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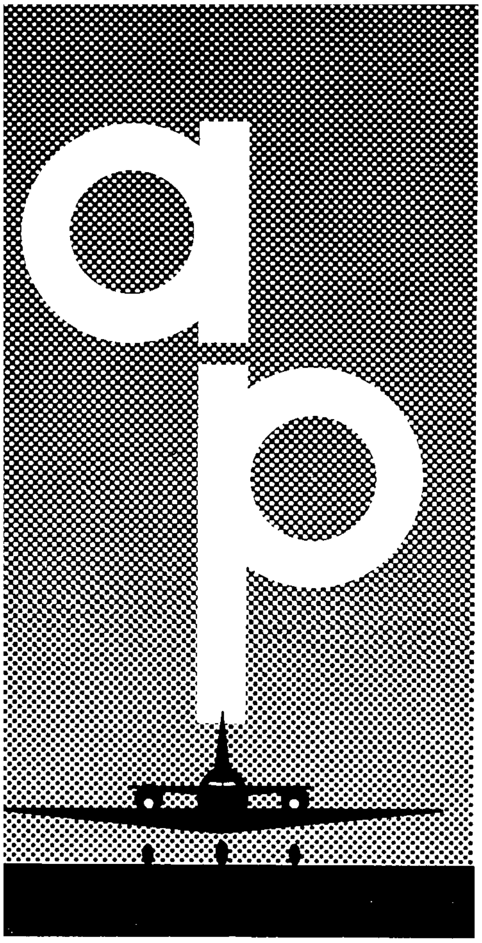

Airframe & Powerplant MECHANICS

POWERPLANT HANDBOOK

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

AIRFRAME AND POWERPLANT

MECHANICS

POWERPLANT HANDBOOK

DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

Flight Standards Service

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PREFACE

This advisory circular is printed for persons preparing for a mechanics certificate with a powerplant rating. It is intended to provide basic information on principles, fundamentals, and technical procedures in the areas relating to the powerplant rating. This is designed to serve as a guide for students enrolled in a formal course of instruction, as well as the individual who is studying on his own.

This volume is devoted to an explanation of the units which make up each of the systems that bring fuel, air, and ignition together in an aircraft engine for combustion. It also contains information on engine construction features, lubrication systems, exhaust systems, cooling systems, cylinder removal and replacement, compression checks, and valve adjustments.

Because there are so many different types of aircraft engines in use today, it is reasonable to expect minor differences to exist in like system components. To avoid undue repetition, the practice of using representative systems and units is carried out throughout the advisory circular. Subject-matter treatment throughout the text is from a generalized point of view and its use can be supplemented by reference to manufacturer's manuals and other textbooks if more detail is desired. This advisory circular is not intended to replace, substitute for, or supersede official regulations or manufacturer's instructions which should be consulted for final authority.

Grateful acknowledgement is extended to the manufacturers of engine, propellers, and powerplant accessories for their cooperation in making material available for inclusion in this handbook.

The advancements in aeronautical technology dictate that this advisory circular be brought up-to-date periodically. It has been updated, errors have been corrected, new material has been added, and some material has been rearranged to improve the usefulness of the handbook. We would appreciate, however, having errors brought to our attention, as well as suggestions for improving its usefulness. Your comments and suggestions will be retained in our files until such time as the next revision is completed.

Address all correspondence relating to this handbook to:

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Oklahoma City, Oklahoma 73125

The companion advisory circulars to AC 65–12A are the Airframe and Powerplant Mechanics General Handbook, AC 65–9A, and the Airframe and Powerplant Mechanics Airframe Handbook, AC 65–15A.

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CHAPTER 1

THEORY AND CONSTRUCTION OF AIRCRAFT ENGINES

GENERAL

For an aircraft to remain in level unaccelerated flight, a thrust must be provided that is equal to and opposite in direction to the aircraft drag. This thrust, or propulsive force, is provided by a suitable type of heat engine.

All heat engines have in common the ability to convert heat energy into mechanical energy, by the flow of some fluid mass through the engine. In all cases, the heat energy is released at a point in the cycle where the pressure is high, relative to atmospheric.

These engines are customarily divided into groups or types depending upon:

(1) The working fluid used in the engine cycle,
(2) the means by which the mechanical energy is transmitted into a propulsive force, and
(3) the method of compressing the engine working fluid.

The types of engines are illustrated in figure 1–1.

Engine Type	*Major Means of Compression*	*Engine Working Fluid*	*Propulsive Working Fluid*
Turbojet.	Turbine-driven compressor.	Fuel/air mixture.	Same as engine working fluid.
Turboprop.	Turbine-driven compressor.	Fuel/air mixture.	Ambient air.
Ramjet.	Ram compression due to high flight speed.	Fuel/air mixture.	Same as engine working fluid.
Pulse-jet.	Compression due to combustion.	Fuel/air mixture.	Same as engine working fluid.
Reciprocating.	Reciprocating action of pistons.	Fuel/air mixture.	Ambient air.
Rocket.	Compression due to combustion.	Oxidizer/fuel mixture.	Same as engine working fluid.

FIGURE 1–1. Types of engines.

The propulsive force is obtained by the displacement of a working fluid (not necessarily the same fluid used within the engine) in a direction opposite to that in which the airplane is propelled. This is an application of Newton's third law of motion. Air is the principal fluid used for propulsion in every type of powerplant except the rocket, in which only the byproducts of combustion are accelerated and displaced.

The propellers of aircraft powered by reciprocating or turboprop engines accelerate a large mass of air through a small velocity change. The fluid (air) used for the propulsive force is a different quantity than that used within the engine to produce the mechanical energy. Turbojets, ramjets, and pulse-jets accelerate a smaller quantity of air through a large velocity change. They use the same working fluid for propulsive force that is used within the engine. A rocket carries its own oxidizer rather than using ambient air for combustion. It discharges the gaseous byproducts of combustion through the exhaust nozzle at an extremely high velocity.

Engines are further characterized by the means of compressing the working fluid before the addition of heat. The basic methods of compression are:

(1) The turbine-driven compressor (turbine engine).
(2) The positive displacement, piston-type com-

pressor (reciprocating engine).

(3) Ram compression due to forward flight speed (ramjet).

(4) Pressure rise due to combustion (pulse-jet and rocket).

A more specific description of the major engine types used in commercial aviation is given later in this chapter.

COMPARISON OF AIRCRAFT POWERPLANTS

In addition to the differences in the methods employed by the various types of powerplants for producing thrust, there are differences in their suitability for different types of aircraft. The following discussion points out some of the important characteristics which determine their suitability.

General Requirements

All engines must meet certain general requirements of efficiency, economy, and reliability. Besides being economical in fuel consumption, an aircraft engine must be economical (the cost of original procurement and the cost of maintenance) and it must meet exacting requirements of efficiency and low weight per horsepower ratio. It must be capable of sustained high-power output with no sacrifice in reliability; it must also have the durability to operate for long periods of time between overhauls. It needs to be as compact as possible, yet have easy accessibility for maintenance. It is required to be as vibration free as possible and be able to cover a wide range of power output at various speeds and altitudes.

These requirements dictate the use of ignition systems that will deliver the firing impulse to the spark plugs or igniter plugs at the proper *time in* all kinds of weather and under other adverse conditions. Fuel-metering devices are needed that will deliver fuel in the correct proportion to the air ingested by the engine regardless of the attitude, altitude, or type of weather in which the engine is operated. The engine needs a type of oil system that delivers oil under the proper pressure to all of the operating parts of the engine when it is running. Also, it must have a system of damping units to damp out the vibrations of the engine when it is operating.

Power and Weight

The useful output of all aircraft powerplants is thrust, the force which propels the aircraft. Since the reciprocating engine is rated in b.hp. (brake horsepower) and the gas turbine engine is rated in pounds of thrust, no direct comparison can be made. However, since the reciprocating engine/propeller combination receives its thrust from the propeller, a comparison can be made by converting the horsepower developed by the reciprocating engine to thrust.

If desired, the thrust of a gas turbine engine can be converted into t.hp. (thrust horsepower). But it is necessary to consider the speed of the aircraft. This conversion can be accomplished by using the formula:

$$\text{t.hp.} = \frac{\text{thrust x aircraft speed (m.p.h.)}}{\text{375 mile-pounds per hour}}.$$

The value 375 mile-pounds per hour is derived from the basic horsepower formula as follows:

$$1 \text{ hp.} = 33{,}000 \text{ ft.-lb. per minute.}$$

$$33{,}000 \times 60 = 1{,}980{,}000 \text{ ft.-lb. per hour.}$$

$$\frac{1{,}980{,}000}{5{,}280} = 375 \text{ mile-pounds per hour.}$$

One horsepower equals 33,000 ft.-lb. per minute or 375 mile-pounds per hour. Under static conditions, thrust is figured as equivalent to approximately 2.6 pounds per hour.

If a gas turbine is producing 4,000 pounds of thrust and the aircraft in which the engine is installed is traveling at 500 m.p.h., the t.hp. will be:

$$\frac{4000 \times 500}{375} = 5{,}333.33 \text{ t.hp.}$$

It is necessary to calculate the horsepower for each speed of an aircraft, since the horsepower varies with speed. Therefore, it is not practical to try to rate or compare the output of a turbine engine on a horsepower basis.

The aircraft engine operates at a relatively high percentage of its maximum power output throughout its service life. The aircraft engine is at full power output whenever a takeoff is made. It may hold this power for a period of time up to the limits set by the manufacturer. The engine is seldom held at a maximum power for more than 2 minutes, and usually not that long. Within a few seconds after lift-off, the power is reduced to a power that is used for climbing and that can be maintained for longer periods of time. After the aircraft has climbed to cruising altitude, the power of the engine(s) is further reduced to a cruise power which can be maintained for the duration of the flight.

If the weight of an engine per brake horsepower (called the specific weight of the engine) is decreased, the useful load that an aircraft can carry and the performance of the aircraft obviously are increased. Every excess pound of weight carried by an aircraft engine reduces its performance. Tremendous gains in reducing the weight of the aircraft engine through improvement in design and metallurgy have resulted in reciprocating engines now producing approximately 1 hp. for each pound of weight.

Fuel Economy

The basic parameter for describing the fuel economy of aircraft engines is usually specific fuel consumption. Specific fuel consumption for turbojets and ramjets is the fuel flow (lbs./hr.) divided by thrust (lbs.), and for reciprocating engines the fuel flow (lbs./hr.) divided by brake horsepower. These are called "thrust specific fuel consumption" and "brake specific fuel consumption," respectively. Equivalent specific fuel consumption is used for the turboprop engine and is the fuel flow in pounds per hour divided by a turboprop's equivalent shaft horsepower. Comparisons can be made between the various engines on a specific fuel consumption basis.

At low speed, the reciprocating and turbopropeller engines have better economy than the turbojet engines. However, at high speed, because of losses in propeller efficiency, the reciprocating or turbopropeller engine's efficiency becomes less than that of the turbojet. Figure 1–2 shows a comparison of average thrust specific fuel consumption of three types of engines at rated power at sea level.

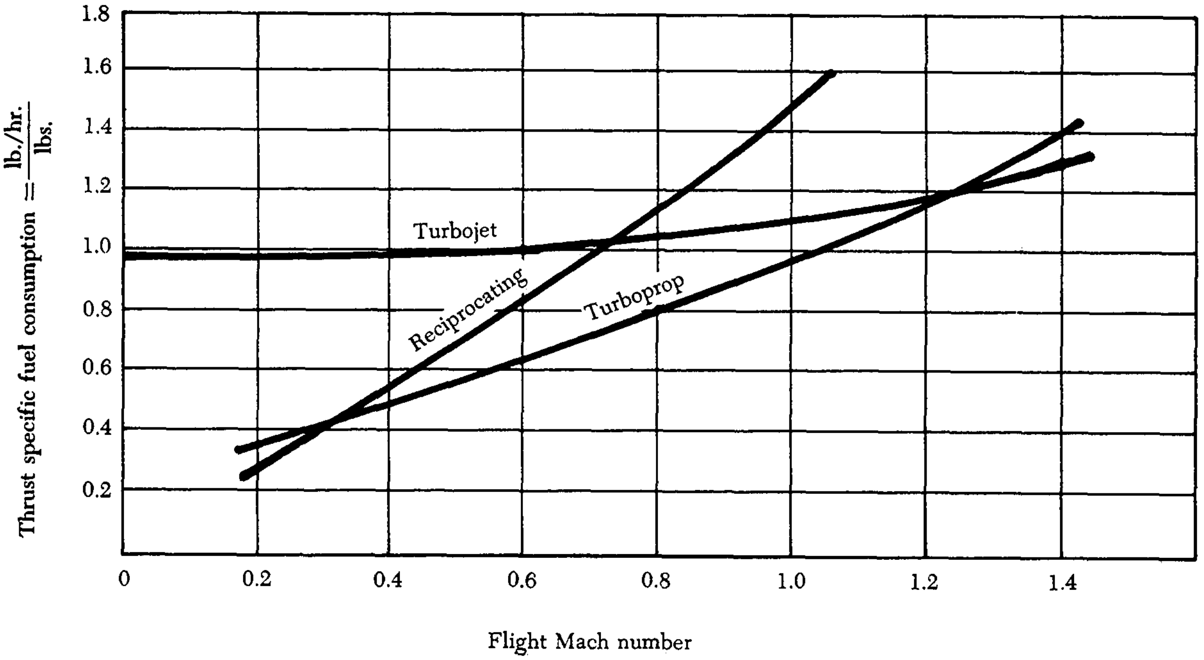


FIGURE 1–2. Comparison of fuel consumption for three types of engines at rated power at sea level.

Durability and Reliability

Durability and reliability are usually considered identical factors since it is difficult to mention one without including the other. An aircraft engine is reliable when it can perform at the specified ratings in widely varying flight attitudes and in extreme weather conditions. Standards of powerplant reliability are agreed upon by the FAA, the engine manufacturer, and the airframe manufacturer. The engine manufacturer ensures the reliability of his product by design, research, and testing. Close control of manufacturing and assembly procedures is maintained, and each engine is tested before it leaves the factory.

Durability is the amount of engine life obtained while maintaining the desired reliability. The fact that an engine has successfully completed its type or proof test indicates that it can be operated in a normal manner over a long period before requiring overhaul. However, no definite time interval between overhauls is specified or implied in the engine rating. The TBO (time between overhauls) varies with the operating conditions such as engine temperatures, amount of time the engine is operated at high-power settings, and the maintenance received.

Reliability and durability are thus built into the engine by the manufacturer, but the continued reliability of the engine is determined by the maintenance, overhaul, and operating personnel. Careful maintenance and overhaul methods, thorough periodical and preflight inspections, and strict observance of the operating limits established by the engine manufacturer will make engine failure a rare occurrence.

Operating Flexibility

Operating flexibility is the ability of an engine to run smoothly and give desired performance at all speeds from idling to full-power output. The aircraft engine must also function efficiently through all the variations in atmospheric conditions encountered in widespread operations.

Compactness

To effect proper streamlining and balancing of an aircraft, the shape and size of the engine must be as compact as possible. In single-engine aircraft, the shape and size of the engine also affect the view of the pilot, making a smaller engine better from this standpoint, in addition to reducing the drag created by a large frontal area.

Weight limitations, naturally, are closely related to the compactness requirement. The more elongated and spreadout an engine is, the more difficult it becomes to keep the specific weight within the allowable limits.

Powerplant Selection

Engine specific weight and specific fuel consumption were discussed in the previous paragraphs, but for certain design requirements, the final powerplant selection may be based on factors other than those which can be discussed from an analytical point of view. For that reason, a general discussion of powerplant selection is included here.

For aircraft whose cruising speeds will not exceed 250 m.p.h. the reciprocating engine is the usual choice. When economy is required in the low-speed range, the conventional reciprocating engine is chosen because of its excellent efficiency. When high-altitude performance is required, the turbosupercharged reciprocating engine may be chosen because it is capable of maintaining rated power to a high altitude (above 30,000 feet).

In the range of cruising speeds from 180 to 350 m.p.h. the turbopropeller engine performs better than other types of engines. It develops more power per pound of weight than does the reciprocating engine, thus allowing a greater fuel load or payload for engines of a given power. The maximum overall efficiency of a turboprop powerplant is less than that of a reciprocating engine at low speed. Turboprop engines operate most economically at high altitudes, but they have a slightly lower service ceiling than do turbosupercharged reciprocating engines. Economy of operation of turboprop engines, in terms of cargo-ton-miles per pound of fuel, will usually be poorer than that of reciprocating engines because cargo-type aircraft are usually designed for low-speed operation. On the other hand, cost of operation of the turboprop may approach that of the reciprocating engine because it burns cheaper fuel.

Aircraft intended to cruise from high subsonic speeds up to Mach 2.0 are powered by turbojet engines. Like the turboprop, the turbojet operates most efficiently at high altitudes. High-speed, turbojet-propelled aircraft fuel economy, in terms of miles per pound of fuel, is poorer than that attained at low speeds with reciprocating engines.

However, reciprocating engines are more complex in operation than other engines. Correct operation of reciprocating engines requires about twice the instrumentation required by turbojets or turboprops, and it requires several more controls. A change in power setting on some reciprocating engine installations may require the adjustment of five controls, but a change in power on a turbojet requires only a change in throttle setting. Furthermore, there are a greater number of critical temperatures and pressures to be watched on reciprocating engine installations than on turbojet or turboprop installations.

TYPES OF RECIPROCATING ENGINES

Many types of reciprocating engines have been designed. However, manufacturers have developed some designs that are used more commonly than others and are therefore recognized as conventional. Reciprocating engines may be classified according to cylinder arrangement with respect to the crankshaft (in-line, V-type, radial, and opposed) or according to the method of cooling (liquid cooled or air cooled). Actually, all engines are cooled by transferring excess heat to the surrounding air. In air-cooled engines, this heat transfer is direct from the cylinders to the air. In liquid-cooled engines, the heat is transferred from the cylinders to the coolant, which is then sent through tubing and cooled within a radiator placed in the airstream. The radiator must be large enough to cool the liquid efficiently. Heat is transferred to air more slowly than it is to a liquid. Therefore, it is necessary to provide thin metal fins on the cylinders of an air-cooled engine in order to have increased surface for sufficient heat transfer. Most aircraft engines are air cooled.

In-line Engines

An in-line engine generally has an even number of cylinders, although some three-cylinder engines have been constructed. This engine may be either liquid cooled or air cooled and has only one crankshaft, which is located either above or below the cylinders. If the engine is designed to operate with the cylinders below the crankshaft, it is called an inverted engine.

The in-line engine has a small frontal area and is better adapted to streamlining. When mounted with the cylinders in an inverted position, it offers the added advantages of a shorter landing gear and greater pilot visibility. The in-line engine has a higher weight-to-horsepower ratio than most other engines. With increase in engine size, the air cooled, in-line type offers additional handicaps to proper cooling; therefore, this type of engine is, to a large degree, confined to low- and medium-horsepower engines used in light aircraft.

Opposed or O-type Engines

The opposed-type engine, shown in figure 1–3, has two banks of cylinders directly opposite each other with a crankshaft in the center. The pistons of both cylinder banks are connected to the single crankshaft. Although the engine can be either liquid cooled or air cooled, the air-cooled version is used predominantly in aviation. It can be mounted with the cylinders in either a vertical or horizontal position.

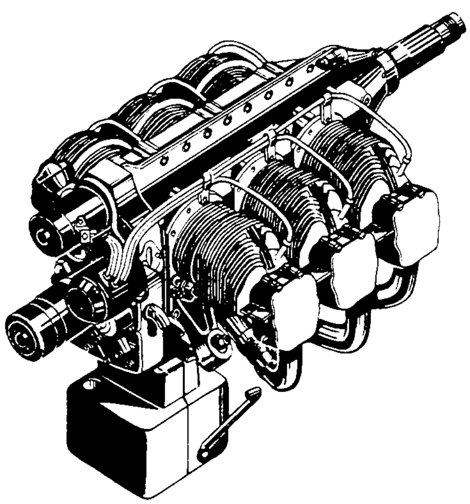


FIGURE 1–3. Opposed engine.

