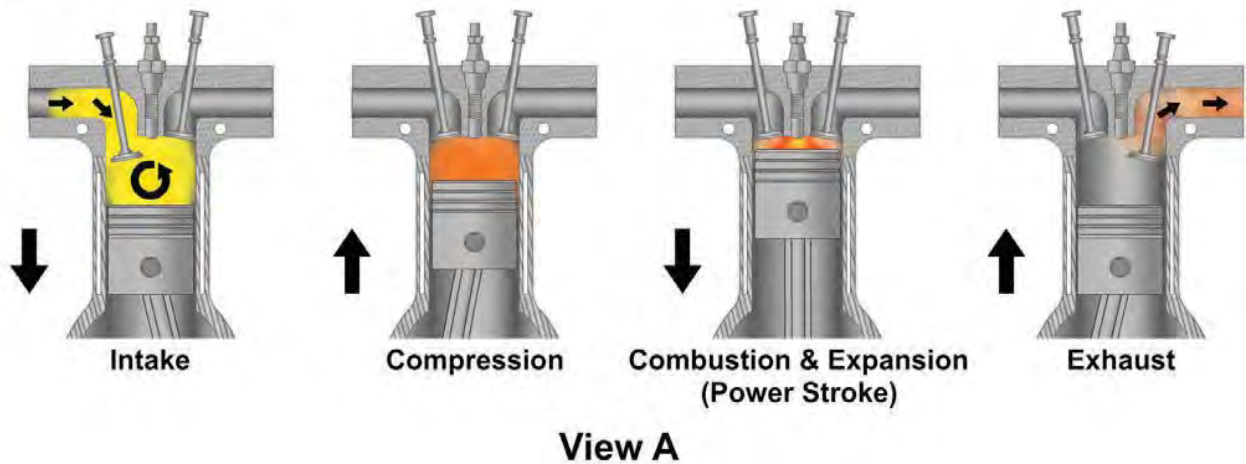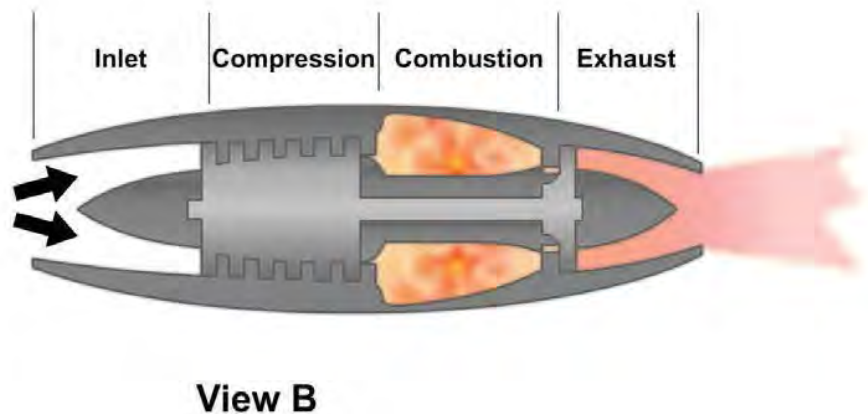
OTTO CYCLE

View A

BRAYTON CYCLE

View B

Figure 6-6 — A comparison of reciprocating and gas turbine engine cycles.

Brayton Cycle

The gas turbine engine operates on the Brayton cycle. The Brayton cycle consists of the same four events as the Otto cycle. However, the cycle is continuous and repetitive in a gas turbine engine. All four events occur at the same time, but in different locations within the gas turbine engine. Though Brayton engines are no longer made, the Brayton cycle describes the heat cycle used in modern gas turbine engines.

During the Brayton cycle, air enters the inlet (1) at atmospheric pressure and constant volume. As the air passes through the compressor (2), it increases in pressure and decreases in volume. In the combustor (3), the air mixes with fuel and burns. During combustion, pressure remains constant, but the increased temperature causes a sharp increase in volume. The gases at constant pressure and increased volume enter the turbine (4) and expand through it. As the gases pass through the turbine rotor, the rotor turns kinetic and thermal energy into mechanical energy to do work. The gases are released through the exhaust (5), with a large drop in volume and at constant pressure. The cycle is now completed. Refer to *Figure 6-6, view B* as we explain the Brayton cycle graphically.

- Inlet/Intake—Air enters the inlet at atmospheric pressure and ambient temperature
- Compression—(Adiabatic Compression) As the air passes through the compressor, it increases in pressure and temperature and decreases in volume

- Combustion—(Isobaric Ignition) Combustion occurs at constant pressure while the addition of heat causes a sharp increase in volume

- Expansion—(Adiabatic Expansion) The gases at constant pressure and increased volume enter the turbine and expand through it. As the gases pass through the turbine rotor, the rotor turns kinetic energy into mechanical energy. The expanding size of the passages causes further increase in volume and a sharp decrease in pressure and temperature

- Exhaust—(Isobaric Exhaust) The gases are released through the stack with a large drop in volume and at constant pressure

GAS TURBINE ENGINES

The gas turbine (*Figure 6-7*) is comprised of four main components: a compressor, a combustor, a turbine, and an accessory drive section (not shown). The working fluid, air, is compressed in the compressor (adiabatic compression - no heat gain or loss), then mixed with fuel and burned by the combustor under constant pressure conditions in the combustion chamber (constant pressure heat addition). The resulting hot gas expands through the turbine to perform work (adiabatic expansion). Much of the power produced in the turbine is used to run the compressor and the rest is available to run auxiliary equipment and do useful work.

There are two primary means of classifying gas turbine engines: (1) by the type of compressor used and (2) by how the power is used.
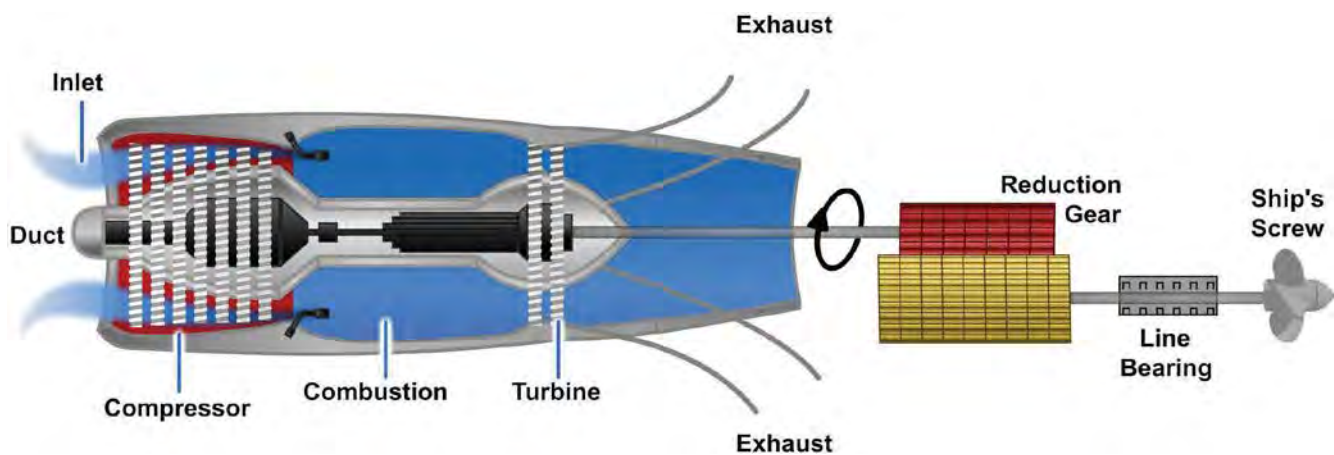

Figure 6-7 — Practical demonstration of turbine operating theory.