The opposed-type engine has a low weight-to-horsepower ratio, and its narrow silhouette makes it ideal for horizontal installation on the aircraft wings. Another advantage is its comparative freedom from vibration.

V-type Engines

In the V-type engines, the cylinders are arranged in two in-line banks generally set 60° apart. Most of the engines have 12 cylinders, which are either liquid cooled or air cooled. The engines are designated by a V, followed by a dash and the piston displacement in cubic inches, for example, V-1710.

Radial Engines

The radial engine consists of a row, or rows, of cylinders arranged radially about a central crankcase (see figure 1–4). This type of engine has proven to be very rugged and dependable. The number of cylinders composing a row may be either three, five, seven, or nine. Some radial engines have two rows of seven or nine cylinders arranged radially about the crankcase. One type has four rows of cylinders with seven cylinders in each row.

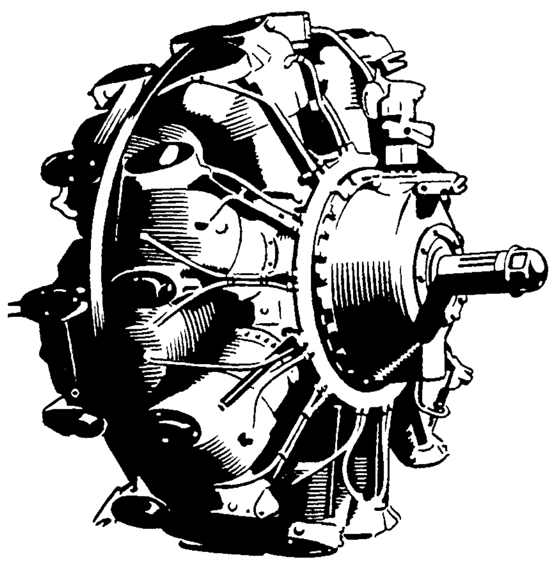


FIGURE 1–4. Radial engine.

The power output from the different sizes of radial engines varies from 100 to 3,800 horsepower.

RECIPROCATING ENGINE DESIGN AND CONSTRUCTION

The basic parts of a reciprocating engine are the crankcase, cylinders, pistons, connecting rods, valves, valve-operating mechanism, and crankshaft. In the head of each cylinder are the valves and spark plugs. One of the valves is in a passage leading from the induction system; the other is in a passage leading to the exhaust system. Inside each cylinder is a movable piston connected to a crankshaft by a connecting rod. Figure 1–5 illustrates the basic parts of a reciprocating engine.

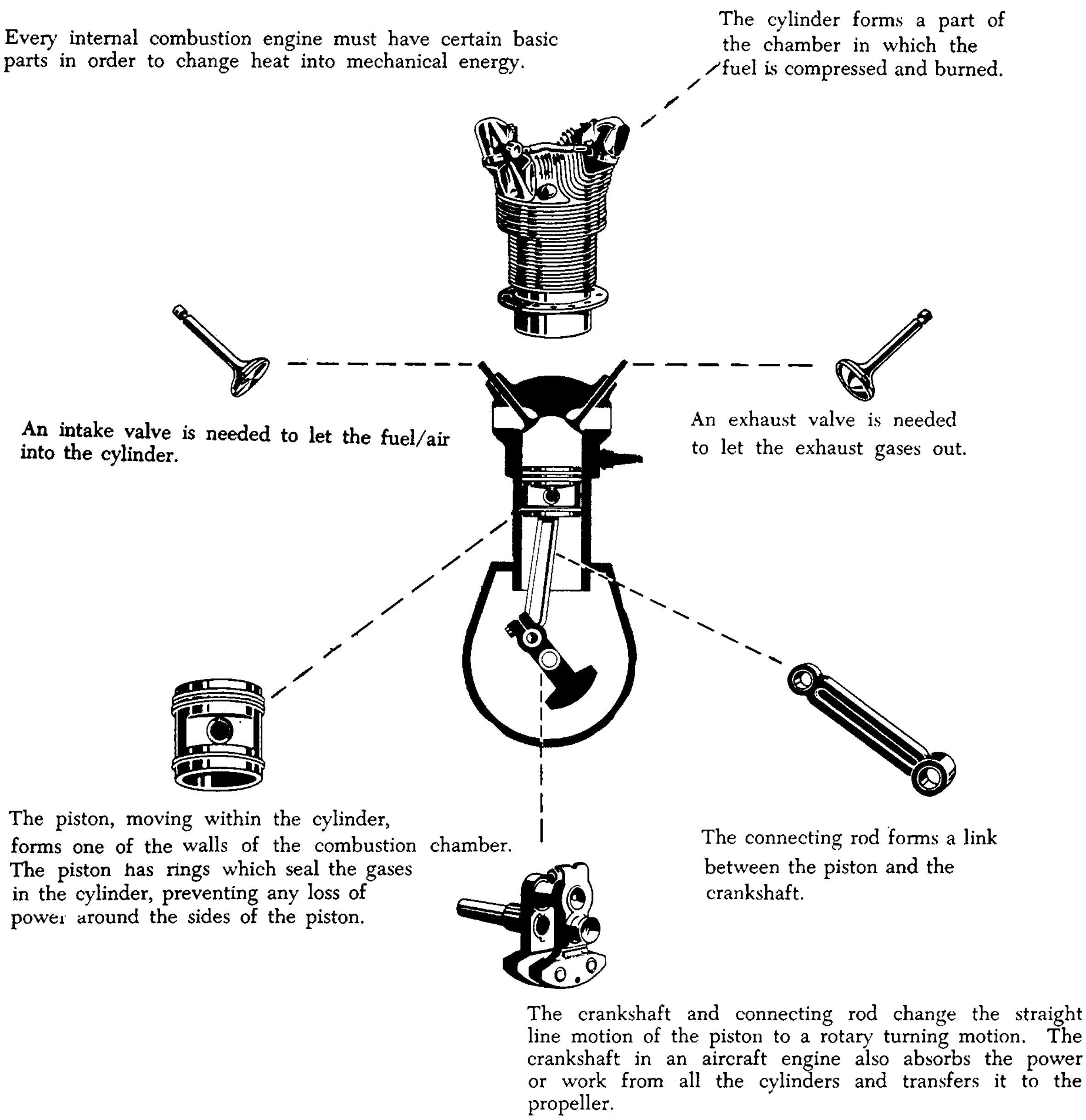


FIGURE 1–5. Basic parts of a reciprocating engine.

Crankcase Sections

The foundation of an engine is the crankcase. It contains the bearings in which the crankshaft revolves. Besides supporting itself, the crankcase must provide a tight enclosure for the lubricating oil and must support various external and internal mechanisms of the engine. It also provides support for attachment of the cylinder assemblies, and the powerplant to the aircraft. It must be sufficiently rigid and strong to prevent misalignment of the crankshaft and its bearings. Cast or forged aluminum alloy is generally used for crankcase construction because it is light and strong. Forged steel crankcases are used on some of the high-power output engines.

The crankcase is subjected to many variations of vibrational and other forces. Since the cylinders are fastened to the crankcase, the tremendous expansion forces tend to pull the cylinder off the crankcase. The unbalanced centrifugal and inertia forces of the crankshaft acting through the main bearing subject the crankcase to bending moments which change continuously in direction and magnitude. The crankcase must have sufficient stiffness to withstand these bending moments without objectional deflections. If the engine is equipped with a propeller reduction gear, the front or drive end will be subjected to additional forces.

In addition to the thrust forces developed by the propeller under high-power output, there are severe centrifugal and gyroscopic forces applied to the crankcase due to sudden changes in the direction of flight, such as those occurring during maneuvers of the airplane. Gyroscopic forces are, of course, particularly severe when a heavy propeller is installed.

Radial Engines

The engine shown in figure 1–6 is a single-row, nine-cylinder radial engine of relatively simple construction, having a one-piece nose and a two-section main crankcase.

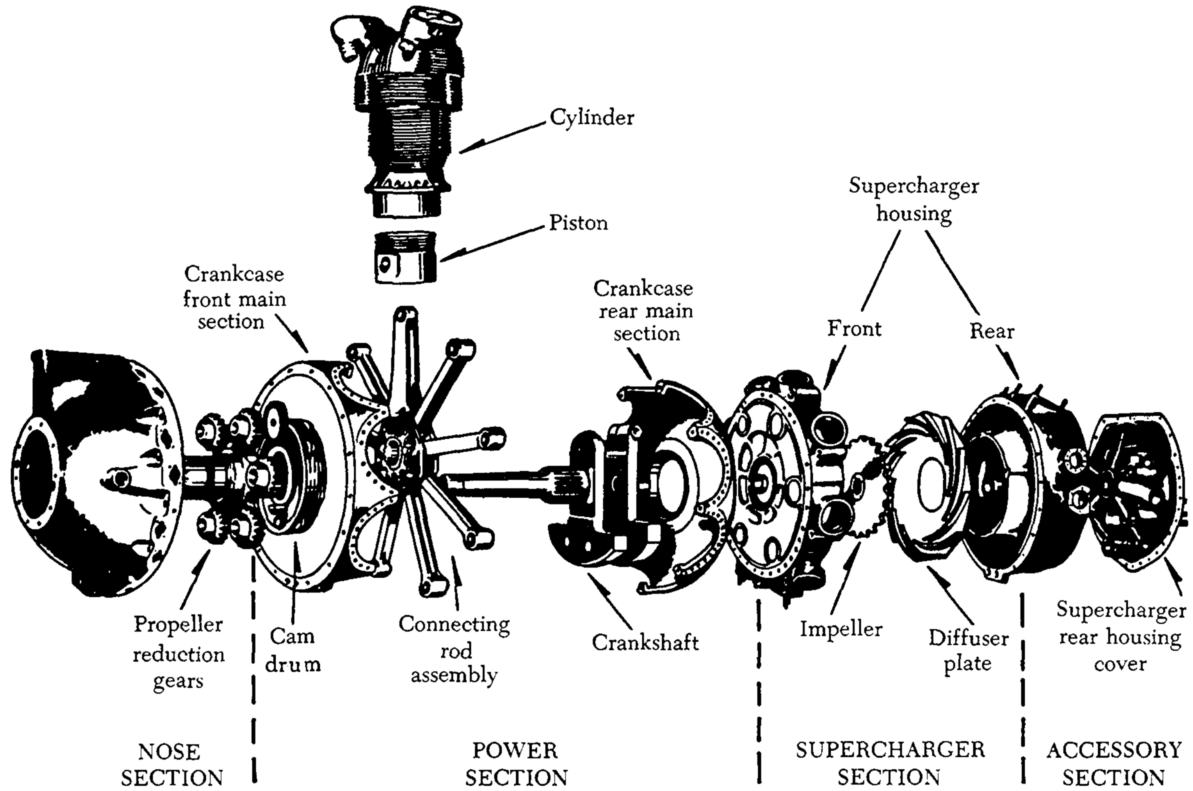


FIGURE 1–6. Engine sections.

The larger twin-row engines are of slightly more complex construction than the single-row engines. For example, the crankcase of the Wright R-3350 engine is composed of the crankcase front section, four crankcase main sections (the front main, the front center, the rear center, and the rear main sections), the rear cam and tappet housing, the supercharger front housing, the supercharger rear housing, and the supercharger rear housing cover. Pratt and Whitney engines of comparable size incorporate the same basic sections, although the construction and the nomenclature differ considerably.

Nose Section

The shape of nose sections varies considerably. In general, it is either tapered or round in order to place the metal under tension or compression instead of shear stresses. A tapered nose section is used quite frequently on direct-drive, low-powered engines, because extra space is not required to house the propeller reduction gear. It is usually cast of either aluminum alloy or magnesium since the low power developed and the use of a lightweight propeller do not require a more expensive forged nose section.

The nose section on engines which develop from 1,000 to 2,500 hp. is usually rounded and sometimes ribbed to get as much strength as possible. Aluminum alloy is the most widely used material because of its adaptability to forging processes and its vibration-absorbing characteristics.

The design and construction of the nose section is an important factor since it is subjected to a wide variation of forces and vibration. For instance, if the valve mechanism is located in front of the cylinders, the vibration and forces occurring at the tappet and guide assembly are applied near the flanged portion of the case. The forces created by the propeller reduction gear are applied to the case as a whole. Careful vibration surveys are conducted during the experimental testing of newly designed engines to see that these conditions will not become detrimental throughout the operating range of the engine.

The mounting of the propeller governor varies. On some engines it is located on the rear section, although this complicates the installation, especially if the propeller is operated or controlled by oil pressure, because of the distance between the governor and propeller. Where hydraulically operated propellers are used, it is good practice to mount the governor on the nose section as close to the propeller as possible to reduce the length of the oil passages. The governor is then driven either from gear teeth on the periphery of the bell gear or by some other suitable means.

Since the nose section transmits many varied forces to the main or power section, it must be properly secured to transmit the loads efficiently. It also must have intimate contact to give rapid and uniform heat conduction, and be oiltight to prevent leakage. This is usually accomplished by an offset or ground joint, secured by studs or capscrews.

On some of the larger engines, a small chamber is located on the bottom of the nose section to collect the oil. This is called the nose section oil sump.

Power Section

On engines equipped with a two-piece master rod and a solid-type crankshaft, the main or power crankcase section may be solid, usually of aluminum alloy. The front end of this section is open when the diaphragm plate in which the front main bearing is mounted is removed. The knuckle pins may be removed through this opening by a suitable knuckle-pin puller. The master rod is then removed by disassembling the split end and pulling the shank out through the master rod cylinder hole. There is also an engine equipped with this crankshaft and master rod arrangement which uses a split case crankcase held together by through bolts.

The split main section (aluminum or magnesium alloy) may be slightly more expensive, but permits better control over the quality of the casting or forging. The split main section is generally necessary when a solid master rod and a split-type crankshaft are used.

This portion of the engine is often called the power section, because it is here that the reciprocating motion of the piston is converted to rotary motion of the crankshaft.

Because of the tremendous loads and forces from the crankshaft assembly and the tendency of the cylinders to pull the crankcase apart, especially in extreme conditions when a high-powered engine is detonated, the main crankcase section must be very well designed and constructed. It is good practice to forge this section from aluminum alloy to obtain uniformity in the density of the metal and maximum strength. One large engine uses a forged alloy steel main section, which is slightly heavier but has very great strength. The design of the forged sections is usually such that both halves can be made in the same die in order to reduce manufacturing costs. Any variations can be taken care of during the machining operation. The two halves are joined on the center line of the cylinders and held together by suitable high-strength bolts.

The machined surfaces on which the cylinders are mounted are called cylinder pads. They are provided with a suitable means of retaining or fastening the cylinders to the crankcase. The general practice in securing the cylinder flange to the pad is to mount studs in threaded holes in the crankcase.

On engines equipped with the steel main section, capscrews are being utilized because the threads may be tapped in the stronger material and are not as likely to be stripped or stretched by installing and removing threaded members.

The inner portion of the cylinder pads are sometimes chamfered or tapered to permit the installation of a large rubber O-ring around the cylinder skirt, which effectively seals the joint between the cylinder and the crankcase pads against oil leakage.

Because oil is thrown about the crankcase, especially on inverted in-line and radial-type engines, the cylinder skirts extend a considerable distance into the crankcase sections to reduce the flow of oil into the inverted cylinders. The piston and ring assemblies, of course, have to be arranged so that they will throw out the oil splashed directly into them.

As mentioned previously, the nose section is secured to one side of the main section unit, and the diffuser or blower section is attached to the other side.

Diffuser Section

The diffuser or supercharger section generally is cast of aluminum alloy, although, in a few cases, the lighter magnesium alloy is used.

Mounting lugs are spaced about the periphery of this section to attach the engine assembly to the engine mount or framework provided for attaching the powerplant to the fuselage of single-engine aircraft or to the wing nacelle structure of multiengine aircraft. The mounting lugs may be either integral with the diffuser section or detachable, as in the case of flexible or dynamic engine mounts.

The mounting arrangement supports the entire powerplant including the propeller, and therefore is designed to provide ample strength for rapid maneuvers or other loadings.

Because of the elongation and contraction of the cylinders, the intake pipes which carry the mixture from the diffuser chamber through the intake valve ports are arranged to provide a slip joint which must be leakproof. The atmospheric pressure on the outside of the case of an unsupercharged engine will be higher than on the inside, especially when the engine is operating at idling speed. If the engine is equipped with a supercharger and operated at full throttle, the pressure will be considerably higher on the inside than on the outside of the case.

If the slip joint connection has a slight leakage, the engine may idle fast due to a slight leaning of the mixture. If the leak is quite large, it may not idle at all. At open throttle, a small leak probably would not be noticeable in operation of the engine, but the slight leaning of the fuel/air mixture might cause detonation or damage to the valves and valve seats.

On some radial engines, the intake pipe has considerable length and on some in-line engines, the intake pipe is at right angles to the cylinders. In these cases, flexibility of the intake pipe or its arrangement eliminates the need for a slip joint. In any case, the engine induction system must be arranged so that it will not leak air and change the desired fuel/air ratio.

Accessory Section

The accessory (rear) section usually is of cast construction, and the material may be either aluminum alloy, which is used most widely, or magnesium, which has been used to some extent. On some engines, it is cast in one piece and provided with means for mounting the accessories, such as magnetos, carburetors, and fuel, oil, and vacuum pumps, and starter, generator, etc., in the various locations required to facilitate accessibility. Other adaptations consist of an aluminum alloy casting and a separate cast magnesium cover plate on which the accessory mounts are arranged.

Recent design practice has been toward standardizing the mounting arrangement for the various accessories so that they will be interchangeable on different makes of engines. For example, the increased demands for electric current on large aircraft and the requirements of higher starting torque on powerful engines have resulted in an increase in the size of starters and generators. This means that a greater number of mounting bolts must be provided and, in some cases, the entire rear section strengthened.

Accessory drive shafts are mounted in suitable bronze bushings located in the diffuser and rear sections. These shafts extend into the rear section and are fitted with suitable gears from which power takeoffs or drive arrangements are carried out to the accessory mounting pads. In this manner the various gear ratios can be arranged to give the proper drive speed to magneto, pump, and other accessories to obtain correct timing or functioning.

In some cases there is a duplication of drives, such as the tachometer drive, to connect instruments located at separate stations.

The accessory section provides a mounting place for the carburetor, or master control, fuel injection pumps, engine-driven fuel pump, tachometer generator, synchronizing generator for the engine analyzer, oil filter, and oil pressure relief valve.

Accessory Gear Trains

Gear trains, containing both spur- and bevel-type gears, are used in the different types of engines for driving engine components and accessories. Spur-type gears are generally used to drive the heavier loaded accessories or those requiring the least play or backlash in the gear train. Bevel gears permit angular location of short stub shafts leading to the various accessory mounting pads.

Practically all high-powered engines are equipped with a supercharger. From 75 to 125 hp. may be required to drive the supercharger. The acceleration and deceleration forces imposed on the supercharger gear train when opening and closing the throttle make some kind of antishock device necessary to relieve excessive loads. The current practice on large radial engines is to use a main accessory drive gear which is fitted with several springs between the rim of the gear and drive shaft. This device, called the spring-loaded accessory drive gear, permits absorption of forces of high magnitude, preventing damage to the accessory gear trains. When an engine is equipped with a two-speed supercharger, the oil-pressure operated clutches act as shock absorbers to protect the supercharger gear train.

On the low-powered, opposed, and in-line engines, the accessory gear trains are usually simple arrangements. Many of these engines use synthetic rubber or spring couplings to protect the magneto and generator gear trains from excessive loads.

Opposed and In-line Types

The crankcases used on engines having opposed or in-line cylinder arrangements vary in form for the different types of engines, but in general they are approximately cylindrical. One or more sides are surfaced to serve as a base to which the cylinders are attached by means of capscrews, bolts, or studs. These accurately machined surfaces are frequently referred to as cylinder pads.

The crankshaft is carried in a position parallel to the longitudinal axis of the crankcase and is generally supported by a main bearing between each throw. The crankshaft main bearings must be supported rigidly in the crankcase. This usually is accomplished by means of transverse webs in the crankcase, one for each main bearing. The webs form an integral part of the structure and, in addition to supporting the main bearings, add to the strength of the entire case.

The crankcase is divided into two sections in a

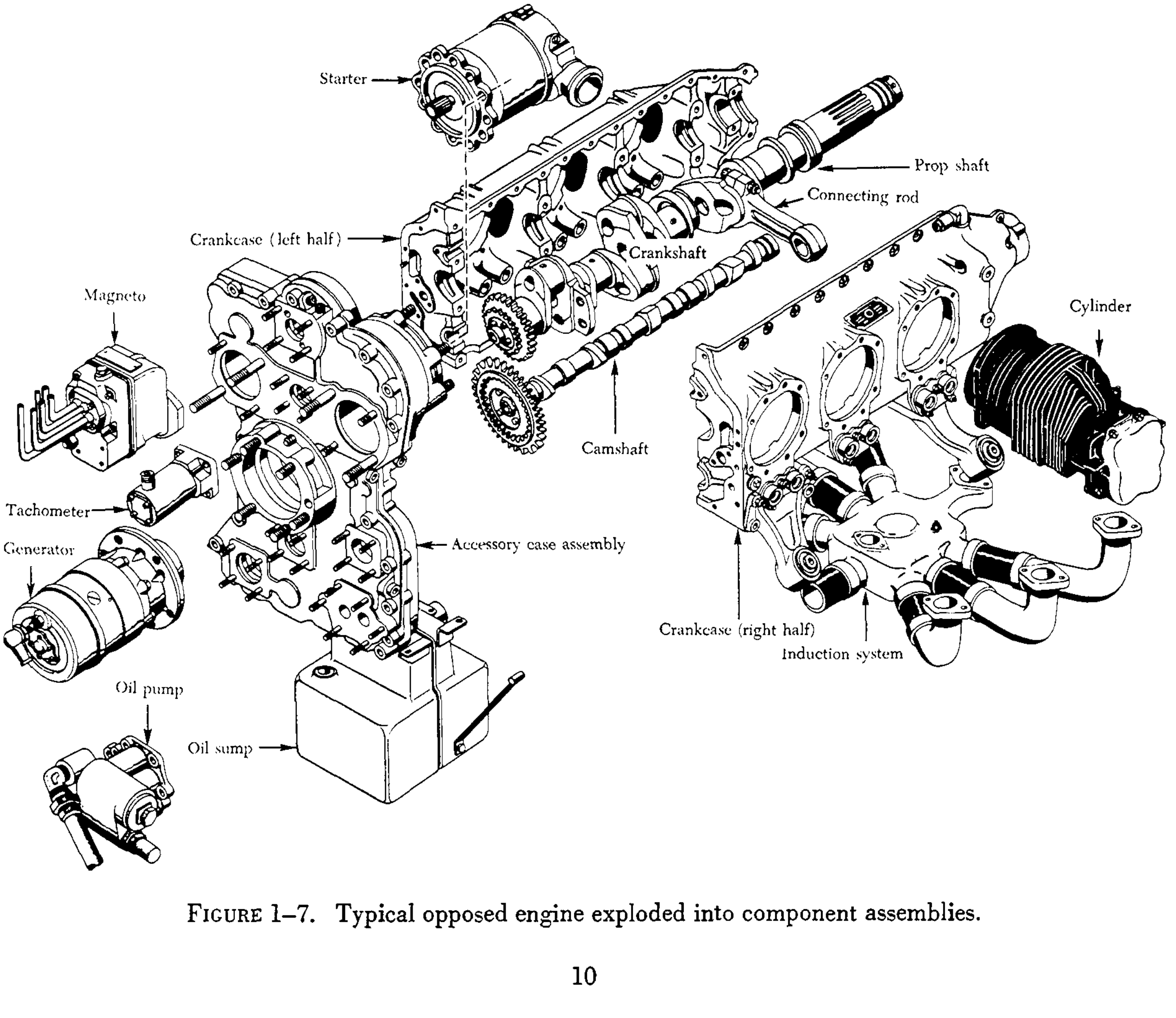


FIGURE 1–7. Typical opposed engine exploded into component assemblies.

longitudinal plane. This division may be in the plane of the crankshaft so that one-half of the main bearing (and sometimes camshaft bearings) are carried in one section of the case and the other half in the opposite section. (See figure 1–7.) Another method is to divide the case in such a manner that the main bearings are secured to only one section of the case on which the cylinders are attached, thereby providing means of removing a section of the crankcase for inspection without disturbing the bearing adjustment.

CRANKSHAFTS

The crankshaft is the backbone of the reciprocating engine. It is subjected to most of the forces developed by the engine. Its main purpose is to transform the reciprocating motion of the piston and connecting rod into rotary motion for rotation of the propeller. The crankshaft, as the name implies, is a shaft composed of one or more cranks located at specified points along its length. The cranks, or throws, are formed by forging offsets into a shaft before it is machined. Since crankshafts must be very strong, they generally are forged from a very strong alloy, such as chromium-nickel-molybdenum steel.

A crankshaft may be of single-piece or multipiece construction. Figure 1–8 shows two representative types of solid crankshafts used in aircraft engines. The four-throw construction may be used either on four-cylinder horizontal opposed or four-cylinder in-line engines.

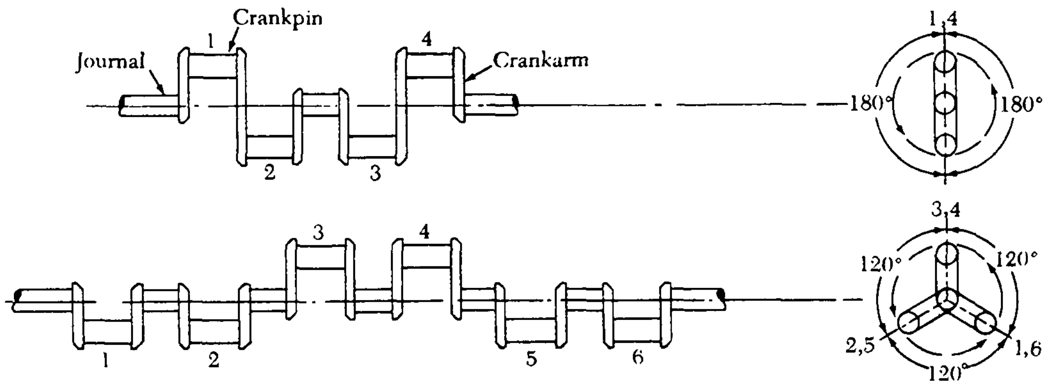


FIGURE 1–8. Solid types of crankshafts.

The six-throw shaft is used on six-cylinder in-line engines, 12-cylinder V-type engines, and six-cylinder opposed engines.

Crankshafts of radial engines may be the single-throw, two-throw, or four-throw type, depending on whether the engine is the single-row, twin-row, or four-row type. A single-throw radial engine crankshaft is shown in figure 1–9.

No matter how many throws it may have, each crankshaft has three main parts—a journal, crankpin, and crank cheek. Counterweights and dampers, although not a true part of a crankshaft, are usually attached to it to reduce engine vibration.

The journal is supported by, and rotates in, a main bearing. It serves as the center of rotation of the crankshaft. It is surface-hardened to reduce wear.

The crankpin is the section to which the connecting rod is attached. It is off-center from the main journals and is often called the throw. Two crank cheeks and a crankpin make a throw. When a force is applied to the crankpin in any direction other than parallel or perpendicular to and through the center line of the crankshaft, it will cause the crankshaft to rotate. The outer surface is hardened by nitriding to increase its resistance to wear and to provide the required bearing surface. The crankpin is usually hollow. This reduces the total weight of the crankshaft and provides a passage for the transfer of lubricating oil. The hollow crankpin also serves as a chamber for collecting sludge, carbon deposits, and other foreign material. Centrifugal force throws these substances to the outside of the chamber and thus keeps them from reaching the connecting-rod bearing surface. On some engines a passage is drilled in the crank cheek to allow oil

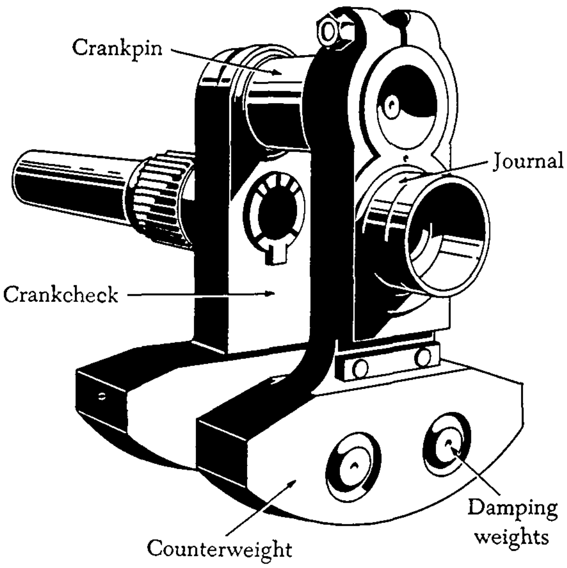


FIGURE 1–9. A single-throw radial engine crankshaft.

from the hollow crankshaft to be sprayed on the cylinder walls.

The crank cheek connects the crankpin to the main journal. In some designs, the cheek extends beyond the journal and carries a counterweight to balance the crankshaft. The crank cheek must be of sturdy construction to obtain the required rigidity between the crankpin and the journal.

In all cases, the type of crankshaft and the number of crankpins must correspond with the cylinder arrangement of the engine. The position of the cranks on the crankshaft in relation to the other cranks of the same shaft is expressed in degrees.

The simplest crankshaft is the single-throw or 360° type. This type is used in a single-row radial engine. It can be constructed in one or two pieces. Two main bearings (one on each end) are provided when this type of crankshaft is used.

The double-throw or 180° crankshaft is used on double-row radial engines. In the radial-type engine, one throw is provided for each row of cylinders.

Crankshaft Balance

Excessive vibration in an engine not only results in fatigue failure of the metal structures, but also causes the moving parts to wear rapidly. In some instances, excessive vibration is caused by a crankshaft which is not balanced. Crankshafts are balanced for static balance and dynamic balance.

A crankshaft is statically balanced when the weight of the entire assembly of crankpins, crank cheeks, and counterweights is balanced around the axis of rotation. When testing the crankshaft for static balance, it is placed on two knife edges. If the shaft tends to turn toward any one position during the test, it is out of static balance.

A crankshaft is dynamically balanced when all the forces created by crankshaft rotation and power impulses are balanced within themselves so that little or no vibration is produced when the engine is operating. To reduce vibration to a minimum during engine operation, dynamic dampers are incorporated on the crankshaft. A dynamic damper is merely a pendulum which is so fastened to the crankshaft that it is free to move in a small arc. It is incorporated in the counterweight assembly. Some crankshafts incorporate two or more of these assemblies, each being attached to a different crank cheek. The distance the pendulum moves and its vibrating frequency correspond to the frequency of the power impulses of the engine. When the vibration frequency of the crankshaft occurs, the pendulum oscillates out of time with the crankshaft vibration, thus reducing vibration to a minimum.

Dynamic Dampers

The construction of the dynamic damper used in one engine consists of a movable slotted-steel counterweight attached to the crank cheek. Two spool-shaped steel pins extend into the slot and pass through oversized holes in the counterweight and crank cheek. The difference in the diameter between the pins and the holes provides a pendulum effect. An analogy of the functioning of a dynamic damper is shown in figure 1–10.

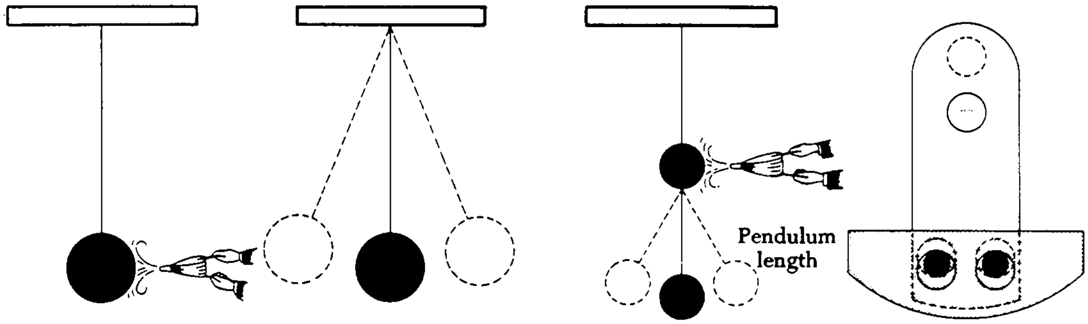
CONNECTING RODS

The connecting rod is the link which transmits forces between the piston and the crankshaft. Connecting rods must be strong enough to remain rigid under load and yet be light enough to reduce the inertia forces which are produced when the rod and piston stop, change direction, and start again at the end of each stroke.

There are three types of connecting-rod assemblies: (1) The plain-type connecting rod, (2) the fork-and-blade connecting rod, and (3) the master-and-articulated-rod assembly. (See figure 1–11.)

Master-and-Articulated Rod Assembly

The master-and-articulated rod assembly is commonly used in radial engines. In a radial engine the piston in one cylinder in each row is connected to the crankshaft by a master rod. All other pistons in the row are connected to the master rod by an



If a simple pendulum is given a series of regular impulses at a speed corresponding to its natural frequency (using a bellows to simulate a power impulse in an engine) it will commence swinging, or vibrating, back and forth from the impulses. Another pendulum, suspended from the first, would absorb the impulses and swing itself, leaving the first stationary. The dynamic damper is a short pendulum hung on the crankshaft and tuned to the frequency of the power impulses to absorb vibration in the same manner.

FIGURE 1–10. Principles of a dynamic damper.

articulated rod. In an 18-cylinder engine which has two rows of cylinders, there are two master rods and 16 articulated rods. The articulated rods are constructed of forged steel alloy in either the I- or H-shape, denoting the cross-sectional shape. Bronze bushings are pressed into the bores in each end of the articulated rod to provide knuckle-pin and piston-pin bearings.

The master rod serves as the connecting link between the piston pin and the crankpin. The crankpin end, or the "big end," contains the crankpin or master rod bearing. Flanges around the big end provide for the attachment of the articulated rods. The articulated rods are attached to the master rod by knuckle pins, which are pressed into holes in the master rod flanges during assembly. A plain bearing, usually called a piston-pin bushing, is installed in the piston end of the master rod to receive the piston pin.

When a crankshaft of the split-spline or split-clamp type is employed, a one-piece master rod is used. The master and articulated rods are assembled and then installed on the crankpin; the crankshaft sections are then joined together. In engines that use the one-piece type of crankshaft, the big end of the master rod is split, as is the master rod bearing. The main part of the master rod is installed on the crankpin; then the bearing cap is set in place and bolted to the master rod.

The centers of the knuckle pins do not coincide with the center of the crankpin. Thus, while the crankpin center describes a true circle for each revolution of the crankshaft, the centers of the knuckle pins describe an elliptical path (see figure 1–12).

The elliptical paths are symmetrical about a center line through the master rod cylinder. It can be seen that the major diameters of the ellipses are not the same. Thus, the link rods will have varying degrees of angularity relative to the center of the crank throw.

Because of the varying angularity of the link rods and the elliptical motion of the knuckle pins, all pistons do not move an equal amount in each cylinder for a given number of degrees of crank throw movement. This variation in piston position between cylinders can have considerable effect on engine operation. To minimize the effect of these factors on valve and ignition timing, the knuckle-pin holes in the master rod flange are not equidistant from the center of the crankpin, thereby offsetting to an extent the effect of the link rod angularity.

Another method of minimizing the adverse effects on engine operation is to use a compensated magneto. In this magneto the breaker cam has a number of lobes equal to the number of cylinders on the engine. To compensate for the variation in piston position due to link rod angularity, the breaker cam lobes are ground with uneven spacing. This allows the breaker contacts to open when the piston is in the correct firing position. This will be further outlined during the discussion on ignition timing in Chapter 4.

Knuckle Pins

The knuckle pins are of solid construction except for the oil passages drilled in the pins, which lubri-

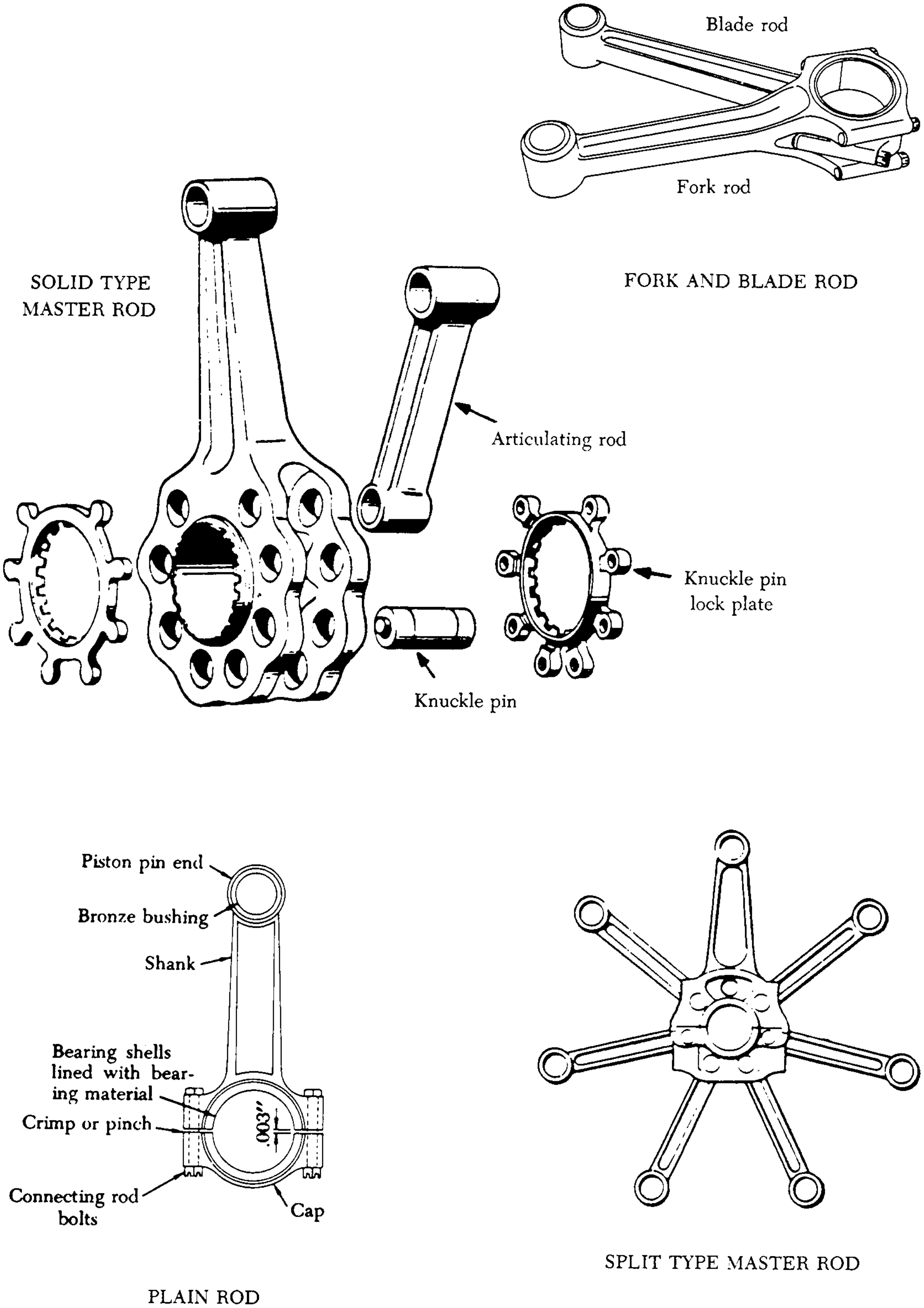


FIGURE 1–11. Connecting rod assemblies.