ENGINE CONSTRUCTION

Compressor Section

The rotor and stators are enclosed in the compressor case. Modern engines use a case that is horizontally divided into upper and lower halves. The halves are normally bolted together with either dowel pins or fitted bolts. These parts ensure proper alignment to each other and in relation to other engine assemblies that bolt to either end of the compressor case.

On some older engines, the case is a one-piece cylinder open on both ends. The one-piece compressor case is simpler to manufacture; however, any repair or detailed inspection of the compressor rotor is impossible. The engine must be removed and taken to a shop where it can be

disassembled for repair or inspection of the rotor or stators. On split-case engines, either the upper or lower case can be removed for maintenance and inspection with the engine in place.

The compressor case is usually made of aluminum or steel. The material used will depend on the engine manufacturer and the accessories attached to the case. The compressor case may have external connections made as part of the case. These connections are normally used to bleed air during starting and acceleration or at low-speed operation.

Preceding the stators and the first stage of the compressor rotor is a row of inlet guide vanes (IGVs). The function of the IGVs varies somewhat, depending on the size of the engine and air-inlet construction. On smaller engines, the air inlet is not totally in line with the first stage of the rotor. The IGVs straighten the airflow and direct it to the first-stage rotor. On large engines, the IGVs can be moved to direct the airflow at the proper angle to reduce drag on the first-stage rotor.

Small and medium engines have stationary stators. On large engines, the pitch of the vanes on several stators can be changed.

The compressor type is also the engine type, so a centrifugal-flow compressor (*Figure 6-8*) is found 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.
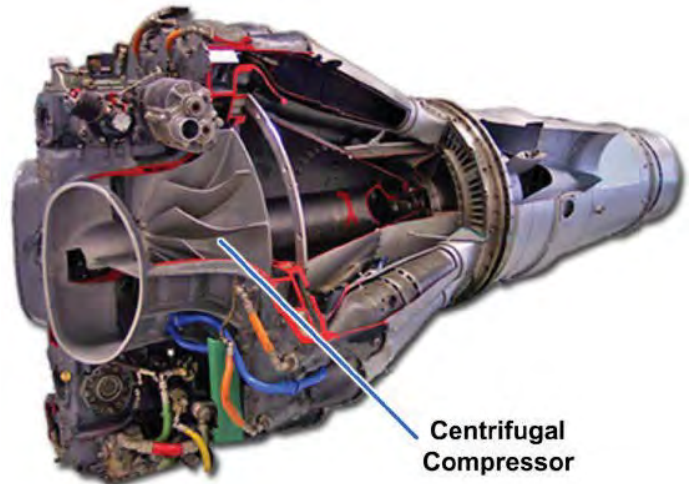

Figure 6-8 — Centrifugal compressor.

Centrifugal Compressor

The centrifugal compressor draws in air at the center or eye of the impeller and accelerates it around and outward. It consists of an impeller, a diffuser, and a compressor manifold. The diffuser is bolted to the manifold, and often the entire assembly is referred to as the diffuser. For ease of understanding, we will treat each unit separately.

The impeller may be either single entry or dual entry (*Figure 6-9*). The principal differences between the single entry and dual entry are the size of the impeller and the ducting arrangement. The single-entry impeller (*Figure 6-9, view A*) permits ducting directly to the inducer vanes, as opposed to the more complicated ducting needed to reach the rear side of the dual-entry type. Although slightly more efficient in receiving air, single-entry impellers must be of greater diameter to provide sufficient air.

Dual-entry impellers (*Figure 6-9, view B*) are smaller in diameter and rotate at higher speeds to ensure sufficient airflow. Most gas turbines of modern design use the dual-entry compressor to reduce engine diameter. A plenum (an enclosure in which air is at a pressure greater than that outside the enclosure) chamber is also required for dual-entry compressors, since the air must enter the engine at almost right angles to the engine axis. The air must surround the compressor at positive pressure to give positive flow.

The compressor draws in air at the hub of the impeller and accelerates it radially outward by centrifugal force through the impeller. It leaves the impeller at high speed and low pressure and flows through the diffuser (*Figure 6-9, view A*). The diffuser converts the high-speed, low-pressure air to low-speed, high-pressure air. The compressor manifold diverts the low-speed, high-pressure air from the diffuser into the combustion chambers. In this design, the manifold has one outlet port for each combustion chamber.

The outlet ports are bolted to an outlet elbow on the manifold. The outlet ports ensure that the same amount of air is delivered to each combustion chamber.

The outlet elbows (known by a variety of names) change the airflow from radial to axial flow. The diffusion process is completed after the turn. Each elbow contains from two to four turning vanes that perform the turning process and reduce air pressure losses by providing a smooth turning surface.

Axial-Flow Compressor

In the axial-flow engine, the air is compressed while continuing its original direction of flow parallel to the axis of the compressor rotor. The compressor is located at the very front of the engine. The purpose of the axial compressor is to take in ambient air, increase the speed and pressure, and discharge the air through the diffuser into the combustion chamber.

The two main elements of an axial-flow compressor are the rotor and stator (*Figure 6-10*). The rotor is the rotating element of the compressor. The stator is the fixed element of the compressor. The rotor and stator are enclosed in the compressor case.
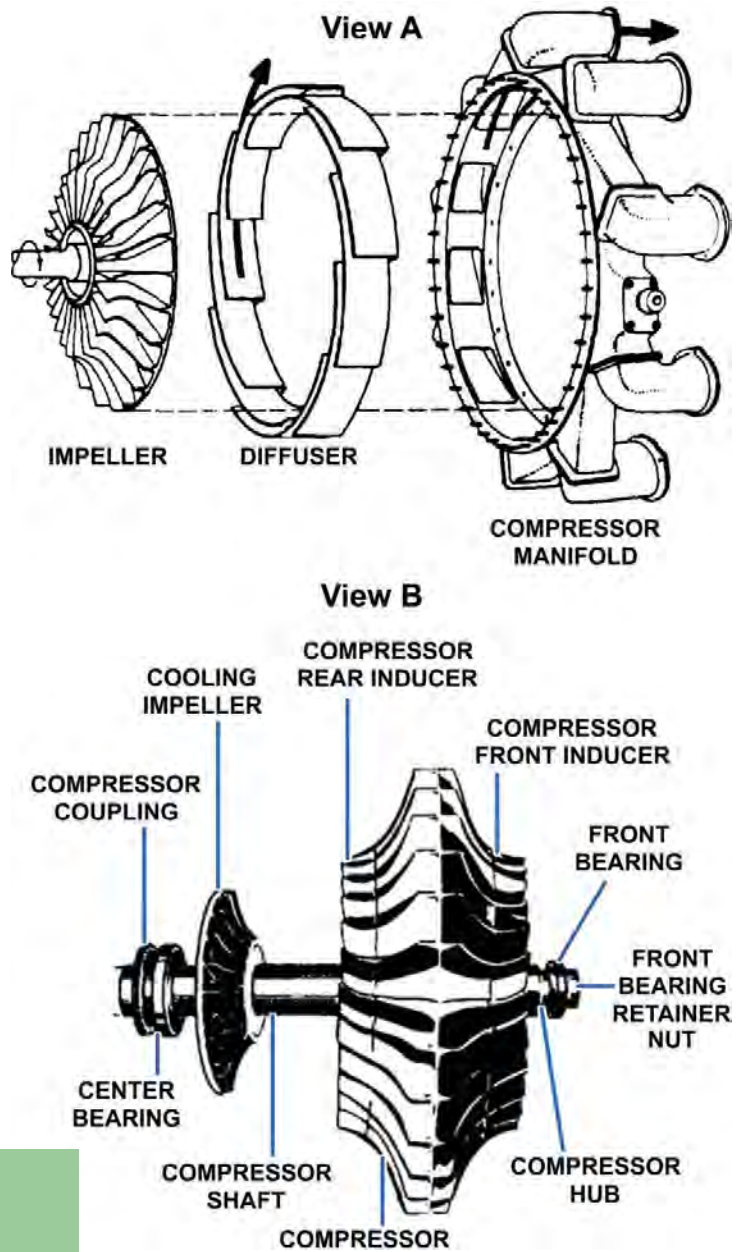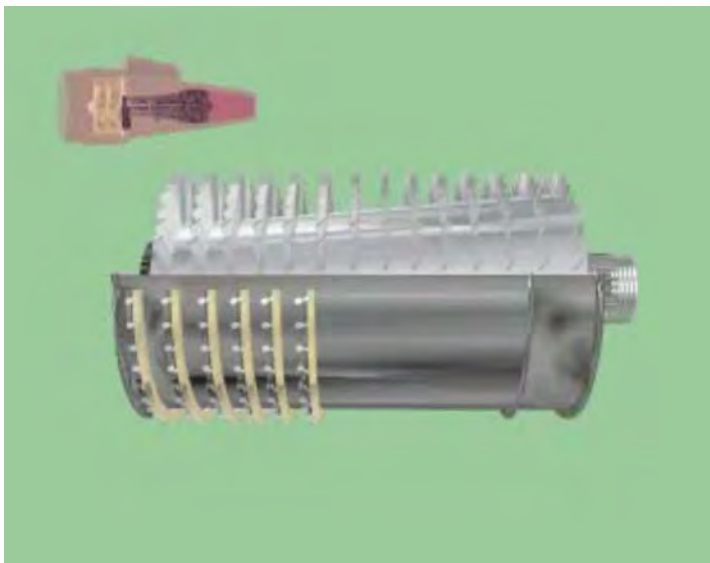