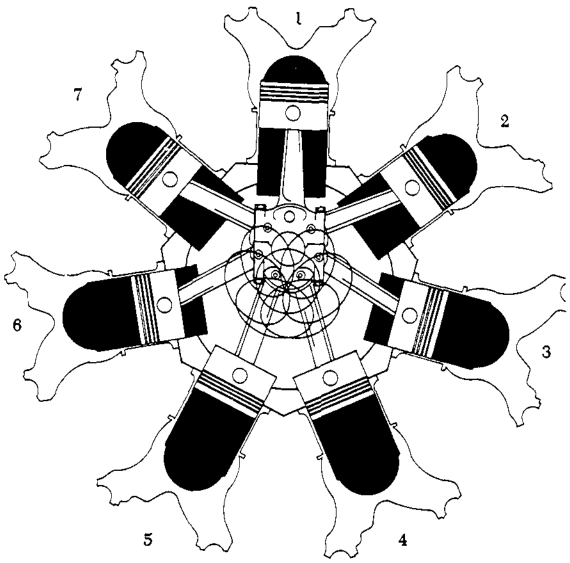


FIGURE 1–12. Elliptical travel path of knuckle pins in an articulated rod assembly.

cate the knuckle-pin bushings. These pins may be installed by pressing into holes in the master rod flanges so that they are prevented from turning in the master rod. Knuckle pins may also be installed with a loose fit so that they can turn in the master rod flange holes, and also turn in the articulating rod bushings. These are called "full-floating" knuckle pins. In either type of installation a lock plate on each side retains the knuckle pin and prevents a lateral movement of it.

Plain-Type Connecting Rods

Plain-type connecting rods are used in in-line and opposed engines. The end of the rod attached to the crankpin is fitted with a cap and a two-piece bearing. The bearing cap is held on the end of the rod by bolts or studs. To maintain proper fit and balance, connecting rods should always be replaced in the same cylinder and in the same relative position.

Fork-and-Blade Rod Assembly

The fork-and-blade rod assembly is used primarily in V-type engines. The forked rod is split at the crankpin end to allow space for the blade rod to fit between the prongs. A single two-piece bearing is used on the crankshaft end of the rod.

PISTONS

The piston of a reciprocating engine is a cylindrical member which moves back and forth within a steel cylinder. The piston acts as a moving wall within the combustion chamber. As the piston moves down in the cylinder, it draws in the fuel/air mixture. As it moves upward, it compresses the charge, ignition occurs, and the expanding gases force the piston downward. This force is transmitted to the crankshaft through the connecting rod. On the return upward stroke, the piston forces the exhaust gases from the cylinder.

Piston Construction

The majority of aircraft engine pistons are machined from aluminum alloy forgings. Grooves are machined in the outside surface of the piston to receive the piston rings, and cooling fins are provided on the inside of the piston for greater heat transfer to the engine oil.

Pistons may be either the trunk type or the slipper type; both are shown in figure 1–13. Slipper-type pistons are not used in modern, high-powered engines because they do not provide adequate strength or wear resistance. The top face of the piston, or head, may be either flat, convex, or concave. Recesses may be machined in the piston head to prevent interference with the valves.

As many as six grooves may be machined around the piston to accommodate the compression rings and oil rings. (See figure 1–13.) The compression rings are installed in the three uppermost grooves; the oil control rings are installed immediately above the piston pin. The piston is usually drilled at the oil control ring grooves to allow surplus oil scraped from the cylinder walls by the oil control rings to pass back into the crankcase. An oil scraper ring is installed at the base of the piston wall or skirt to prevent excessive oil consumption. The portions of the piston walls that lie between each pair of ring grooves are called the ring lands.

In addition to acting as a guide for the piston head, the piston skirt incorporates the piston-pin bosses. The piston-pin bosses are of heavy construction to enable the heavy load on the piston head to be transferred to the piston pin.

Piston Pin

The piston pin joins the piston to the connecting rod. It is machined in the form of a tube from a nickel steel alloy forging, casehardened and ground. The piston pin is sometimes called a wristpin because of the similarity between the relative motions of the piston and the articulated rod and that of the human arm.

The piston pin used in modern aircraft engines is the full-floating type, so called because the pin is

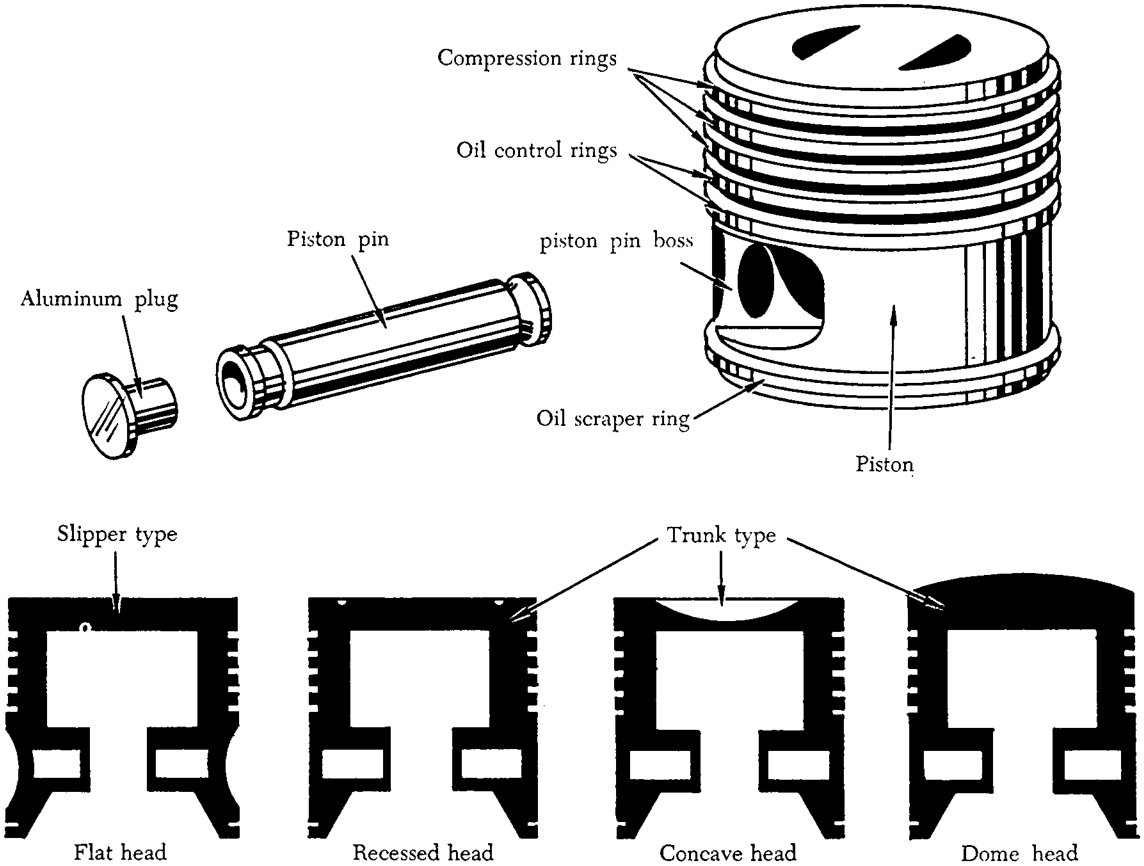


FIGURE 1–13. Piston assembly and types of pistons.

free to rotate in both the piston and in the connecting rod piston-pin bearing.

The piston pin must be held in place to prevent the pin ends from scoring the cylinder walls. In earlier engines, spring coils were installed in grooves in the piston-pin bores at either end of the pin. The current practice is to install a plug of relatively soft aluminum in the pin ends to provide a good bearing surface against the cylinder wall.

PISTON RINGS

The piston rings prevent leakage of gas pressure from the combustion chamber and reduce to a minimum the seepage of oil into the combustion chamber. The rings fit into the piston grooves but spring out to press against the cylinder walls; when properly lubricated, the rings form an effective gas seal.

Piston Ring Construction

Most piston rings are made of high-grade cast iron. After the rings are made, they are ground to the cross section desired. They are then split so that they can be slipped over the outside of the piston and into the ring grooves which are machined in the piston wall. Since their purpose is to seal the clearance between the piston and the cylinder wall, they must fit the cylinder wall snugly enough to provide a gastight fit; they must exert equal pressure at all points on the cylinder wall; and they must make a gastight fit against the sides of the ring grooves.

Gray cast iron is most often used in making piston rings. However, many other materials have been tried. In some engines, chrome-plated mild steel piston rings are used in the top compression ring groove because these rings can better withstand the high temperatures present at this point.

Compression Ring

The purpose of the compression rings is to prevent the escape of gas past the piston during engine operation. They are placed in the ring grooves immediately below the piston head. The number of compression rings used on each piston is determined by the type of engine and its design, although most aircraft engines use two compression rings plus one or more oil control rings.

The cross section of the ring is either rectangular or wedge shaped with a tapered face. The tapered face presents a narrow bearing edge to the cylinder wall which helps to reduce friction and provide better sealing.

Oil Control Rings

Oil control rings are placed in the grooves immediately below the compression rings and above the piston pin bores. There may be one or more oil control rings per piston; two rings may be installed in the same groove, or they may be installed in separate grooves. Oil control rings regulate the thickness of the oil film on the cylinder wall. If too much oil enters the combustion chamber, it will burn and leave a thick coating of carbon on the combustion chamber walls, the piston head, the spark plugs, and the valve heads. This carbon can cause the valves and piston rings to stick if it enters the ring grooves or valve guides. In addition, the carbon can cause spark plug misfiring as well as detonation, preignition, or excessive oil consumption. To allow the surplus oil to return to the crankcase, holes are drilled in the piston ring grooves or in the lands next to these grooves.

Oil Scraper Ring

The oil scraper ring usually has a beveled face and is installed in the groove at the bottom of the piston skirt. The ring is installed with the scraping edge away from the piston head or in the reverse position, depending upon cylinder position and the engine series. In the reverse position, the scraper ring retains the surplus oil above the ring on the upward piston stroke, and this oil is returned to the crankcase by the oil control rings on the downward stroke.

CYLINDERS

The portion of the engine in which the power is developed is called the cylinder. The cylinder provides a combustion chamber where the burning and expansion of gases take place, and it houses the piston and the connecting rod.

There are four major factors that need to be considered in the design and construction of the cylinder assembly. These are:

(1) It must be strong enough to withstand the internal pressures developed during engine operation.

(2) It must be constructed of a lightweight metal to keep down engine weight.

(3) It must have good heat-conducting properties for efficient cooling.

(4) It must be comparatively easy and inexpensive to manufacture, inspect, and maintain.

The head is either produced singly for each cylinder in air-cooled engines, or is cast "in-block" (all cylinder heads in one block) for liquid-cooled engines. The cylinder head of an air-cooled engine is generally made of aluminum alloy, because aluminum alloy is a good conductor of heat and its light weight reduces the overall engine weight. Cylinder heads are forged or die-cast for greater strength. The inner shape of a cylinder head may be flat, semispherical, or peaked, in the form of a house roof. The semispherical type has proved most satisfactory because it is stronger and aids in a more rapid and thorough scavenging of the exhaust gases.

The cylinder used in the air-cooled engine is the overhead valve type shown in figure 1–14. Each cylinder is an assembly of two major parts: (1) The cylinder head, and (2) the cylinder barrel. At assembly, the cylinder head is expanded by heating and then screwed down on the cylinder barrel which

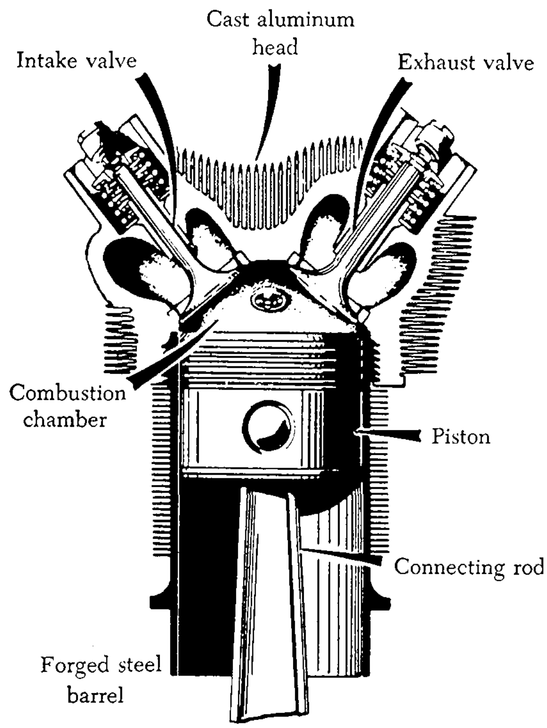


FIGURE 1–14. Cutaway view of the cylinder assembly.

has been chilled; thus, when the head cools and contracts, and the barrel warms up and expands, a gastight joint results. While the majority of the cylinders used are constructed in this manner, some are one-piece aluminum alloy sand castings. The piston bore of a sand cast cylinder is fitted with a steel liner which extends the full length of the cylinder barrel section and projects below the cylinder flange of the casting. This liner is easily removed, and a new one can be installed in the field.

Cylinder Heads

The purpose of the cylinder head is to provide a place for combustion of the fuel/air mixture and to give the cylinder more heat conductivity for adequate cooling. The fuel/air mixture is ignited by the spark in the combustion chamber and commences burning as the piston travels toward top dead center on the compression stroke. The ignited charge is rapidly expanding at this time, and pressure is increasing so that as the piston travels through the top dead center position, it is driven downward on the power stroke. The intake and exhaust valve ports are located in the cylinder head along with the spark plugs and the intake and exhaust valve actuating mechanisms.

After casting, the spark plug bushings, valve guides, rocker arm bushings, and valve seats are installed in the cylinder head. Spark plug openings may be fitted with bronze or steel bushings that are shrunk and screwed into the openings. Stainless steel Heli-Coil spark plug inserts are used in many engines currently manufactured. Bronze or steel valve guides are usually shrunk or screwed into drilled openings in the cylinder head to provide guides for the valve stems. These are generally located at an angle to the center line of the cylinder. The valve seats are circular rings of hardened metal which protect the relatively soft metal of the cylinder head from the hammering action of the valves and from the exhaust gases.

The cylinder heads of air-cooled engines are subjected to extreme temperatures; it is therefore necessary to provide adequate fin area, and to use metals which conduct heat rapidly. Cylinder heads of air-cooled engines are usually cast or forged singly. Aluminum alloy is used in the construction for a number of reasons. It is well adapted for casting or for the machining of deep, closely spaced fins, and it is more resistant than most metals to the corrosive attack of tetraethyl lead in gasoline. The greatest improvement in air cooling has resulted from reducing the thickness of the fins and increasing their depth. In this way the fin area has been increased from approximately 1,200 sq. in. to more than 7,500 sq. in. per cylinder in modern engines. Cooling fins taper from 0.090 in. at the base to 0.060 in. at the tip end. Because of the difference in temperature in the various sections of the cylinder head, it is necessary to provide more cooling-fin area on some sections than on others. The exhaust valve region is the hottest part of the internal surface; therefore, more fin area is provided around the outside of the cylinder in this section.

Cylinder Barrels

In general, the cylinder barrel in which the piston operates must be made of a high-strength material, usually steel. It must be as light as possible, yet have the proper characteristics for operating under high temperatures. It must be made of a good bearing material and have high tensile strength.

The cylinder barrel is made of a steel alloy forging with the inner surface hardened to resist wear of the piston and the piston rings which bear against it. This hardening is usually done by exposing the steel to ammonia or cyanide gas while the steel is very hot. The steel soaks up nitrogen from the gas which forms iron nitrides on the exposed surface. As a result of this process, the metal is said to be nitrided.

In some instances the barrel will have threads on the outside surface at one end so that it can be screwed into the cylinder head. Some air-cooled cylinder barrels have replaceable aluminum cooling fins attached to them, while others have the cooling fins machined as an integral part of the barrel.

CYLINDER NUMBERING

Occasionally it is necessary to refer to the left or right side of the engine or to a particular cylinder. Therefore, it is necessary to know the engine directions and how cylinders of an engine are numbered.

The propeller shaft end of the engine is always the front end, and the accessory end is the rear end, regardless of how the engine is mounted in an aircraft. When referring to the right side or left side of an engine, always assume you are viewing it from the rear or accessory end. As seen from this position, crankshaft rotation is referred to as either clockwise or counterclockwise.

Radial engine cylinders are numbered clockwise as viewed from the accessory end. In-line and V-type engine cylinders are usually numbered from the rear. In V-engines, the cylinder banks are known as the right bank and the left bank, as viewed from the accessory end.

The numbering of engine cylinders is shown in figure 1–15. Note that the cylinder numbering of the opposed engine shown begins with the right rear as No. 1, and the left rear as No. 2. The one forward of No. 1 is No. 3; the one forward of No. 2, is No. 4, and so on. The numbering of opposed engine cylinders is by no means standard. Some manufacturers number their cylinders from the rear and others from the front of the engine. Always refer to the appropriate engine manual to determine the correct numbering system used by the manufacturer.

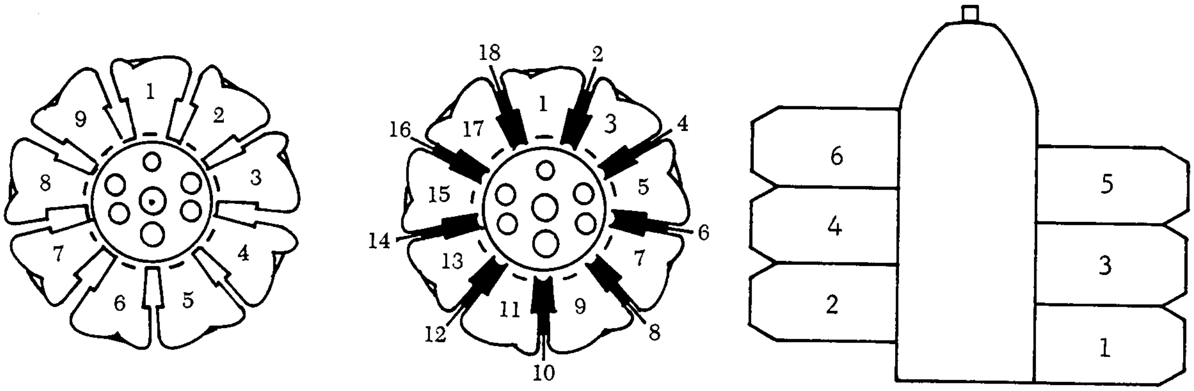


FIGURE 1–15. Numbering of engine cylinders.

Single-row radial engine cylinders are numbered clockwise when viewed from the rear end. Cylinder No. 1 is the top cylinder. In double-row engines, the same system is used, in that the No. 1 cylinder is the top one in the rear row. No. 2 cylinder is the first one clockwise from No. 1, but No. 2 is in the front row. No. 3 cylinder is the next one clockwise to No. 2, but is in the rear row. Thus, all odd-numbered cylinders are in the rear row, and all even-numbered cylinders are in the front row.

FIRING ORDER

The firing order of an engine is the sequence in which the power event occurs in the different cylinders. The firing order is designed to provide for balance and to eliminate vibration to the greatest extent possible. In radial engines the firing order must follow a special pattern, since the firing impulses must follow the motion of the crankthrow during its rotation. In in-line engines the firing orders may vary somewhat, yet most orders are arranged so that the firing of cylinders is evenly distributed along the crankshaft. Six-cylinder in-line engines generally have a firing order of 1–5–3–6–2–4. Cylinder firing order in opposed engines can usually be listed in pairs of cylinders, as each pair fires across the center main bearing. The firing order of six-cylinder opposed engines is 1–4–5–2–3–6. The firing order of one model four-cylinder opposed engine is 1–4–2–3, but on another model it is 1–3–2–4.

Single-Row Radial Engines

On a single-row radial engine, first, all the odd-numbered cylinders fire in numerical succession; then the even-numbered cylinders fire in numerical succession. On a five-cylinder radial engine, for example, the firing order is 1–3–5–2–4, and on a seven-cylinder radial engine it is 1–3–5–7–2–4–6. The firing order of a nine-cylinder radial engine is 1–3–5–7–9–2–4–6–8.

Double-Row Radial Engines

On a double-row radial engine, the firing order is somewhat complicated. The firing order is arranged with the firing impulse occurring in a cylinder in one row and then in a cylinder in the other row; therefore, two cylinders in the same row never fire in succession.

An easy method for computing the firing order of a 14-cylinder, double-row radial engine is to start with any number from 1 to 14, and ***add 9 or subtract 5*** (these are called the firing order numbers), whichever will give an answer between 1 and 14, inclusive. For example, starting with 8, 9 cannot be added since the answer would then be more than 14; therefore, subtract 5 from 8 to get 3, add 9 to 3 to get 12, subtract 5 from 12 to get 7, subtract 5 from 7 to get 2, and so on.

The firing order numbers of an 18-cylinder, double-row radial engine are 11 and 7; that is, begin with any number from 1 to 18 and ***add 11 or subtract 7***. For example, beginning with 1, add 11 to get 12; 11 cannot be added to 12 because the total would be more than 18, so subtract 7 to get 5, add 11 to 5 to get 16, subtract 7 from 16 to get 9, subtract 7 from 9 to get 2, add 11 to 2 to get 13, and continue this process for 18 cylinders.

VALVES

The fuel/air mixture enters the cylinders through the intake valve ports, and burned gases are expelled through the exhaust valve ports. The head of each valve opens and closes these cylinder ports. The valves used in aircraft engines are the conventional poppet type. The valves are also typed by their shape and are called either mushroom or tulip because of their resemblance to the shape of these plants. Figure 1–16 illustrates various shapes and types of these valves.

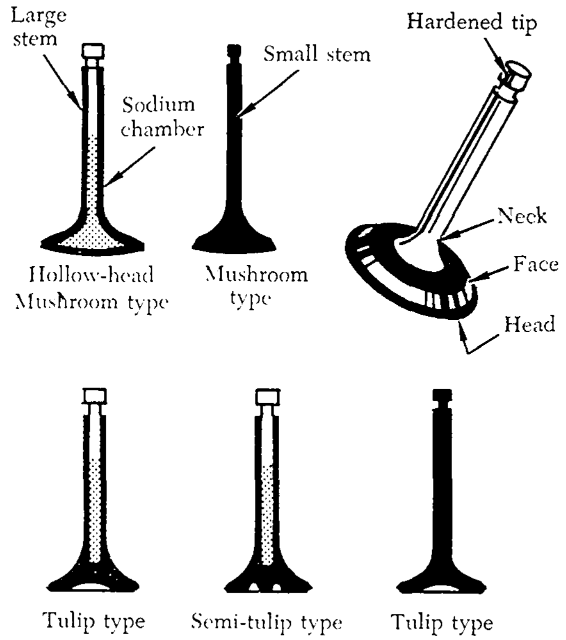


FIGURE 1–16. Valve types.

Valve Construction

The valves in the cylinders of an aircraft engine are subjected to high temperatures, corrosion, and operating stresses; thus, the metal alloy in the valves must be able to resist all these factors.

Because intake valves operate at lower temperatures than exhaust valves, they can be made of chrome-nickel steel. Exhaust valves are usually made of nichrome, silchrome, or cobalt-chromium steel.

The valve head has a ground face which forms a seal against the ground valve seat in the cylinder head when the valve is closed. The face of the valve is usually ground to an angle of either 30° or 45°. In some engines, the intake-valve face is ground to an angle of 30°, and the exhaust valve face is ground to a 45° angle.

Valve faces are often made more durable by the application of a material called stellite. About 1/16 inch of this alloy is welded to the valve face and ground to the correct angle. Stellite is resistant to high-temperature corrosion and also withstands the shock and wear associated with valve operation. Some engine manufacturers use a nichrome facing on the valves. This serves the same purpose as the stellite material.

The valve stem acts as a pilot for the valve head and rides in the valve guide installed in the cylinder head for this purpose. The valve stem is surface-hardened to resist wear. The neck is the part that forms the junction between the head and the stem. The tip of the valve is hardened to withstand the hammering of the valve rocker arm as it opens the valve. A machined groove on the stem near the tip receives the split-ring stem keys. These stem keys form a lock ring to hold the valve spring retaining washer in place.

Some intake and exhaust valve stems are hollow and partially filled with metallic sodium. This material is used because it is an excellent heat conductor. The sodium will melt at approximately 208° F., and the reciprocating motion of the valve circulates the liquid sodium and enables it to carry away heat from the valve head to the valve stem, where it is dissipated through the valve guide to the cylinder head and the cooling fins. Thus, the operating temperature of the valve may be reduced as much as 300° to 400° F. Under no circumstances should a sodium-filled valve be cut open or subjected to treatment which may cause it to rupture. Exposure of the sodium in these valves to the outside air will result in fire or explosion with possible personal injury.

The most commonly used intake valves have solid stems, and the head is either flat or tulip shaped. Intake valves for low-power engines are usually flat headed.

In some engines, the intake valve may be the tulip type and have a smaller stem than the exhaust valve, or it may be similar to the exhaust valve but have a solid stem and head. Although these valves are similar, they are not interchangeable since the faces of the valves are constructed of different material. The intake valve will usually have a flat milled on the tip to identify it.

VALVE-OPERATING MECHANISM

For a reciprocating engine to operate properly, each valve must open at the proper time, stay open for the required length of time, and close at the proper time. Intake valves are opened just before the piston reaches top dead center, and exhaust valves remain open after top dead center. At a particular instant, therefore, both valves are open at the same time (end of the exhaust stroke and beginning of the intake stroke). This valve-overlap permits better volumetric efficiency and lowers the cylinder operating temperature. This timing of the valves is controlled by the valve-operating mechanism.

The valve lift (distance that the valve is lifted off its seat) and the valve duration (length of time the valve is held open) are both determined by the shape of the cam lobes.

Typical cam lobes are illustrated in figure 1–17. The portion of the lobe that gently starts the valve-operating mechanism moving is called a ramp, or step. The ramp is machined on each side of the cam lobe to permit the rocker arm to be eased into contact with the valve tip and thus reduce the shock load which would otherwise occur.

The valve-operating mechanism consists of a cam ring or camshaft equipped with lobes, which work against a cam roller or a cam follower. (See figs. 1–18 and 1–19.) The cam follower, in turn, pushes a push rod and ball socket, which, in turn, actuates a rocker arm which opens the valve. Springs, which slip over the stem of the valves and which are held in place by the valve-spring retaining washer and stem key, close each valve and push the valve mechanism in the opposite direction when the cam roller or follower rolls along a low section of the cam ring.

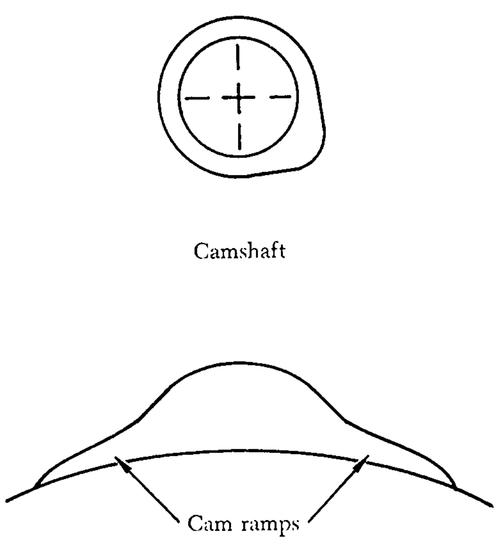


FIGURE 1–17. Typical cam lobes.

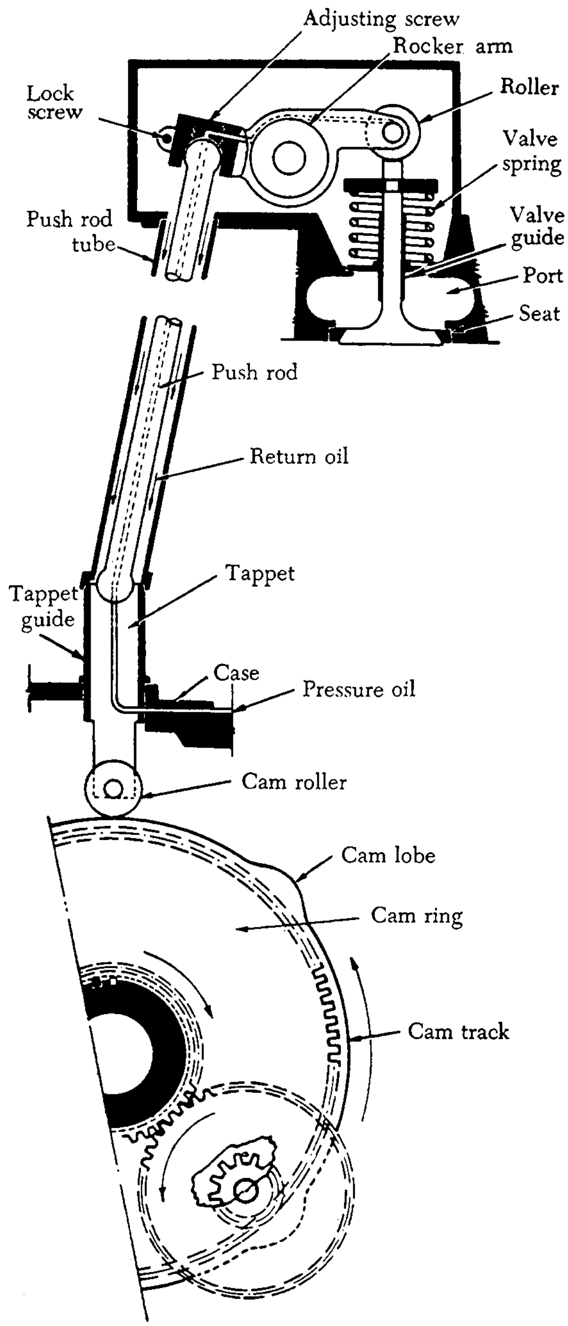


FIGURE 1–18. Valve-operating mechanism (radial engine).

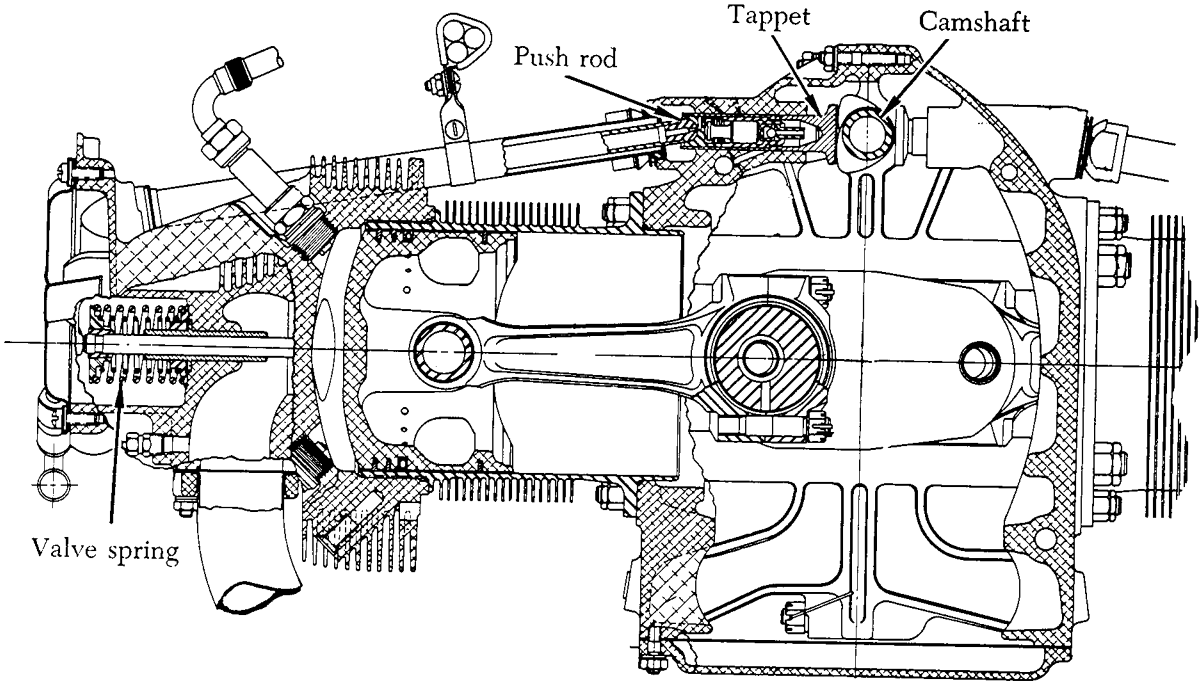


FIGURE 1–19. Valve-operating mechanism (opposed engine).

Cam Ring

The valve mechanism of a radial engine is operated by one or two cam rings, depending upon the number of rows of cylinders. In a single-row radial engine one ring with a double cam track is used. One track operates the intake valves; the other, the exhaust valves. The cam ring is a circular piece of steel with a series of cams or lobes on the outer surface. The surface of these lobes and the space between them (on which the cam rollers ride) is known as the cam track. As the cam ring revolves, the lobes cause the cam roller to raise the tappet in the tappet guide, thereby transmitting the force through the push rod and rocker arm to open the valve.

In a single-row radial engine, the cam ring is usually located between the propeller reduction gearing and the front end of the power section. In a twin-row radial engine, a second cam for the operation of the valves in the rear row is installed between the rear end of the power section and the supercharger section.

The cam ring is mounted concentrically with the crankshaft and is driven by the crankshaft at a reduced rate of speed through the cam intermediate drive gear assembly. The cam ring has two parallel sets of lobes spaced around the outer periphery, one set (cam track) for the intake valves and the other for the exhaust valves. The cam rings used may have four or five lobes on both the intake and the exhaust tracks. The timing of the valve events is determined by the spacing of these lobes and the speed and direction at which the cam rings are driven in relation to the speed and direction of the crankshaft.

The method of driving the cam varies on different makes of engines. The cam ring can be designed with teeth on either the inside or outside periphery. If the reduction gear meshes with the teeth on the outside of the ring, the cam will turn in the direction of rotation of the crankshaft. If the ring is driven from the inside, the cam will turn in the opposite direction from the crankshaft. This method is illustrated in figure 1–18.

A study of figure 1–20 will show that a four-lobe cam may be used on either a seven-cylinder or nine-cylinder engine. On the seven-cylinder it will rotate in the same direction as the crankshaft, and on the nine-cylinder, opposite the crankshaft rotation. On the nine-cylinder engine the spacing between cylinders is 40°, and the firing order is 1–3–5–7–9–2–4–6–8. This means that there is a space of 80° between firing impulses. The spacing on the four lobes of the cam ring is 90°, which is greater than the spacing between impulses. Therefore, to obtain proper relation of valve operations and firing order, it is necessary to drive the cam opposite the crankshaft rotation.

5 cylinders		7 cylinders		9 cylinders		
Number of lobes	Speed	Number of lobes	Speed	Number of lobes	Speed	Direction of rotation
3	1/6	4	1/8	5	1/10	With crankshaft.
2	1/4	3	1/6	4	1/8	Opposite crankshaft.

FIGURE 1–20. Radial engines, cam ring table.

Using the four-lobe cam on the seven-cylinder engine, the spacing between the firing of the cylinders will be greater than the spacing of the cam lobes. Therefore, it will be necessary for the cam to rotate in the same direction as the crankshaft.

A formula that sometimes is used in figuring cam speed is: Cam ring speed $= 1/2 \div$ by the number of lobes on either cam track.

One-half is the speed at which the cam would operate if it were equipped with a single lobe for each valve. It is divided by the number of lobes, which will determine how much the speed will have to be reduced.

In a twin-row, 14-cylinder radial engine which has seven cylinders in each row or bank, the valve mechanism may consist of two separate assemblies, one for each row. It could be considered as two seven-cylinder engines in tandem having the firing impulses properly spaced or lapped. For instance, in a twin-row engine, two four-lobe cam rings may be used. The cams are driven by gears attached to the crankshaft through gear teeth on the periphery of each cam.

Camshaft

The valve mechanism of an opposed engine is operated by a camshaft. The camshaft is driven by a gear that mates with another gear attached to the crankshaft (see figure 1–21). The camshaft always rotates at one-half the crankshaft speed. As the camshaft revolves, the lobes cause the tappet assembly to rise in the tappet guide, transmitting the force through the push rod and rocker arm to open the valve.

Tappet Assembly

The tappet assembly consists of:

(1) A cylindrical tappet, which slides in and out in a tappet guide installed in one of the crankcase sections around the cam ring.
(2) A cam follower or tappet roller, which follows the contour of the cam ring and lobes.
(3) A tappet ball socket or push rod socket.
(4) A tappet spring.

The function of the tappet assembly is to convert the rotational movement of the cam lobe into reciprocating motion and to transmit this motion to the push rod, rocker arm, and then to the valve tip, opening the valve at the proper time. The purpose of the tappet spring is to take up the clearance between the rocker arm and the valve tip to reduce the shock load when the valve is opened. A hole is drilled through the tappet to allow engine oil to flow to the hollow push rods to lubricate the rocker assemblies.

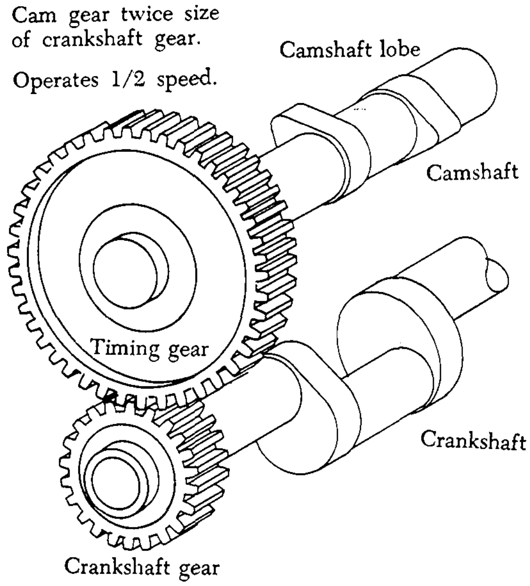


FIGURE 1–21. Cam drive mechanism opposed-type aircraft engine.

Hydraulic Valve Tappets

Some aircraft engines incorporate hydraulic tappets which automatically keep the valve clearance at zero, eliminating the necessity for any valve clearance adjustment mechanism. A typical hydraulic tappet (zero-lash valve lifter) is shown in figure 1–22.

When the engine valve is closed, the face of the tappet body (cam follower) is on the base circle or back of the cam, as shown in figure 1–22. The light plunger spring lifts the hydraulic plunger so that its outer end contacts the push rod socket, exerting a light pressure against it, thus eliminating any clearance in the valve linkage. As the plunger moves outward, the ball check valve moves off its seat. Oil from the supply chamber, which is directly connected with the engine lubrication system, flows in and fills the pressure chamber. As the camshaft rotates, the cam pushes the tappet body and the hydraulic lifter cylinder outward. This

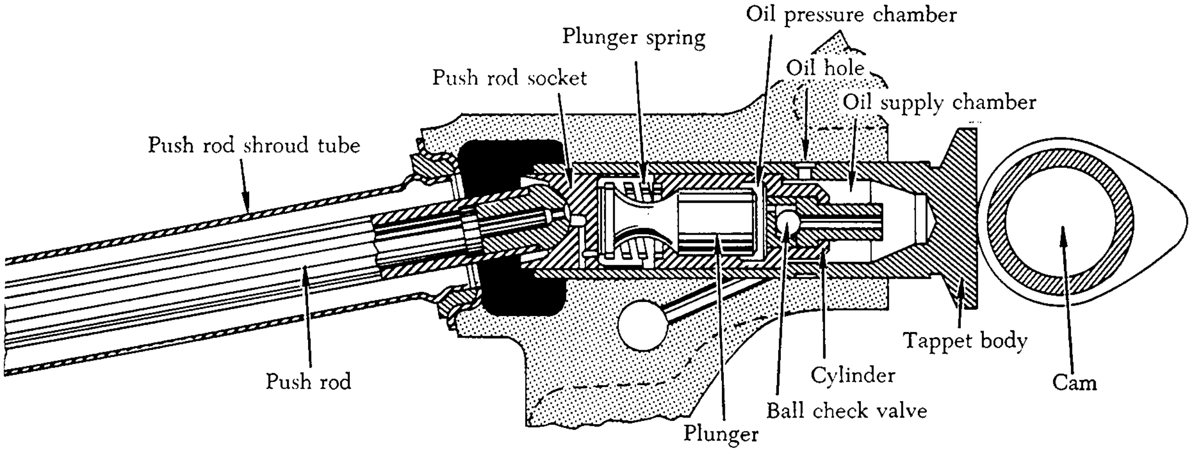


FIGURE 1–22. Hydraulic valve tappets.

action forces the ball check valve onto its seat; thus, the body of oil trapped in the pressure chamber acts as a cushion. During the interval when the engine valve is off its seat, a predetermined leakage occurs between plunger and cylinder bore which compensates for any expansion or contraction in the valve train. Immediately after the engine valve closes, the amount of oil required to fill the pressure chamber flows in from the supply chamber, preparing for another cycle of operation.