Figure 6-9 — Centrifugal compressor.

Figure 6-10 — Rotor and stator elements of an axial-flow compressor.

The rotor has fixed blades that force the air rearward much like an aircraft propeller. In front of the first rotor stage are the IGVs. These vanes direct the intake air toward the first set of rotor blades. Directly behind each rotor stage is a stator. The stator directs the air rearward to the next rotor stage (*Figure 6-11*). Each consecutive pair of rotor and stator blades constitutes a pressure stage.

The action of the rotor increases air compression at each stage and accelerates the air rearward. By virtue of this increased velocity, energy is transferred from the compressor to the air in the form of velocity energy.

The number of stages required is determined by the amount of air and total pressure rise required. The greater the number of stages, the higher the compression ratio. Most present day engines use from 10 to 16 stages.

Figure 6-11 — Rotor and stator elements.

The compressor case is usually made of aluminum or steel. The material used will depend on the engine manufacturer, the weight requirements of the engine, and the accessories attached to the case. The compressor case may have external connections made as part of the case. These connections are normally used as bleed air ports to aid in the prevention of stalls during starting and acceleration or at low-speed operation.

Rotors

The two main types of axial compressor rotors are the drum type and the disk type.

Drum-Type and Disc-Type Rotors

The drum-type rotor (*Figures 6-12 and 6-13*) 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.

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

Figure 6-12 — Drum-type compressor rotor.

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. Many engine designs now use combination disc and drum compressor rotor assemblies due to their split spool design concept.
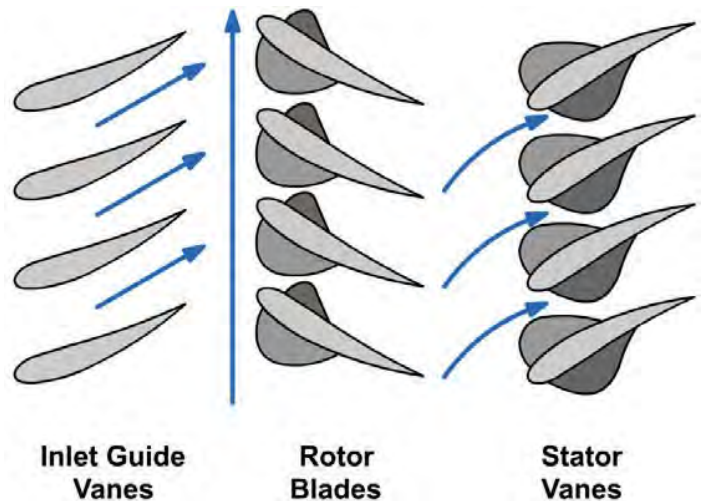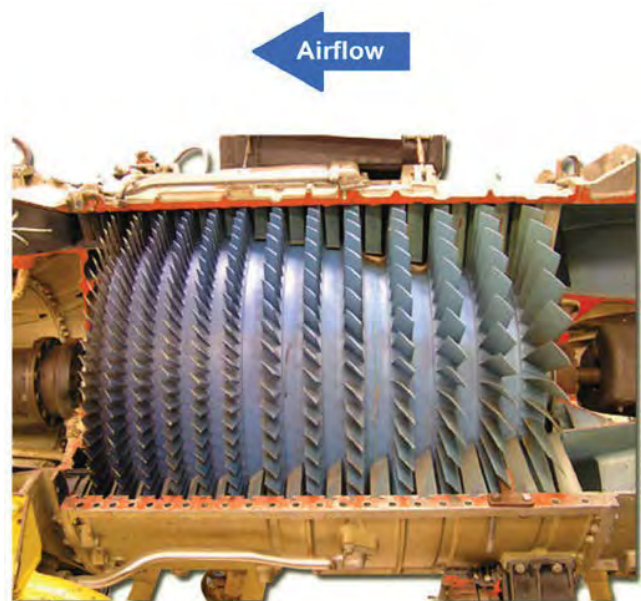
Figure 6-13 — Drum-type compressor rotor.

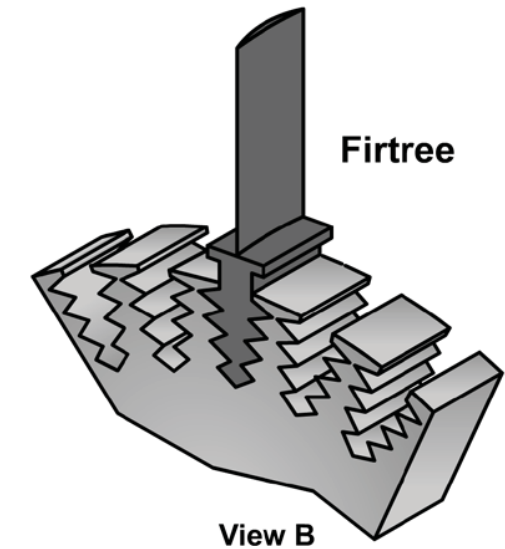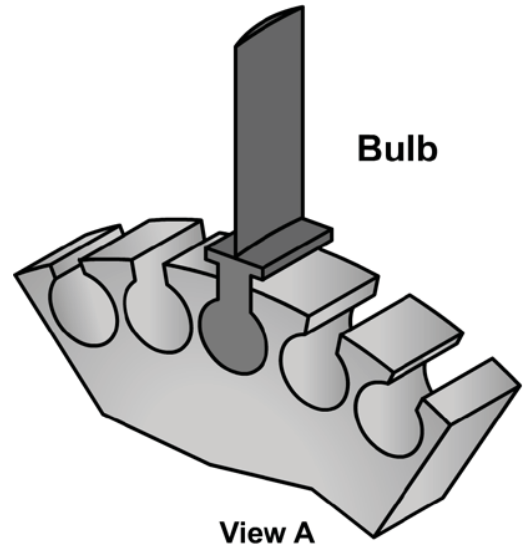Rotor blades (*Figure 6-14*) are usually made of stainless or iron-based, super-strength alloys. Methods of attaching the blades in the rotor disk rims vary in different designs, but they are commonly fitted into disks by either bulb (*Figure 6-14, view A*) or firtree (*Figure 6-14, view B*) type roots. The blades are then locked with grub screws, peening, lock wires, pins, or keys.