Push Rod

The push rod, tubular in form, transmits the lifting force from the valve tappet to the rocker arm. A hardened-steel ball is pressed over or into each end of the tube. One ball end fits into the socket of the rocker arm. In some instances the balls are on the tappet and rocker arm, and the sockets are on the push rod. The tubular form is employed because of its lightness and strength. It permits the engine lubricating oil under pressure to pass through the hollow rod and the drilled ball ends to lubricate the ball ends, rocker-arm bearing, and valve-stem guide. The push rod is enclosed in a tubular housing that extends from the crankcase to the cylinder head.

Rocker Arms

The rocker arms transmit the lifting force from the cams to the valves. Rocker arm assemblies are supported by a plain, roller, or ball bearing, or a combination of these, which serves as a pivot. Generally one end of the arm bears against the push rod and the other bears on the valve stem. One end of the rocker arm is sometimes slotted to accommodate a steel roller. The opposite end is constructed with either a threaded split clamp and locking bolt or a tapped hole.

The arm may have an adjusting screw for adjusting the clearance between the rocker arm and the valve stem tip. The screw is adjusted to the specified clearance to make certain that the valve closes fully.

Valve Springs

Each valve is closed by two or three helical-coiled springs. If a single spring were used, it would vibrate or surge at certain speeds. To eliminate this difficulty, two or more springs (one inside the other) are installed on each valve. Each spring will therefore vibrate at a different engine speed, and rapid damping out of all spring-surge vibrations during engine operation will result. Two or more springs also reduce danger of weakness and possible failure by breakage due to heat and metal fatigue.

The springs are held in place by split locks installed in the recess of the valve spring upper retainer or washer, and engage a groove machined into the valve stem. The functions of the valve springs are to close the valve and to hold the valve securely on the valve seat.

Hydraulic Valve Lifters

Hydraulic valve lifters are normally adjusted at the time of overhaul. They are assembled dry (no lubrication), clearances checked, and adjustments are usually made by use of pushrods having different lengths. A minimum and maximum valve clearance is established. Any measurement between these extremes is acceptable but approximately half way between the extremes is desired. Hydraulic valve lifters require less maintenance, are better lubricated, and operate more quietly than the screw adjustment type.

BEARINGS

A bearing is any surface which supports, or is supported by, another surface. A good bearing must be composed of material that is strong enough to withstand the pressure imposed on it and should permit the other surface to move with a minimum of friction and wear. The parts must be held in position within very close tolerances to provide efficient and quiet operation, and yet allow freedom of motion. To accomplish this, and at the same time reduce friction of moving parts so that power loss is not excessive, lubricated bearings of many types are used. Bearings are required to take radial loads, thrust loads, or a combination of the two.

There are two ways in which bearing surfaces move in relation to each other. One is by the sliding movement of one metal against the other, and the second is for one surface to roll over the other. The three different types of bearings in general use are plain, roller, and ball (see figure 1–23).

Plain Bearings

Plain bearings are generally used for the crankshaft, cam ring, camshaft, connecting rods, and the accessory drive shaft bearings. Such bearings are usually subjected to radial loads only, although some have been designed to take thrust loads.

Plain bearings are usually made of nonferrous (having no iron) metals, such as silver, bronze, aluminum, and various alloys of copper, tin, or lead. Master rod or crankpin bearings in some engines are thin shells of steel, plated with silver on both the inside and the outside surfaces and with lead-tin plated over the silver on the inside surface only. Smaller bearings, such as those used to support various shafts in the accessory section, are called bushings. Porous Oilite bushings are widely used in this instance. They are impregnated with oil so that the heat of friction brings the oil to the bearing surface during engine operation.

Ball Bearings

A ball bearing assembly consists of grooved inner and outer races, one or more sets of balls, and, in bearings designed for disassembly, a bearing retainer. They are used for supercharger impeller shaft bearings and rocker arm bearings in some engines. Special deep-groove ball bearings are used in aircraft engines to transmit propeller thrust to the engine nose section.

Roller Bearings

Roller bearings are made in many types and shapes, but the two types generally used in the aircraft engine are the straight roller and the tapered roller bearings. Straight roller bearings are used where the bearing is subjected to radial loads only. In tapered roller bearings, the inner- and outer-race bearing surfaces are cone shaped. Such bearings will withstand both radial and thrust loads. Straight roller bearings are used in high-power aircraft engines for the crankshaft main bearings. They are also used in other applications where radial loads are high.

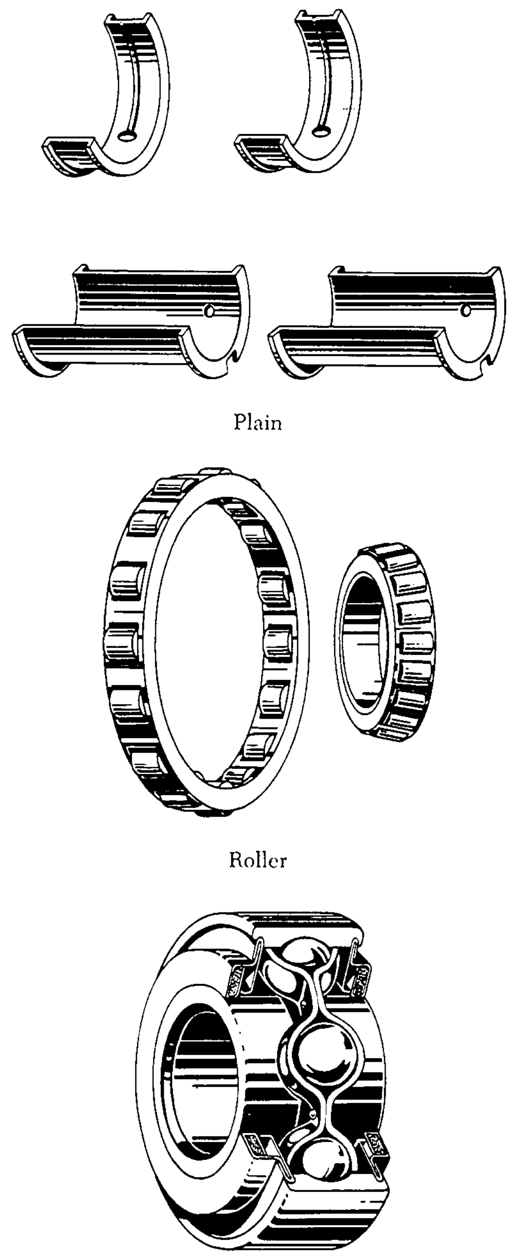


FIGURE 1–23. Bearings.

PROPELLER REDUCTION GEARING

The increased brake horsepower delivered by a high-horsepower engine results partly from increased crankshaft r.p.m. It is therefore necessary to provide reduction gears to limit the propeller rotation speed to a value at which efficient operation is obtained. Whenever the speed of the blade tips approaches the speed of sound, the efficiency of the propeller decreases rapidly. The general practice has been to provide reduction gearing for propellers of engines whose speeds are above 2,000 r.p.m., because propeller efficiency decreases rapidly above this speed.

Since reduction gearing must withstand extremely high stresses, the gears are machined from steel forgings. Many types of reduction gearing systems are in use. The three types (fig. 1–24) most commonly used are:

(1) Spur planetary.
(2) Bevel planetary.
(3) Spur and pinion.

The planetary reduction gear systems are used with radial and opposed engines, and the spur and pinion system is used with in-line and V-type engines. Two of these types, the spur planetary and the bevel planetary, are discussed here.

The spur planetary reduction gearing consists of a large driving gear or sun gear splined (and sometimes shrunk) to the crankshaft, a large stationary gear, called a bell gear, and a set of small spur planetary pinion gears mounted on a carrier ring. The ring is fastened to the propeller shaft, and the planetary gears mesh with both the sun gear and the stationary bell or ring gear. The stationary gear is bolted or splined to the front-section housing. When the engine is operating, the sun gear rotates. Because the planetary gears are meshed with this ring, they also must rotate. Since they also mesh with the stationary gear, they will walk or roll around it as they rotate, and the ring in which they are mounted will rotate the propeller shaft in the same direction as the crankshaft but at a reduced speed.

In some engines, the bell gear is mounted on the propeller shaft, and the planetary pinion gear cage is held stationary. The sun gear is splined to the crankshaft and thus acts as a driving gear. In such an arrangement, the propeller travels at a reduced speed, but in opposite direction to the crankshaft.

In the bevel planetary reduction gearing system, the driving gear is machined with beveled external teeth and is attached to the crankshaft. A set of mating bevel pinion gears is mounted in a cage attached to the end of the propeller shaft. The pinion gears are driven by the drive gear and walk around the stationary gear, which is bolted or splined to the front-section housing. The thrust of the bevel pinion gears is absorbed by a thrust ball bearing of special design. The drive and the fixed gears are generally supported by heavy-duty ball bearings. This type of planetary reduction assembly is more compact than the other one described and can therefore be used where a smaller propeller gear step-down is desired.

PROPELLER SHAFTS

Propeller shafts may be three major types; tapered, splined, or flanged. Tapered shafts are identified by taper numbers. Splined and flanged shafts are identified by SAE numbers.

The propeller shaft of most low-power output engines is forged as part of the crankshaft. It is tapered and a milled slot is provided so that the propeller hub can be keyed to the shaft. The keyway and key index of the propeller are in relation to the #1 cylinder top dead center. The end of the shaft is threaded to receive the propeller retaining nut. Tapered propeller shafts are common on older and in-line engines.

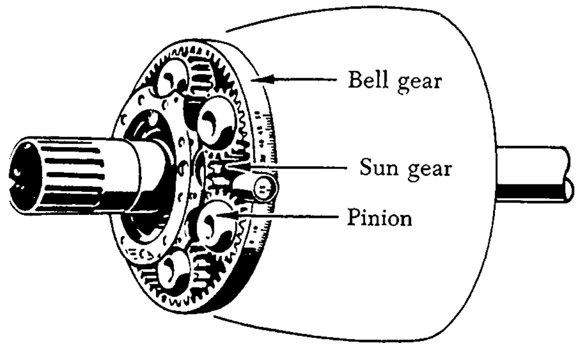
The propeller shaft of a high-output engine generally is splined. It is threaded on one end for a propeller hub nut. The thrust bearing, which absorbs propeller thrust, is located around the shaft and transmits the thrust to the nose-section housing. The shaft is threaded for attaching the thrust-bearing retaining nut. On the portion protruding from the housing (between the two sets of threads), splines are located to receive the splined propeller hub. The shaft is generally machined from a steel-alloy forging throughout its length. The propeller shaft may be connected by reduction gearing to the engine crankshaft, but in smaller engines the propeller shaft is simply an extension of the engine crankshaft. To turn the propeller shaft, the engine crankshaft must revolve.

Flanged propeller shafts are used on medium or low powered reciprocating and turbojet engines. One end of the shaft is flanged with drilled holes to accept the propeller mounting bolts. The installation may be a short shaft with internal threading to accept the distributor valve to be used with a controllable propeller. The flanged propeller shaft is a normal installation on most approved reciprocating engines.

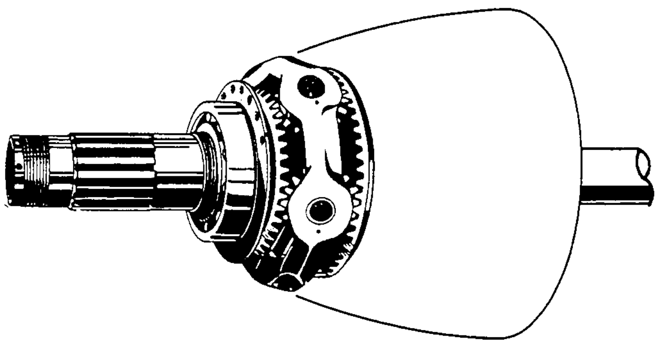
RECIPROCATING ENGINE OPERATING PRINCIPLES

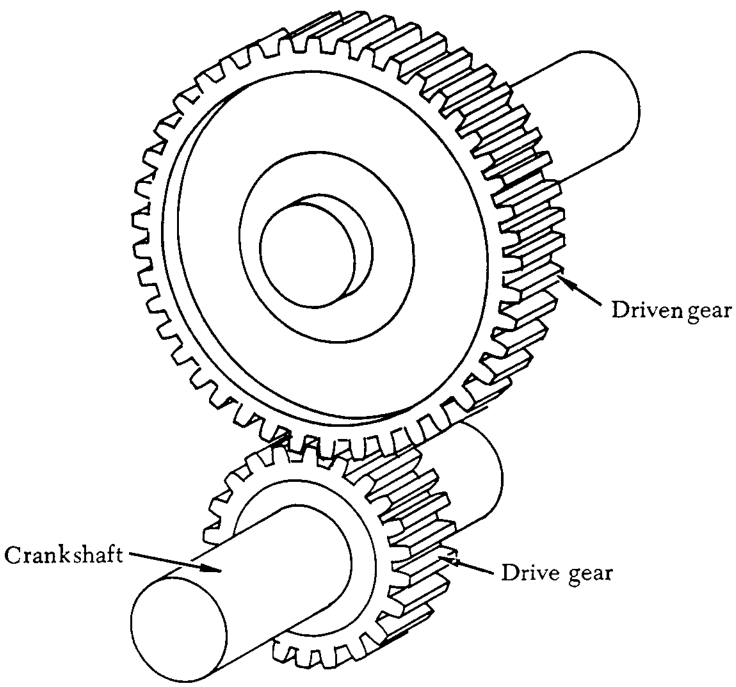
A study of this section will help in understanding the basic operating principles of reciprocating engines. The principles which govern the relationship between the pressure, volume, and temperature of gases are the basic principles of engine operation.

An internal-combustion engine is a device for converting heat energy into mechanical energy. Gasoline is vaporized and mixed with air, forced or drawn into a cylinder, compressed by a piston, and then ignited by an electric spark. The conversion of the resultant heat energy into mechancial energy and then into work is accomplished in the cylinder. Figure 1–25 illustrates the various engine compo-



Spur-planetary


Bevel planetary



Spur and pinion

FIGURE 1–24. Reduction gears.

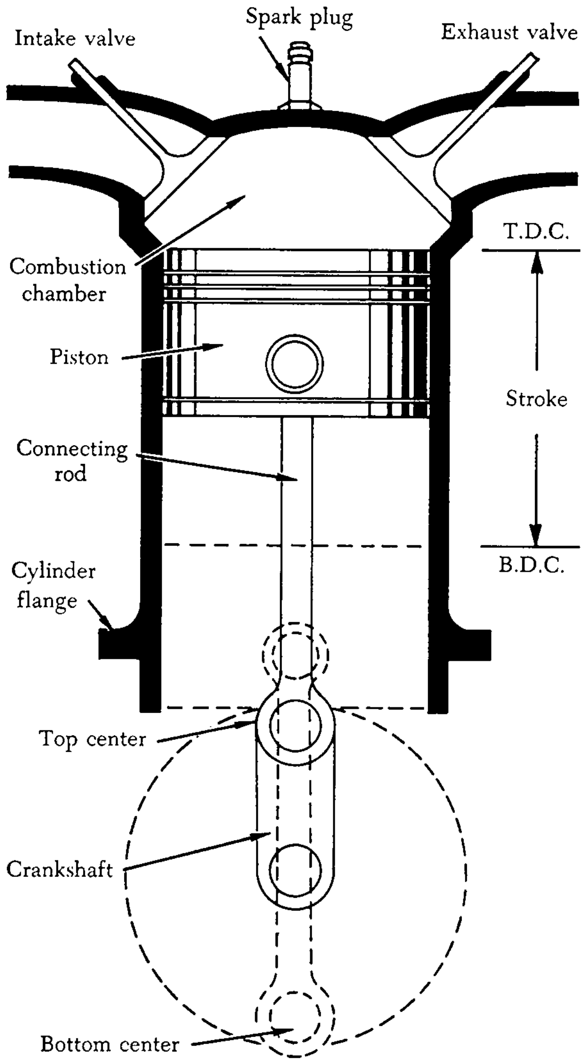


FIGURE 1–25. Components and terminology of engine operation.

nents necessary to accomplish this conversion and also presents the principal terms used to indicate engine operation.

The operating cycle of an internal combustion reciprocating engine includes the series of events required to induct, compress, ignite, burn, and expand the fuel/air charge in the cylinder, and to scavenge or exhaust the byproducts of the combustion process.

When the compressed mixture is ignited, the resultant gases of combustion expand very rapidly and force the piston to move away from the cylinder head. This downward motion of the piston, acting on the crankshaft through the connecting rod, is converted to a circular or rotary motion by the crankshaft.

A valve in the top or head of the cylinder opens to allow the burned gases to escape, and the momentum of the crankshaft and the propeller forces the piston back up in the cylinder where it is ready for the next event in the cycle. Another valve in the cylinder head then opens to let in a fresh charge of the fuel/air mixture.

The valve allowing for the escape of the burning exhaust gases is called the exhaust valve, and the valve which lets in the fresh charge of the fuel/air mixture is called the intake valve. These valves are opened and closed mechanically at the proper times by the valve-operating mechanism.

The bore of a cylinder is its inside diameter. The stroke is the distance the piston moves from one end of the cylinder to the other, specifically, from T.D.C. (top dead center) to B.D.C. (bottom dead center), or vice versa (see figure 1–25).

OPERATING CYCLES

There are two operating cycles in general use: (1) The two-stroke cycle, and (2) the four-stroke cycle. At the present time, the two-stroke-cycle engine is fast disappearing from the aviation scene and will not be discussed. As the name implies, two-stroke-cycle engines require only one upstroke and one downstroke of the piston to complete the required series of events in the cylinder. Thus the engine completes the operating cycle in one revolution of the crankshaft.

Most aircraft reciprocating engines operate on the four-stroke cycle, sometimes called the Otto cycle after its originator, a German physicist. The four-stroke-cycle engine has many advantages for use in aircraft. One advantage is that it lends itself readily to high performance through supercharging.

In this type of engine, four strokes are required to complete the required series of events or operating cycle of each cylinder, as shown in figure 1–26. Two complete revolutions of the crankshaft (720°) are required for the four strokes; thus, each cylinder in an engine of this type fires once in every two revolutions of the crankshaft.

FOUR-STROKE CYCLE

In the following discussion of the four-stroke-cycle engine operation, it should be realized that the timing of the ignition and the valve events will vary considerably in different engines. Many factors influence the timing of a specific engine, and it is most important that the engine manufacturer's recommendations in this respect be followed in maintenance and overhaul. The timing of the valve and ignition events is always specified in degrees of crankshaft travel.