Stators

The stator vanes project radially toward the rotor axis and fit closely on either side of each stage of the rotor. The stators have two functions.

They receive air from the air inlet duct or from each preceding stage of the rotor and then deliver the air to the next stage or to combustors at a workable velocity and pressure. They also control the direction of air to each rotor stage to obtain the maximum compressor-blade efficiency. The stator vanes are usually made of steel with corrosion- and erosion-resistant qualities. Frequently, the

Figure 6-14 — Bulb and firtree root-type rotor blades.

vanes are shrouded by a band of suitable material to simplify the fastening problem. The vanes are welded into the shrouds, and the outer shrouds are secured to the inner wall of the compressor case by retaining screws.

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, and is known as 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. 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.

Combustion Chambers

There are three types of combustion chambers: (1) can type, (2) annular type, and (3) can-annular type. The can-type chamber is used primarily on engines that have a centrifugal compressor. The annular and can-annular types are used on axial flow compressors.

Can Type

The can-type combustion chamber (*Figure 6-15*) has individual liners and cases mounted around the axis of the engine. Each chamber contains a fuel nozzle. This arrangement makes removing a chamber easy, but it is bulky and makes a structurally weak engine. The outer casing is welded to a ring that directs the gases into the turbine nozzle. Each of the casings is linked to the others with a short tube. This arrangement ensures that combustion occurs in all the burners during engine start. Inside each of these tubes is a flame tube that joins an adjacent inner liner.

Can-type combustion chambers are arranged radially around the axis of the engine. The amount of chambers will vary in number. In the

Figure 6-15 — Can-type combustion liner.

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. 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 two types of fuel nozzles (*Figure 6-16*) 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.
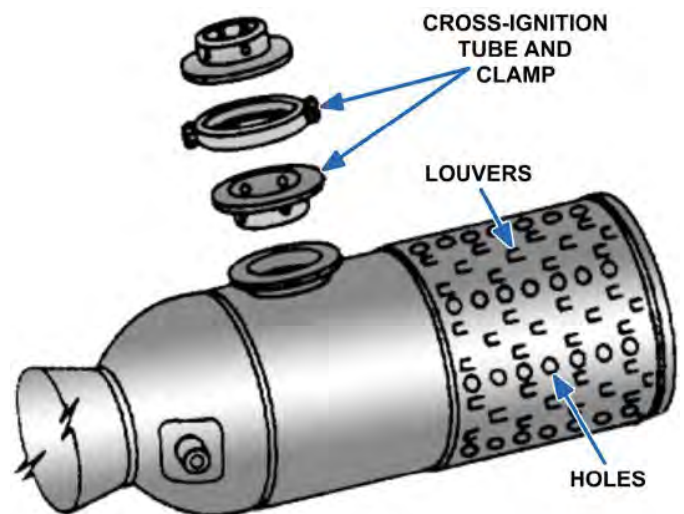
The liners of the can-type combustors have the usual perforations of various sizes and shapes. Each hole has a specific purpose and effect on the flame propagation within the liner. The air entering the combustion chamber is divided by the proper holes. Louvers and slots divide the main streams into 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.

Annular Type

The annular combustor is usually found on axial-flow engines. It is probably one of the most popular combustion systems in use. The construction consists of a housing and liner *(Figure 6-17)*.

On large engines, the liner consists of an undivided circular shroud extending all the way around the outside of the turbine shaft housing. A large one-piece combustor case covers the liner and is attached at the turbine section and diffuser section.

The dome of the liner has small slots and holes to admit primary air and to impart a swirling motion for better atomization of fuel. There are also holes in the dome for the fuel nozzles to extend through into the combustion area. The inner and outer liners form the combustion space. The outer liner keeps flame from contacting the combustor case, and the inner liner prevents flame from contacting the turbine shaft housing.

Large holes and slots are located along the liners to (1) admit some cooling air into the combustion space towards the rear of the space to help cool the hot gases to a safe level, (2) center the flame, and (3) admit air for combustion. The gases are cooled enough to prevent warpage of the liners.

The space between the liners and the case and shaft housing forms the path for secondary air. The secondary air provides film cooling of the liners and the combustor case and shaft housing. At the end of the combustion space and just before the first-stage turbine nozzle, the secondary air is mixed with the combustion gases to cool them enough to prevent warping and melting of the turbine section.
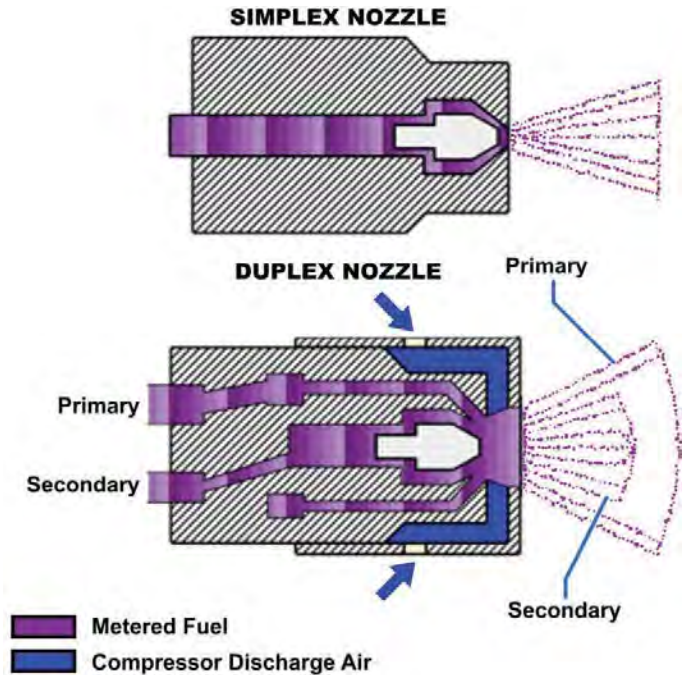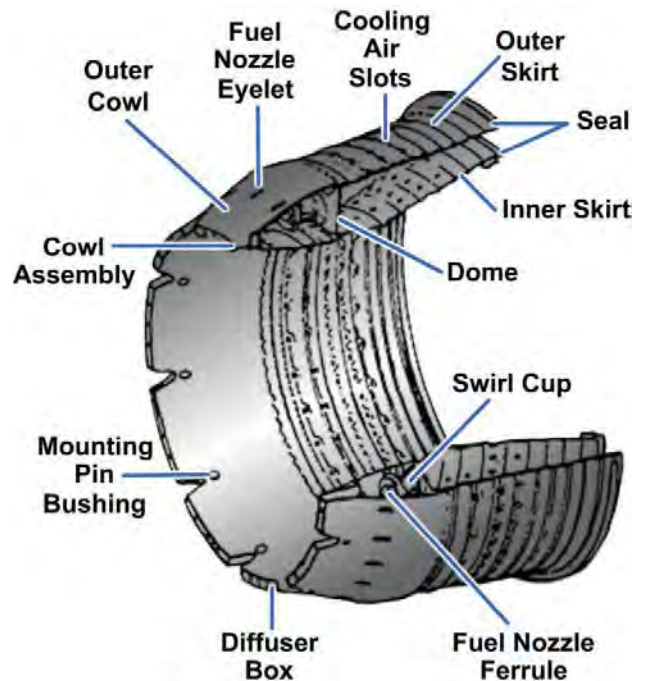

Figure 6-16 — Simplex/duplex spray nozzles.