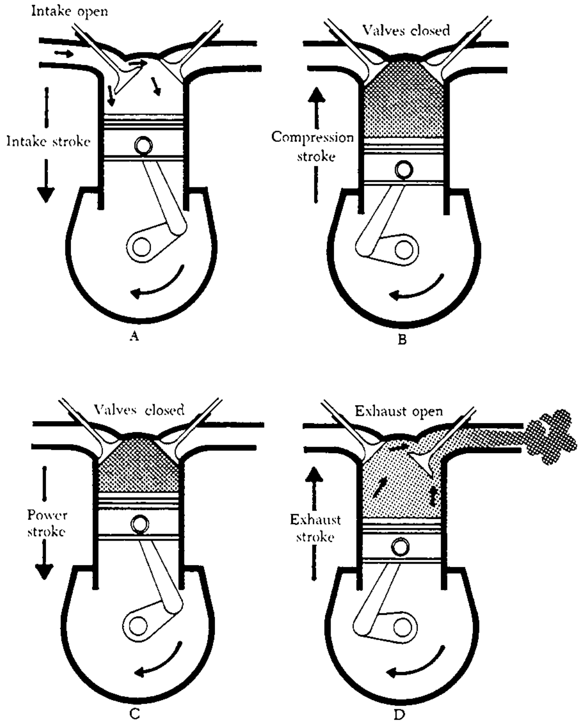


FIGURE 1–26. Four-stroke cycle.

In the following paragraphs, the timing of each event is specified in terms of degrees of crankshaft travel on the stroke during which the event occurs. It should be remembered that a certain amount of crankshaft travel is required to open a valve fully; therefore, the specified timing represents the start of opening rather than the full-open position of the valve.

Intake Stroke

During the intake stroke, the piston is pulled downward in the cylinder by the rotation of the crankshaft. This reduces the pressure in the cylinder and causes air under atmospheric pressure to flow through the carburetor, which meters the correct amount of fuel. The fuel/air mixture passes through the intake pipes and intake valves into the cylinders. The quantity or weight of the fuel/air charge depends upon the degree of throttle opening.

The intake valve is opened considerably before the piston reaches top dead center on the exhaust stroke, in order to induce a greater quantity of the fuel/air charge into the cylinder and thus increase the horsepower. The distance the valve may be opened before top dead center, however, is limited by several factors, such as the possibility that hot gases remaining in the cylinder from the previous cycle may flash back into the intake pipe and the induction system.

In all high-power aircraft engines, both the intake and the exhaust valves are off the valve seats at top dead center at the start of the intake stroke. As mentioned above, the intake valve opens before top dead center on the exhaust stroke (valve lead), and the closing of the exhaust valve is delayed considerably after the piston has passed top dead center and has started the intake stroke (valve lag). This timing is called valve overlap and is designed to aid in cooling the cylinder internally by circulating the cool incoming fuel/air mixture, to increase the amount of the fuel/air mixture induced into the cylinder, and to aid in scavenging the byproducts of combustion.

The intake valve is timed to close about 50° to 75° past bottom dead center on the compression stroke depending upon the specific engine, to allow the momentum of the incoming gases to charge the cylinder more completely. Because of the comparatively large volume of the cylinder above the piston when the piston is near bottom dead center, the slight upward travel of the piston during this time does not have a great effect on the incoming flow of gases. This late timing can be carried too far because the gases may be forced back through the intake valve and defeat the purpose of the late closing.

Compression Stroke

After the intake valve is closed, the continued upward travel of the piston compresses the fuel/air mixture to obtain the desired burning and expansion characteristics.

The charge is fired by means of an electric spark as the piston approaches top dead center. The time of ignition will vary from 20° to 35° before top dead center, depending upon the requirements of the specific engine, to ensure complete combustion of the charge by the time the piston is slightly past the top dead center position.

Many factors affect ignition timing, and the engine manufacturer has expended considerable time in research and testing to determine the best setting. All engines incorporate devices for adjusting the ignition timing, and it is most important that the ignition system be timed according to the engine manufacturer's recommendations.

Power Stroke

As the piston moves through the top dead center position at the end of the compression stroke and starts down on the power stroke, it is pushed downward by the rapid expansion of the burning gases within the cylinder head with a force that can be greater than 15 tons (30,000 p.s.i.) at maximum power output of the engine. The temperature of these burnning gases may be between 3,000° and 4,000°F.

As the piston is forced downward during the power stroke by the pressure of the burning gases exerted upon it, the downward movement of the connecting rod is changed to rotary movement by the crankshaft. Then the rotary movement is transmitted to the propeller shaft to drive the propeller. As the burning gases are expanded, the temperature drops to within safe limits before the exhaust gases flow out through the exhaust port.

The timing of the exhaust valve opening is determined by, among other considerations, the desirability of using as much of the expansive force as possible and of scavenging the cylinder as completely and rapidly as possible. The valve is opened considerably before bottom dead center on the power stroke (on some engines at 50° and 75° before B.D.C.) while there is still some pressure in the cylinder. This timing is used so that the pressure can force the gases out of the exhaust port as soon as possible. This process frees the cylinder of waste heat after the desired expansion has been obtained and avoids overheating the cylinder and the piston. Thorough scavenging is very important, because any exhaust products remaining in the cylinder will dilute the incoming fuel/air charge at the start of the next cycle.

Exhaust Stroke

As the piston travels through bottom dead center at the completion of the power stroke and starts upward on the exhaust stroke, it will begin to push the burned exhaust gases out the exhaust port. The speed of the exhaust gases leaving the cylinder creates a low pressure in the cylinder. This low or reduced pressure speeds the flow of the fresh fuel/air charge into the cylinder as the intake valve is beginning to open. The intake valve opening is timed to occur at 8° to 55° before top dead center on the exhaust stroke on various engines.

RECIPROCATING ENGINE POWER AND EFFICIENCIES

All aircraft engines are rated according to their ability to do work and produce power. This section presents an explanation of work and power and how they are calculated. Also discussed are the various efficiencies that govern the power output of a reciprocating engine.

Work

The physicist defines work as "Work is force times distance. Work done by a force acting on a body is equal to the magnitude of the force multiplied by the distance through which the force acts."

Work (W) = Force (F) x Distance (D).

Work is measured by several standards, the most common unit is called foot-pound. If a 1-pound mass is raised 1 foot, 1 ft.-lb. (foot-pound) of work has been performed. The greater the mass and the greater the distance, the greater the work.

Horsepower

The common unit of mechanical power is the hp. (horsepower). Late in the 18th century, James Watt, the inventor of the steam engine, found that an English workhorse could work at the rate of 550 ft.-lb. per second, or 33,000 ft.-lb. per minute, for a reasonable length of time. From his observations came the hp., which is the standard unit of power in the English system of measurement. To calculate the hp. rating of an engine, divide the power developed in ft.-lb. per minute by 33,000, or the power in ft.-lb. per second by 550.

$$\text{hp.} = \frac{\text{ft.-lb. per min.}}{33{,}000}, \text{ or}$$
$$= \frac{\text{ft.-lb. per sec.}}{550}.$$

As stated above, work is the product of force and ditsance, and power is work per unit of time. Consequently, if a 33,000-lb. weight is lifted through a vertical distance of 1 ft. in 1min., the power expended is 33,000 ft.-lb. per min., or exactly 1 hp.

Work is performed not only when a force is applied for lifting; force may be applied in any direction. If a 100-lb. weight is dragged along the ground, a force is still being applied to perform work, although the direction of the resulting motion is approximately horizontal. The amount of this force would depend upon the roughness of the ground.

If the weight were attached to a spring scale graduated in pounds, then dragged by pulling on the scale handle, the amount of force required could be measured. Assume that the force required is 90 lbs., and the 100-lb. weight is dragged 660 ft. in 2 min. The amount of work performed in the 2 min. will be 59,400 ft.-lb., or 29,700 ft.-lb. per min. Since 1 hp. is 33,000 ft.-lb. per min., the hp. expended in this case will be 29,700 divided by 33,000, or 0.9 hp.

Piston Displacement

When other factors remain equal, the greater the piston displacement the greater the maximum horsepower an engine will be capable of developing. When a piston moves from bottom dead center to top dead center, it displaces a specific volume. The volume displaced by the piston is known as piston displacement and is expressed in cubic inches for most American-made engines and cubic centimeters for others.

The piston displacement of one cylinder may be obtained by multiplying the area of the cross section of the cylinder by the total distance the piston moves in the cylinder in one stroke. For multi-cylinder engines this product is multiplied by the number of cylinders to get the total piston displacement of the engine.

Since the volume (V) of a geometric cylinder equals the area (A) of the base multiplied by the altitude (H), it is expressed mathematically as:

$$V = A \times H.$$

For our purposes, the area of the base is the area of the cross section of the cylinder or of the piston top.

Area Of A Circle

To find the area of a circle it is necessary to use a number called pi. This number represents the ratio of the circumference to the diameter of any circle. Pi cannot be found exactly because it is a never-ending decimal, but expressed to four decimal places it is 3.1416, which is accurate enough for most computations.

The area of a circle, as in a rectangle or triangle, must be expressed in square units. The distance that is one-half the diameter of a circle is known as the radius. The area of any circle is found by squaring the radius and multiplying by pi. (π). The formula is expressed thus:

$$A = \pi R^2.$$

Where A is the area of a circle; pi is the given constant; and r is the radius of the circle, which is equal to ½ the diameter or $R = \frac{D}{2}$

Example

Compute the piston displacement of the PWA 14 cylinder engine having a cylinder with a 5.5 inch diameter and a 5.5 inch stroke. Formulas required are:

$$R = \frac{D}{2}$$

$$A = \pi R^2$$

$$V = A \times H$$

$$\text{Total } V = V \times N \text{ (number of cylinders)}$$

Substitute values into these formulas and complete the calculation.

$$R = \frac{D}{2} \quad R = 5.5/2 = 2.75$$

$$A = \pi R^2 \quad A = 3.1416\ (2.75 \times 2.75)$$

$$A = 3.1416 \times 7.5625 = 23.7584 \text{ sq. inches}$$

$$V = A \times H \quad V = 23.7584 \times 5.5 \quad V = 130.6712$$

Total $V = V \times N$ Total $V = 130.6712 \times 14$ Total $V = 1829.3968$

Rounded off to the next whole number total piston displacement equals 1830 cu. in.

Another method of calculating the piston displacement uses the diameter of the piston instead of the radius in the formula for the area of the base.

$A = \frac{1}{4}\ (\pi)\ (D)^2$

Substituting $A = \frac{1}{4} \times 3.1416 \times 5.5 \times 5.5$

$A = .7854 \times 30.25 \quad A = 23.758$ square inches.

From this point on the calculations are identical to the preceding example.

Compression Ratio

All internal-combustion engines must compress the fuel/air mixture to receive a reasonable amount of work from each power stroke. The fuel/air charge in the cylinder can be compared to a coil spring, in that the more it is compressed the more work it is potentially capable of doing.

The compression ratio of an engine (see figure 1–27) is a comparison of the volume of space in a cylinder when the piston is at the bottom of the stroke to the volume of space when the piston is at the top of the stroke. This comparison is expressed as a ratio, hence the term "compresion ratio." Compression ratio is a controlling factor in the maximum horsepower developed by an engine, but it is limited by present-day fuel grades and the high engine speeds and manifold pressures required for takeoff. For example, if there are 140 cu. in. of space in the cylinder when the piston is at the bottom and there are 20 cu. in. of space when the piston is at the top of the stroke, the compression ratio would be 140 to 20. If this ratio is expressed in fraction form, it would be 140/20, or 7 to 1, usually represented as 7:1.

To grasp more thoroughly the limitation placed on compression ratios, manifold pressure and its effect on compression pressures should be understood. Manifold pressure is the average absolute pressure of the air or fuel/air charge in the intake manifold and is measured in units of inches of mercury (Hg). Manifold pressure is dependent on engine speed (throttle setting) and supercharging. The engine-driven internal supercharger (blower) and the external exhaust-driven supercharger (turbo) are actually centrifugal-type air compressors. The operation of these superchargers increases the weight of the charge entering the cylinder. When either one or both are used with the aircraft engine, the manifold pressure may be considerably higher than the pressure of the outside atmosphere. The advantage of this condition is that a greater amount of charge is forced into a given cylinder volume, and a greater power results.

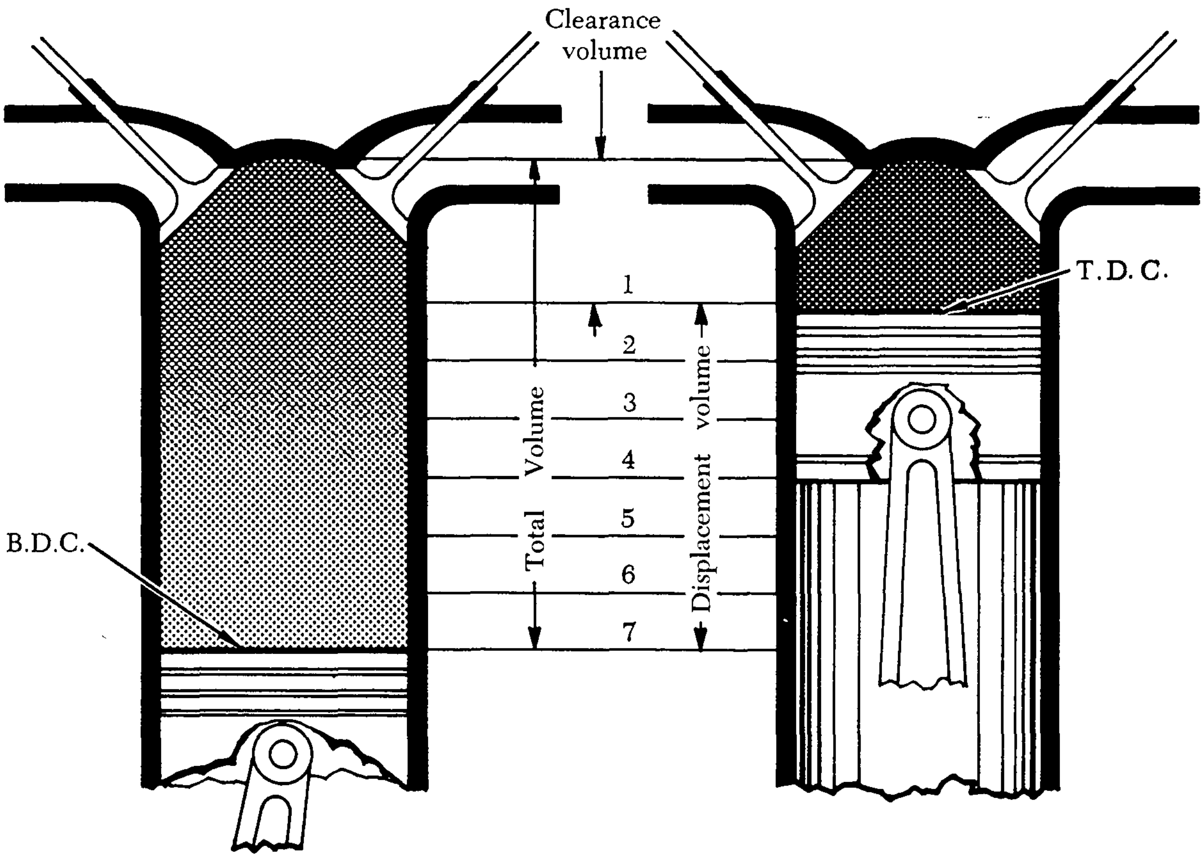


FIGURE 1–27. Compression ratio.

Compression ratio and manifold pressure determine the pressure in the cylinder in that portion of the operating cycle when both valves are closed. The pressure of the charge before compression is determined by manifold pressure, while the pressure at the height of compression (just prior to ignition) is determined by manifold pressure times the compression ratio. For example, if an engine were operating at a manifold pressure of 30″ Hg with a compression ratio of 7:1, the pressure at the instant before ignition would be approximately 210″ Hg. However, at a manifold pressure of 60″ Hg the pressure would be 420″ Hg.

Without going into great detail, it has been shown that the compression event magnifies the effect of varying the manifold pressure, and the magnitude of both affects the pressure of the fuel charge just before the instant of ignition. If the pressure at this time becomes too high, premature ignition or knock will occur and produce overheating.

One of the reasons for using engines with high compression ratios is to obtain long-range fuel economy, that is, to convert more heat energy into useful work than is done in engines of low compression ratio. Since more heat of the charge is converted into useful work, less heat is absorbed by the cylinder walls. This factor promotes cooler engine operation, which in turn increases the thermal efficiency.

Here, again, a compromise is needed between the demand for fuel economy and the demand for maximum horsepower without knocking. Some manufacturers of high-compression engines suppress knock at high manifold pressures by injecting an antiknock fluid into the fuel/air mixture. The fluid acts primarily as a coolant so that more power can be delivered by the engine for short periods, such as at takeoff and during emergencies, when power is critical. This high power should be used for short periods only.

Indicated Horsepower

The indicated horsepower produced by an engine is the horsepower calculated from the indicated mean effective pressure and the other factors which affect the power output of an engine. Indicated horsepower is the power developed in the combustion chambers without reference to friction losses within the engine.

This horsepower is calculated as a function of the actual cylinder pressure recorded during engine operation. To facilitate the indicated horsepower calculations, a mechanical indicating device, attached to the engine cylinder, scribes the actual pressure existing in the cylinder during the complete operating cycle. This pressure variation can be represented by the kind of graph shown in figure 1–28. Notice that the cylinder pressure rises on the compression stroke, reaches a peak after top center, then decreases as the piston moves down on the power stroke. Since the cylinder pressure varies during the operating cycle, an average pressure, line AB, is computed. This average pressure, if applied steadily during the time of the power stroke, would do the same amount of work as the varying pressure during the same period. This average pressure is known as indicated mean effective pressure and is included in the indicated horsepower calculation with other engine specifications. If the characteristics and the indicated mean effective pressure of an engine are known, it is possible to calculate the indicated horsepower rating.

The indicated horsepower for a four-stroke-cycle engine can be calculated from the following formula, in which the letter symbols in the numerator are arranged to spell the word "plank" to assist in memorizing the formula:

$$\text{Indicated horsepower} = \frac{\text{PLANK}}{33{,}000}.$$

Where:

P = Indicated mean effective pressure in p.s.i.

L = Length of the stroke in ft. or in fractions of a foot.

A = Area of the piston head or cross-sectional area of the cylinder, in sq. in.

N = Number of power strokes per minute; $\frac{\text{r.p.m.}}{2}$.

K = Number of cylinders.

In the formula above, the area of the piston times the indicated mean effective pressure gives the force acting on the piston in pounds. This force multiplied by the length of the stroke in feet gives the work performed in one power stroke, which, multiplied by the number of power strokes per minute, gives the number of ft.-lb. per minute of work produced by one cylinder. Multiplying this result by the number of cylinders in the engine gives the amount of work performed, in ft.-lb., by the engine. Since hp. is defined as work done at the rate of 33,000 ft.-lb. per min., the total number of ft.-lb. of work performed by the engine is divided by 33,000 to find the indicated horsepower.

Example

Given:

Indicated mean effective pressure (P)	= 165 lbs./sq. in.
Stroke (L)	= 6 in. or .5 ft.
Bore	= 5.5 in.
r.p.m.	= 3,000
No. of cylinders (K)	= 12

$$\text{Indicated hp.} = \frac{\text{PLANK}}{33{,}000 \text{ ft.-lbs./min.}}.$$

Find indicated hp.:

A is found by using the equation

$A = 1/4\pi D^2$

$A = 1/4 \times 3.1416 \times 5.5 \times 5.5$

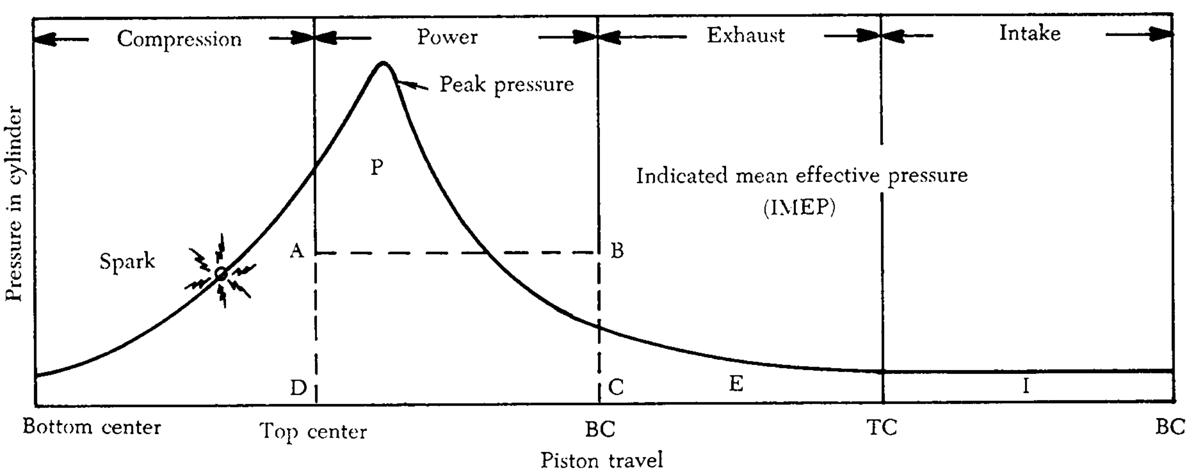


FIGURE 1–28. Cylinder pressure during power cycle.