Figure 6-17 — Combustor liner.

The annular-type combustion chamber is a very efficient system that minimizes bulk and can be used most effectively in limited space. There are some disadvantages, however. On some engines, the liners are one-piece and cannot be removed without engine disassembly.

The difference between the two is in the liner. On large engines, the liner consists of an undivided circular shroud extending all the way around the outside of the turbine shaft housing. A large one-piece combustor case covers the liner and is attached at the turbine section and diffuser section.

Can-Annular Type

The can-annular type of combustion chamber combines some of the features of both the can and the annular burners. In the can-annular type of chamber, individual cans are placed inside an annular case. The cans are essentially individual combustion chambers (*Figure 6-18*) with concentric rings of perforated holes to admit air for cooling. On some models, each can has a round perforated tube that runs down the middle of the can. The tube carries additional air, which enters the can through the perforations to provide more air for combustion and cooling.
The effect is to permit more burning per inch of can length than could otherwise be done.

The can-annular combustion chambers are arranged radially around the axis of the engine, the axis in this instance being the rotor shaft

Figure 6-18 — Components and airflow of a can-annular combustion chamber.

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 as 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 6-19* also shows that each of the combustion chambers contains a central bullet-shaped perforated liner.

A split-spool compressor 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.
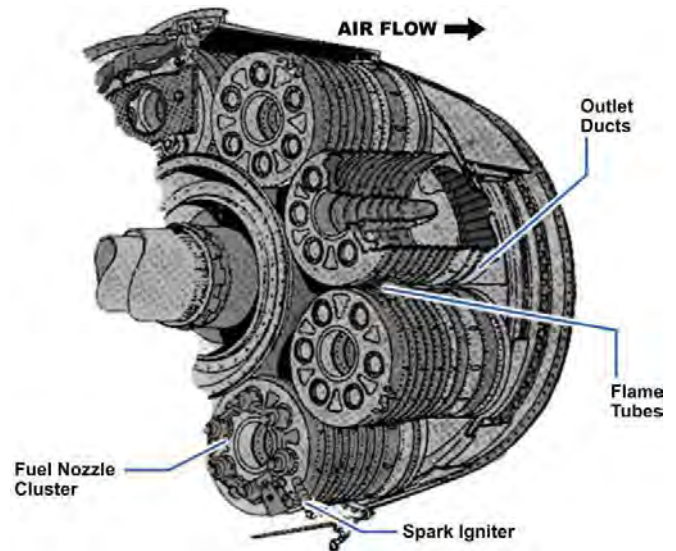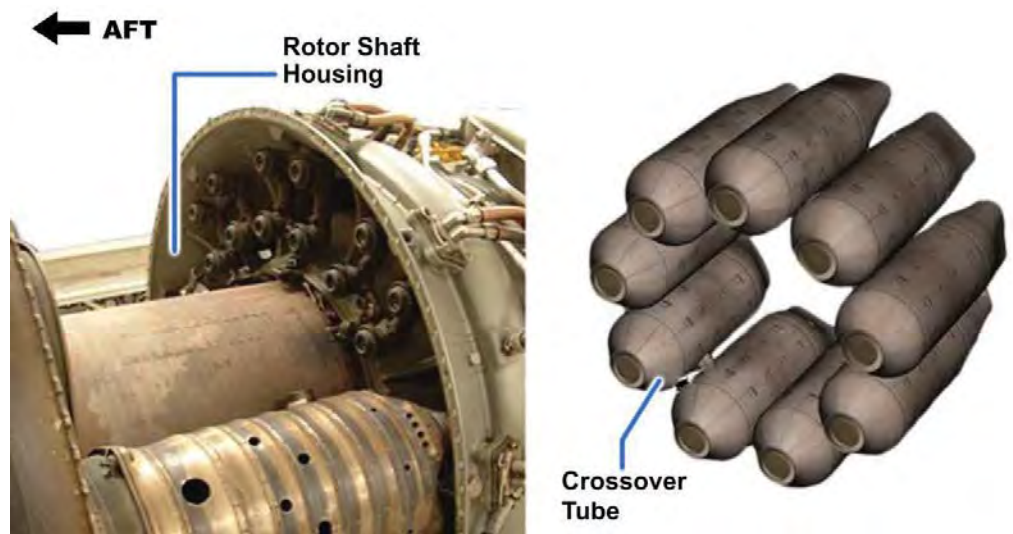

Figure 6-19 — Can-annular combustion chamber and components.

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 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 6-19* shows how the forward face of the chambers presents apertures that align with the six fuel nozzles of the corresponding fuel nozzle cluster. In the can-annular type combustion chamber, the nozzles are 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 motion results in better atomization of the fuel, thus better burning and efficiency.

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 6-20* 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.
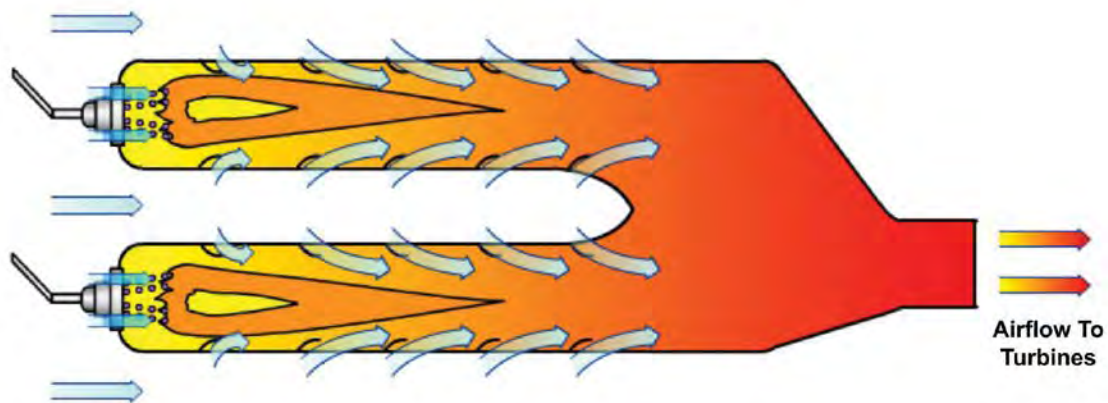

Figure 6-20 — Airflow through a can-annular chamber.

Classification by Type of Shafting

The Navy uses single-shaft, split-shaft, and the twin-spool types of gas turbines. This section will discuss the most common types in naval vessels, the single shaft and split shaft.

In current U.S. Navy service, the single-shaft engine is used for driving ship's service generators. The split-shaft engine is used for main propulsion.

Figure 6-21, view A is a block diagram of a single-shaft gas turbine. The power output shaft is connected directly to the same turbine rotor that drives the compressor. In most cases, there is a speed decreaser or reduction gear between the rotor and the power output shaft. However, there is still a mechanical connection throughout the entire engine. The arrangement shown is typical for the gas turbine generator sets aboard the CG class ships.

In the split-shaft gas turbine (*Figure 6-21, view B*), there is no mechanical connection between the gas generator turbine and the power turbine. The power turbine is the component that does the usable work. The gas-generator turbine provides the power to drive the compressor and accessories.

With this type of engine, the output speed can be varied by varying the gas generator speed. Also, under certain conditions, the gas generator can run at reduced revolutions per minute (rpm) and still provide maximum power turbine rpm. This action greatly improves fuel economy and also extends the life of the gas generator turbine.

Turbines

The purpose of the turbine is to transform a portion of the kinetic (velocity) energy of the exhaust gases into mechanical energy to drive the compressor and necessary accessories.

In theory, design, and operating characteristics, the turbines used in gas turbine engines are quite similar to the turbines used in a steam plant. The gas turbine differs from the steam turbine chiefly in (1) the type of blading material used, (2) the means provided for cooling the turbine shaft bearings, and (3) the lower ratio of blade length to wheel diameter.

The terms gas-generator turbine and power turbine are used to differentiate between the turbines. The gas-generator turbine powers the gas generator and accessories. The power turbine powers the ship's propeller through the reduction gear and shafting.

The turbine that drives the gas generator is located directly behind the combustion chamber outlet. This turbine consists of two basic elements: the stator or nozzle and the rotor. Part of a stator element is shown in *Figure 6-22*. A rotor element is shown in *Figure 6-23*.

The rotor element of the turbine consists of a shaft and bladed wheel(s). The wheel(s) are attached to the main power transmitting shaft of the gas turbine engine. The jets of combustion gas leaving the vanes of the stator element act upon the turbine blades and cause the turbine wheel to rotate in a speed range of 3,600 to 42,000 rpm, depending upon the type of engine. The high rotational speed imposes severe centrifugal loads on the turbine wheel. At the same time, the high temperature (1,050 to 2,300 degrees Fahrenheit) results in a lowering of the strength of the material. Consequently, the engine speed and temperature must be controlled to keep turbine operation within safe limits. The operating life of the turbine blading usually determines the life of the gas turbine engine.
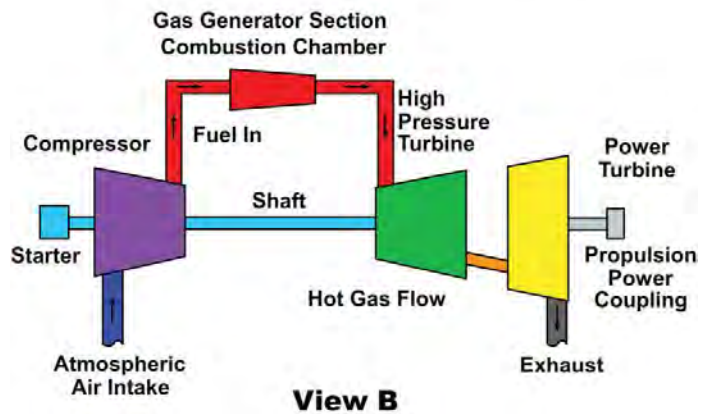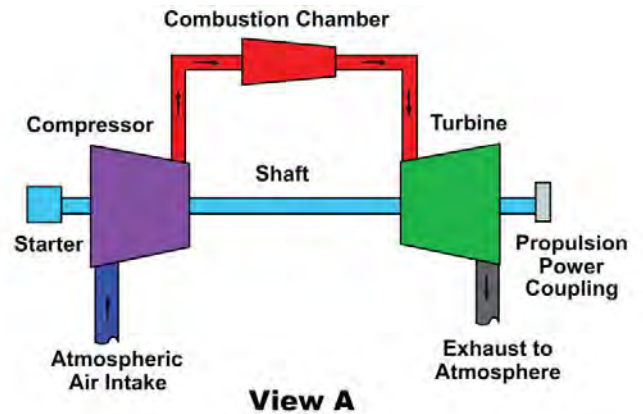

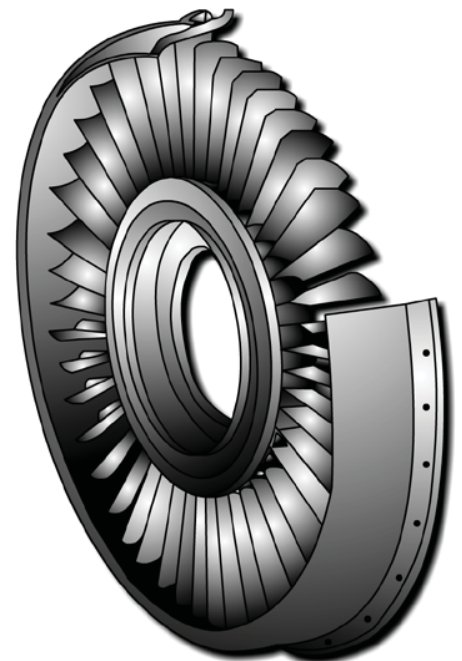**Figure 6-21 — Single-shaft and split-shaft gas turbine.**

Figure 6-22 — Stator element of the turbine assembly.

The turbine wheel is a dynamically balanced unit consisting of blades attached to a rotating disk. The disk, in turn, is attached to the rotor shaft of the engine. The high-velocity exhaust gases leaving the turbine nozzle vanes act on the blades of the turbine wheel. This action causes the assembly to rotate at a high rate of speed. This turbine rotation, in turn, causes the compressor to rotate.

Figure 6-23 — Rotor element of the turbine assembly.

The power turbine (*Figure 6-24*) is a multistage unit located behind the gas-generator turbine. There is no mechanical connection between the two turbines. The power turbine is connected to a reduction gear through a clutch mechanism. A controllable reversible-pitch (CRP) propeller is used to change direction of the vessel.

EXHAUST SECTION

The exhaust 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.

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.

STARTING SYSTEMS

Figure 6-24 — Power turbine.

Gas turbine engines use a starter to turn the compressor at sufficient speed to initiate and sustain combustion. The gas turbine ignition uses high voltage and a spark of high heat intensity. The high-energy, capacitor-discharge type of ignition system provides both high voltage and an exceptionally hot spark. This system assures ignition of the fuel-air mixture at high altitudes.

There are two types of capacitor discharge ignition systems: the high-voltage and the low-voltage systems with dc or ac input. The high-voltage system produces a double spark. The double spark is a high-voltage component. This component ionizes (makes conductive) the gap between the igniter
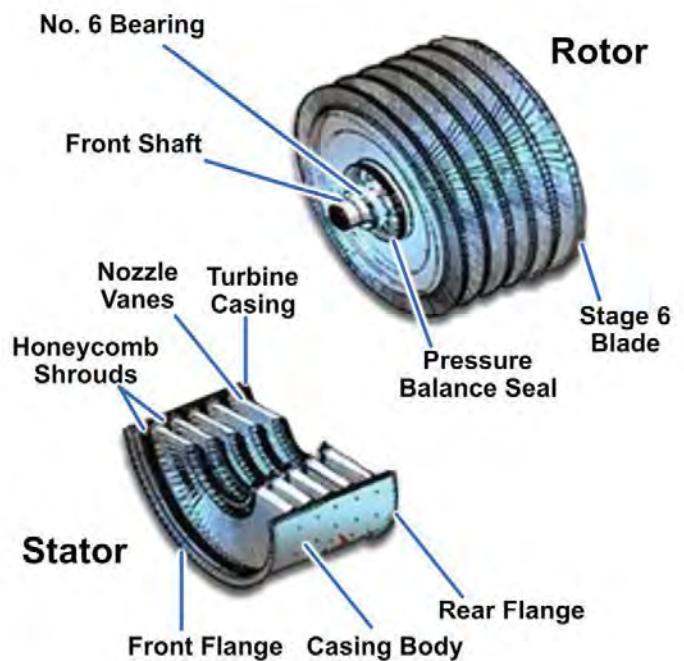
plug electrodes so that the high-energy, low-voltage component may follow. In the low-voltage system, the spark is similar to the high-voltage system, but uses a self-ionizing igniter plug. *Figure 6-25* shows a typical spark igniter.

ACCESSORY DRIVE SECTION

The primary purpose of the accessory drive section is to provide space for the mounting of the accessories required for the operation and control of the engine. The accessory drive section also serves as an oil reservoir and/or sump and houses the accessory drive gears and reduction gears.

The accessory section of the gas turbine engine is usually mounted beneath the compressor section. This section contains an accessory drive gearbox, a housing (case), and provisions for mounting the engine-driven accessories (constant speed drive transmission, fuel and oil pumps, electrical tachometer generators, etc.). The accessory gearbox also includes many of the gas turbine engine's internal lubrication system components.

The three common locations for the accessory section are on the side of the air inlet housing, under the compressor front frame, or under the compressor rear frame.

GAS TURBINE OPERATION

Machinery Control System (MCS)

The MCS provides centralized and remote monitoring of machinery systems of the propulsion, electrical, auxiliary, damage control systems. The MCS controls and monitors designated systems throughout the ship, including control of the propulsion plant from the bridge.

Figure 6-25 — Spark igniter.

The system also provides bell and logging. The MCS is comprised of the hardware and software, including the user interfaces, required to enable monitoring and control of the machinery plant. On older, legacy designs the MCS is centralized, with all of the required plant information connected via cable from a central location to the appropriate consoles by functionality (propulsion, electric power, auxiliaries, fuel control, damage control, ballast control, etc.).

Most current machinery control systems are distributed with the capability to control the ship's machinery systems from numerous workstations throughout the ship. The distributed control system relies on a network to allow communication between workstations, control equipment, and controlled/monitored devices.

The CG-class ships refer to this system as the CG Smart Ship Engineering Control System Equipment (ECSE).
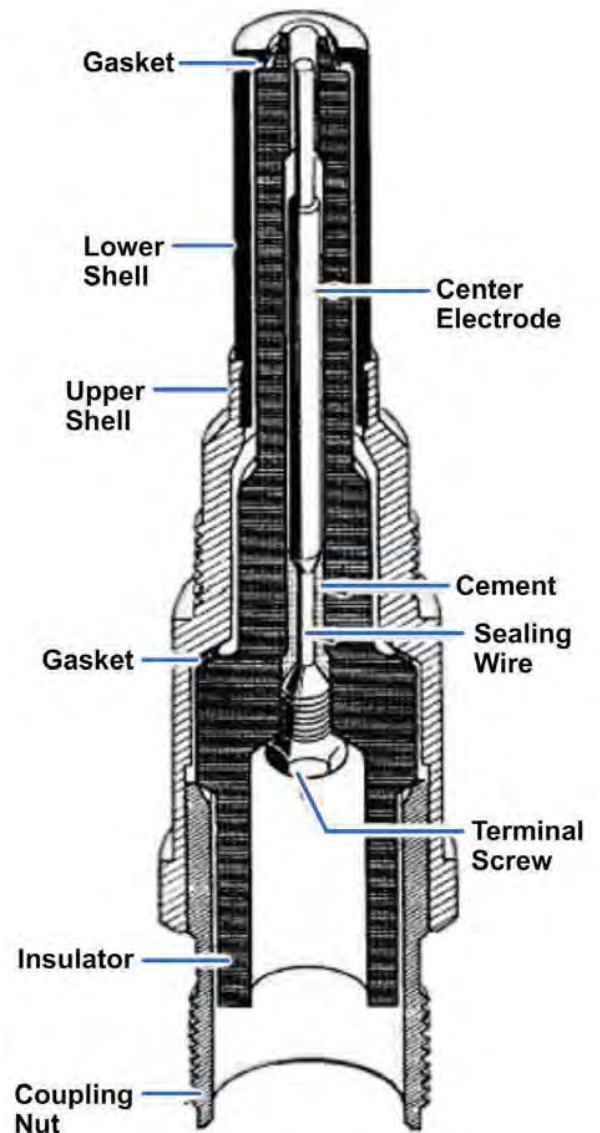
Central Control Station (CCS)

The CCS (*Figure 6-26*) is the primary operating station for the propulsion plant. The CCS is located remotely from the machinery spaces and is the main engineering watch station from which the engineering plant can be controlled and monitored. This configuration allows for monitoring and control of the engineering plant with a minimum of personnel.

The four consoles located in CCS are the propulsion auxiliary control console (PACC), the electrical plant control console (EPCC), the damage control console (DCC), and the engineering officer of the watch/logging unit (EOOW/LU). The shaft control unit (SCU) 1 and the SCU 2 are located in main engine room (MER) 1 and MER 2, respectively. The repair station console (RSC) is located in repair station 2.
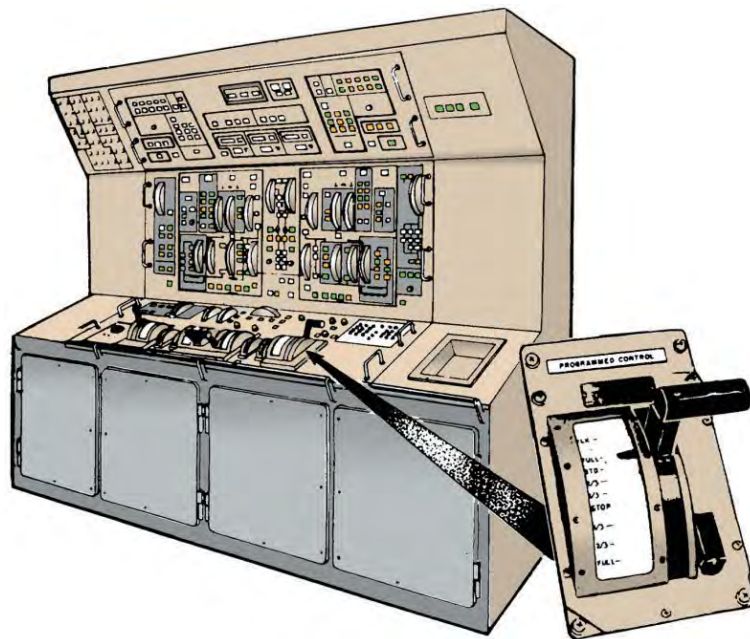

Figure 6-26 — Central control console.

On the CG-47 class ships, the PACC, EPCC, FSCC, and DCC are located in the CCS. On the DDG-51 class ships, the PACC, EPCC, EOOW/LU, and DCC are located in the CCS.

Console Types

Operation of main propulsion gas turbine engines is done from several different locations. The major classes of Navy ships that use the LM2500 gas turbine engine (GTE) have three control points. On the twin-shaft GTE powered ships, the main engine control is called the propulsion and auxiliary control console (PACC), and the console for the CG-class Smart Ship is called the integrated ships control (ISC) operator station unit (OSU).

Propulsion Local Control Console/Local Operating Panel

The propulsion local control console (PLCC) and the local operating panel (LOP) contain the principal electronic equipment necessary for controlling the associated propulsion plant. Under normal conditions, the PLCC operator does not control the propulsion plant. Instead, the transfer electronics are designed to allow the PLCC operator to take control of the propulsion plant at any time. The PLCC normally acts as the receiver of the propulsion commands from the PACC. The PLCC then processes these command signals and provides the appropriate output signal to the propulsion plant equipment.

The LOP also provides throttle control for each GTE and propeller pitch control.

Propulsion Control Console (PCC) and Propulsion Auxiliary Control Console (PACC)

The PCC is the console normally used to operate the ship's main GTEs and propulsion equipment. It also provides control and indications required for starting, controlling, monitoring, and stopping the propulsion system and the associated systems. This console also has a special purpose computer that provides semi-automatic control of the gas turbine engines and the propeller blade displays and automatic printouts. *Figure 6-27* shows a propulsion control system.

Ships that have the PACC also have the capability of monitoring and controlling some of the auxiliary systems.

Figure 6-27 — Propulsion control system.

The propulsion plant may be operated from the following three stations:

- The local control console
- The central control console
- The ship control console (SCC)

Local Control Console

The local control console is a secondary operating station. It is located in the engine room near the propulsion equipment. It controls and contains the necessary controls and indicators to permit direct local (manual) control of the propulsion equipment. The direct local mode of control, although still electronic, permits operation of the equipment in a manual mode. The local control console provides facilities for local control of plant starting, normal operation, monitoring, and stopping. The two main controls on this console are the remote throttle control and the pitch control. The remote throttle provides control of the power produced by the gas turbine engine. This control is graduated in percent of gas turbine engine speed and has control levers similar to an airplane throttle. The pitch lever provides control of the propeller pitch angle. By varying the pitch angle, the ship's speed may be changed. The pitch lever is graduated in feet of pitch either ahead or astern.

Ship Control Console

This station is located on the ship's bridge. This console has a throttle control, a propulsion plant alarm, and shaft speed and propeller pitch indicators. This station, also known as the bridge control unit (BCU) on the CG-51 class, may have direct throttle control of the engineering plant. This control console allows the officer of the deck (OOD) to have direct throttle and pitch control, eliminating the need to pass an engine order verbally to CCS. Quicker maneuvering of the ship is possible with control at the SCC.

EPCC (FLT II)

The EPCC (*Figure 6-28*) provides the operation with automatic and manual controls, displays of performance parameters, status indications, and alarm indications for remote operation of the ship's electric plant. Controls are provided for generator start/stop, generator paralleling, voltage and frequency raise/lower functions, and circuit breaker close/trip functions. Logic is provided for continuous monitoring of the electric plant operating configuration and supplying electric plant status information. The EPCC is constantly monitored underway.

Engineering Officer of the Watch/Logging Unit (EOOW/LU)

The EOOW/LU (*Figure 6-29*) provides a centralized location for the EOOW to monitor the status of the DDG-51 class machinery plants. The EOOW/LU is also used for accumulating, processing, and displaying the status of the machinery about the DDG-51 class ship.

Shaft Control Unit (SCU)

The SCU (*Figure 6-30*) controls the propulsion plant for its respective shaft, including auxiliary machinery such as bleed air, fuel service, propeller hydraulics, and lube oil. The SCU performs the same function as the PLCC on a CG-47 class ship.

Damage Control Console (DCC)

The DCC *(Figure 6-31)* is used primarily for starting or stopping the ship's fire

Figure 6-28 — Electrical plant control console.

Figure 6-29 — Engineering officer of the watch console.

pumps and monitoring high-temperature alarms throughout the ship, and is also in the CCS. During normal operations, the DCC is operated either by the EOOW, the PACC operator, or the EPCC operator.

Console Operating Overview

Using modern electronics, computers, and precisely placed sensing equipment, the operator at the CCS can "see" and manipulate the entire propulsion plant. The operator is assisted by sensor-scanning equipment that can check out the plant more thoroughly in a fraction of a second than an engine-room messenger could in 30 minutes. The scanning circuits are wired with information about the operating parameters of all the critical points monitored and will sound off immediately if these are

exceeded. The operator's control is extended not only by remote operation of all engine controls but also by wired-in expertise from electronic components that "know" all the right steps and procedures for all normal plant operations as well as most emergency procedures.

There are two directions of information flow in a gas turbine propulsion system. The first is from the sensing and measuring devices on the plant equipment. The second is from the operator and the console to the engine control devices. The first or input flow begins as an electrical signal from a sensor. These signals are "conditioned" so that they can be handled by the digital computer. Some of the signals are displayed on indicators at the operating stations. Most of these indicators are for vital equipment functions.

The control of high-performance engines and other machinery is a complex operation. Automatic central-type operating systems permit a single operator to perform this operation by extending individual ability to sense and to control. As these systems prove their effectiveness and reliability, their use will increase.

ADVANTAGES AND DISADVANTAGES OF THE GAS TURBINE PROPULSION SYSTEM

The gas turbine, when compared to other types of engines, offers many advantages. Its greatest asset is its high power-to-weight ratio. This asset has

Figure 6-30 — Shaft control unit.

Figure 6-31 — Damage control console.

made it, in the forms of turboprop or turbojet engines, the preferred engine for aircraft. Compared to the gasoline piston engine, which has the next best power-to-weight characteristics, the gas turbine operates on cheaper and safer fuel. The smoothness of the gas turbine, compared with reciprocating engines, has made it even more desirable in aircraft because less vibration reduces strain on the airframe. In a warship, the lack of low-frequency vibration in gas turbines makes them preferable to diesel engines because there is less noise for a submarine to pick up at long range. Modern production techniques have made gas turbines economical in terms of horsepower per dollar on initial installation, and their increasing reliability makes them a cost-effective alternative to steam turbine or diesel engine installation. In terms of fuel economy, modern marine gas turbines can compete with

diesel engines and may be superior to boiler/steam turbine plants when these are operating on distillate fuel.

However, there are some disadvantages to gas turbines. Since they are high-performance engines, many parts are under high stress. Improper maintenance and lack of attention to details of procedure will impair engine performance and may ultimately lead to engine failure. A pencil mark on a compressor turbine blade or a fingerprint in the wrong place can cause failure of the part. The turbine takes in large quantities of air that may contain substances or objects that can harm the engine. Most gas turbine propulsion control systems are complex because several factors have to be controlled, and numerous operating conditions and parameters must be monitored. The control systems must react quickly to turbine operating conditions to avoid casualties to the equipment. Gas turbines produce loud, high-pitched noises that can damage the human ear. In shipboard installations, special soundproofing is necessary, adding to the complexity of the installation and making access for maintenance more difficult.

From a tactical standpoint, there are two major drawbacks to the gas turbine engine. The first is the large amount of exhaust heat produced by the engines. Most current anti-ship missiles are heat seekers, and the infrared signature of a gas turbine engine makes it an easy target. Countermeasures, such as exhaust gas cooling and infrared decoys, have been developed to reduce this problem.

The second tactical disadvantage is the requirement for depot maintenance and repair of major casualties. The turbines cannot be repaired in place on the ship and must be removed and replaced by rebuilt engines if anything goes wrong. Here too, design has reduced the problem; an engine change can be accomplished wherever crane service or a Navy tender is available, and the replacement engine can be obtained.

SUMMARY

This chapter has given you some basic information on gas turbine engines and gas turbine control systems.

Additional Resources and References:

Construction Mechanic Basic, NAVEDTRA 14264A, Center for Seabees and Facilities Engineering (CSFE), Port Hueneme, CA, October 2010.

Gas Turbine Systems Technician (Electrical) 3/Gas Turbine Systems Technician (Mechanical) 3, Volume 1, NAVEDTRA 14113, Center for Naval Engineering, Norfolk, VA, September 1989.

Machinist's Mate (Surface), NAVEDTRA 14150A, Surface Warfare Officers School (SWOS), Newport, RI, September 2013.

"Marine Gas Turbines," *Naval Ships' Technical Manual (NSTM),* Chapter 234, Naval Sea Systems Command (NAVSEA), Washington, DC, October 2006.