$= 23.76$ sq. in.

N is found by multiplying the r.p.m. by 1/2:

$N = 1/2 \times 3{,}000$

$= 1{,}500$ r.p.m.

Now, substituting in the formula:

$$\text{Indicated hp.} = \frac{165 \times .5 \times 23.76 \times 1{,}500 \times 12}{33{,}000 \text{ ft.-lbs./min.}}$$

$$= 1069.20.$$

Brake Horsepower

The indicated horsepower calculation discussed in the preceding paragraph is the theoretical power of a frictionless engine. The total horsepower lost in overcoming friction must be subtracted from the indicated horsepower to arrive at the actual horsepower delivered to the propeller. The power delivered to the propeller for useful work is known as b.hp. (brake horsepower). The difference between indicated and brake horsepower is known as friction horsepower, which is the horsepower required to overcome mechanical losses such as the pumping action of the pistons and the friction of the pistons and the friction of all moving parts.

In practice, the measurement of an engine's b.hp. involves the measurement of a quantity known as torque, or twisting moment. Torque is the product of a force and the distance of the force from the axis about which it acts, or

Torque = Force x Distance
(at right angles to the force).

Torque is a measure of load and is properly expressed in pound-inches (lb.-in.) or pound-feet (lb.-ft.) and should not be confused with work, which is expressed in inch-pounds (in.-lbs.) or foot-pounds (ft.-lbs.).

There are a number of devices for measuring torque, of which the Prony brake, dynamometer, and torquemeter are examples. Typical of these devices is the Prony brake (figure 1–29), which measures the usable power output of an engine on a test stand. It consists essentially of a hinged collar, or brake, which can be clamped to a drum splined to the propeller shaft. The collar and drum form a friction brake which can be adjusted by a wheel. An arm of a known length is rigidly attached to or is a part of the hinged collar and terminates at a point which bears on a set of scales. As the propeller shaft rotates, it tends to carry the hinged collar of the brake with it and is prevented from doing so only by the arm that bears on the scale. The scale reads the force necessary to arrest the motion of the arm. If the resulting force registered on the scale is multiplied by the length of the arm, the resulting product is the torque exerted by the rotating shaft. Example: If the scale registers 200 lbs. and the length of the arm is

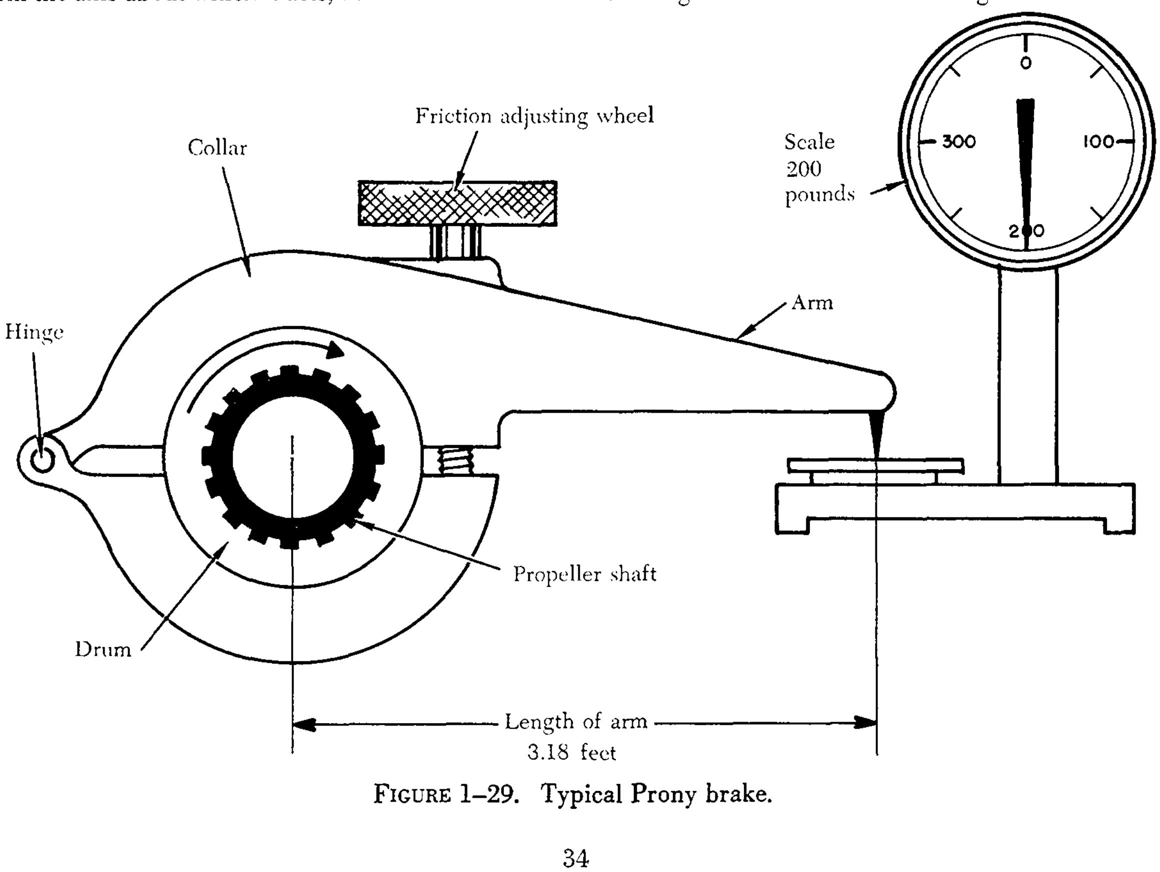


FIGURE 1–29. Typical Prony brake.

3.18 ft., the torque exerted by the shaft is:

$$200 \text{ lb.} \times 3.18 \text{ ft.} = 636 \text{ lb.-ft.}$$

Once the torque is known, the work done per revolution of the propeller shaft can be computed without difficulty by the equation:

$$\text{Work per revolution} = 2\pi \times \text{torque.}$$

If work per revolution is multiplied by the r.p.m., the result is work per minute, or power. If the work is expressed in ft.-lbs. per min., this quantity is divided by 33,000; the result is the brake horsepower of the shaft. In other words:

$$\text{Power} = \text{Work per revolution} \times \text{r.p.m.}$$

$$\text{and b.hp.} = \frac{\text{Work per revolution} \times \text{r.p.m.}}{33{,}000},$$

$$\text{or b.hp.} = \frac{2\pi \times \text{force on the scales (lbs.)} \times \text{length of arm (ft.)} \times \text{r.p.m.}}{33{,}000}.$$

Example

Given:

Force on scales $= 200$ lbs.
Length of arm $= 3.18$ ft.
r.p.m. $= 3{,}000$
$\pi = 3.1416.$

Find b.hp.:

Substituting in equation—

$$\text{b.hp.} = \frac{6.2832 \times 200 \times 3.18 \times 3{,}000}{33{,}000}$$

$$= 363.2$$

$$= 363.$$

As long as the friction between the brake collar and propeller shaft drum is great enough to impose an appreciable load on the engine, but is not great enough to stop the engine, it is not necessary to know the amount of friction between the collar and drum to compute the b.hp. If there were no load imposed, there would be no torque to measure, and the engine would "run away." If the imposed load is so great that the engine stalls, there may be considerable torque to measure, but there will be no r.p.m. In either case it is impossible to measure the b.hp. of the engine. However, if a reasonable amount of friction exists between the brake drum and the collar and the load is then increased, the tendency of the propeller shaft to carry the collar and arm about with it becomes greater, thus imposing a greater force upon the scales. As long as the torque increase is proportional to the r.p.m. decrease, the horsepower delivered at the shaft remains unchanged. This can be seen from the equation in which 2π and 33,000 are constants and torque and r.p.m. are variables. If the change in r.p.m. is inversely proportional to the change in torque, their product will remain unchanged. Therefore, b.hp. remains unchanged. This is important. It shows that horsepower is the function of both torque and r.p.m., and can be changed by changing either torque or r.p.m., or both.

Friction Horsepower

Friction horsepower is the indicated horsepower minus brake horsepower. It is the horsepower used by an engine in overcoming the friction of moving parts, drawing in fuel, expelling exhaust, driving oil and fuel pumps, and the like. On modern aircraft engines, this power loss through friction may be as high as 10 to 15% of the indicated horsepower.

Friction and Brake Mean Effective Pressures

The IMEP (indicated mean effective pressure), discussed previously, is the average pressure produced in the combustion chamber during the operating cycle and is an expression of the theoretical, frictionless power known as indicated horsepower. In addition to completely disregarding power lost to friction, indicated horsepower gives no indication as to how much actual power is delivered to the propeller shaft for doing useful work. However, it is related to actual pressures which occur in the cylinder and can be used as a measure of these pressures.

To compute the friction loss and net power output, the indicated horsepower of a cylinder may be thought of as two separate powers, each producing a different effect. The first power overcomes internal friction, and the horsepower thus consumed is known as friction horsepower. The second power, known as brake horsepower, produces useful work at the propeller. Logically, therefore, that portion of IMEP that produces brake horsepower is called BMEP (brake mean effective pressure). The remaining pressure used to overcome internal friction is called FMEP (friction mean effective pressure). This is illustrated in figure 1–30. IMEP is a useful expression of total cylinder power output, but is not a real physical quantity; likewise, FMEP and BMEP are theoretical but useful expressions of friction losses and net power output.

Although BMEP and FMEP have no real existence in the cylinder, they provide a convenient means of representing pressure limits, or rating engine performance throughout its entire operating range. This is true since there is a relationship between IMEP, BMEP, and FMEP.

One of the basic limitations placed on engine operation is the pressure developed in the cylinder during combustion. In the discussion of compression ratios and indicated mean effective pressure, it was found that, within limits, the increased pressure resulted in increased power. It was also noted that if the cylinder pressure was not controlled

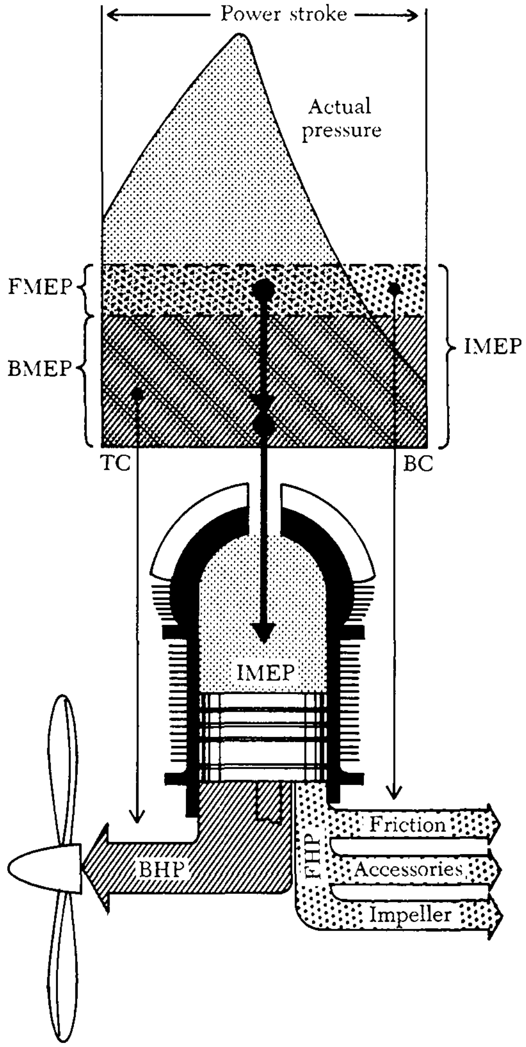


FIGURE 1–30. Powers and pressures.

within close limits, it would impose dangerous internal loads that might result in engine failure. It is therefore important to have a means of determining these cylinder pressures as a protective measure and for efficient application of power.

If the b.hp. is known, the BMEP can be computed by means of the following equation:

$$BMEP = \frac{b.hp. \times 33{,}000}{LANK}.$$

Example

Given:

b.hp. $= 1{,}000$
Stroke $= 6$ in.
Bore $= 5.5$ in.
r.p.m. $= 3{,}000$
No. of cyls. $= 12$.

Find BMEP:

Find length of stroke (in ft.):
$L = 0.5$.

Find area of cylinder bore:
$A = 1/4\pi D^2$
$= 0.7854 \times 5.5 \times 5.5$
$= 23.76$ sq. in.

Find No. of power strokes per min.:
$N = 1/2 \times$ r.p.m.
$= 1/2 \times 3{,}000$
$= 1{,}500$.

Then substituting in the equation:

$$BMEP = \frac{1{,}000 \times 33{,}000}{.5 \times 23.76 \times 1{,}500 \times 12}$$

$= 154.32$ lbs. per sq. in.

Thrust Horsepower

Thrust horsepower can be considered as the result of the engine and the propeller working together. If a propeller could be designed to be 100% efficient, the thrust- and the brake-horsepower would be the same. However, the efficiency of the propeller varies with the engine speed, attitude, altitude, temperature, and airspeed, thus the ratio of the thrust horsepower and the brake horsepower delivered to the propeller shaft will never be equal. For example, if an engine develops 1,000 b.hp., and it is used with a propeller having 85 percent efficiency, the thrust horsepower of that engine-propeller combination is 85 percent of 1,000 or 850 thrust hp. Of the four types of horsepower discussed, it is the thrust horsepower that determines the performance of the engine-propeller combination.

EFFICIENCIES

Thermal Efficiency

Any study of engines and power involves consideration of heat as the source of power. The heat produced by the burning of gasoline in the cylinders causes a rapid expansion of the gases in the cylinder, and this, in turn, moves the pistons and creates mechanical energy.

It has long been known that mechanical work can be converted into heat and that a given amount of heat contains the energy equivalent of a certain amount of mechanical work. Heat and work are theoretically interchangeable and bear a fixed relation to each other. Heat can therefore be measured in work units (for example, ft.-lbs.) as well as in heat units. The B.t.u. (British thermal unit) of heat is the quantity of heat required to raise the temperature of 1 lb. of water 1° F. It is equivalent to 778 ft.-lbs. of mechanical work. A pound of petroleum fuel, when burned with enough air to consume it completely, gives up about 20,000 B.t.u., the equivalent of 15,560,000 ft.-lbs. of mechanical work. These quantities express the heat energy of the fuel in heat and work units, respectively.

The ratio of useful work done by an engine to the heat energy of the fuel it uses, expressed in work or heat units, is called the thermal efficiency of the engine. If two similar engines use equal amounts of fuel, obviously the engine which converts into work the greater part of the energy in the fuel (higher thermal efficiency) will deliver the greater amount of power. Furthermore, the engine which has the higher thermal efficiency will have less waste heat to dispose of to the valves, cylinders, pistons, and cooling system of the engine. A high thermal efficiency also means a low specific fuel consumption and, therefore, less fuel for a flight of a given distance at a given power. Thus, the practical importance of a high thermal efficiency is threefold, and it constitutes one of the most desirable features in the performance of an aircraft engine.

Of the total heat produced, 25 to 30% is utilized for power output; 15 to 20% is lost in cooling (heat radiated from cylinder head fins); 5 to 10% is lost in overcoming friction of moving parts; and 40 to 45% is lost through the exhaust. Anything which increases the heat content that goes into mechanical work on the piston, which reduces the friction and pumping losses, or which reduces the quantity of unburned fuel or the heat lost to the engine parts, increases the thermal efficiency.

The portion of the total heat of combustion which is turned into mechanical work depends to a great extent upon the compression ratio. Compression ratio is the ratio of the piston displacement plus combustion chamber space to the combustion chamber space. Other things being equal, the higher the compression ratio, the larger is the proportion of the heat energy of combustion turned into useful work at the crankshaft. On the other hand, increasing the compression ratio increases the cylinder head temperature. This is a limiting factor, for the extremely high temperature created by high compression ratios causes the material in the cylinder to deterioriate rapidly and the fuel to detonate.

The thermal efficiency of an engine may be based on either b.hp. or i.hp. and is represented by the formula:

$$\text{Indicated thermal efficiency} = \frac{\text{i.hp.} \times 33{,}000}{\text{weight of fuel burned/min.} \times \text{heat value} \times 778}.$$

The formula for brake thermal efficiency is the same as shown above, except the value for b.hp. is inserted instead of the value for i.hp.

Example

An engine delivers 85 b.hp. for a period of 1 hr. and during that time consumes 50 lbs. of fuel. Assuming the fuel has a heat content of 18,800 B.t.u. per lb., find the thermal efficiency of the engine:

$$\frac{85 \times 33{,}000}{.833 \times 18{,}800 \times 778} = \frac{2{,}805{,}000}{12{,}184{,}569}.$$

Brake thermal efficiency = 0.23 or 23%.

Reciprocating engines are only about 34% thermally efficient; that is, they transform only about 34% of the total heat produced by the burning fuel into mechanical energy. The remainder of the heat is lost through the exhaust gases, the cooling system, and the friction within the engine. Thermal distribution in a reciprocating engine is illustrated in figure 1–31.

Mechanical Efficiency

Mechanical efficiency is the ratio that shows how much of the power developed by the expanding gases in the cylinder is actually delivered to the output shaft. It is a comparison between the b.hp. and the i.hp. It can be expressed by the formula:

$$\text{Mechanical efficiency} = \frac{\text{b.hp.}}{\text{i.hp.}}.$$

Brake horsepower is the useful power delivered to the propeller shaft. Indicated horsepower is the total hp. developed in the cylinders. The difference between the two is f.hp. (friction horsepower), the power lost in overcoming friction.

The factor that has the greatest effect on mechanical efficiency is the friction within the engine itself. The friction between moving parts in an engine remains practically constant throughout an engine's speed range. Therefore, the mechanical efficiency of an engine will be highest when the engine is running at the r.p.m. at which maximum b.hp. is developed. Mechanical efficiency of the average aircraft reciprocating engine approaches 90%.

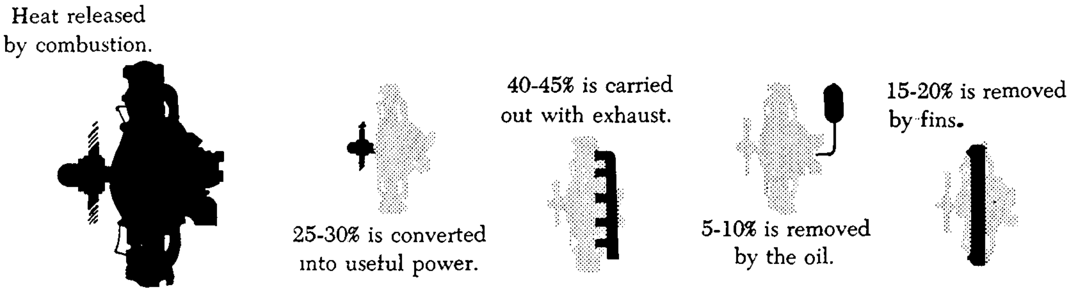


FIGURE 1–31. Thermal distribution in an engine.

Volumetric Efficiency

Volumetric efficiency, another engine efficiency, is a ratio expressed in terms of percentages. It is a comparison of the volume of fuel/air charge (corrected for temperature and pressure) inducted into the cylinders to the total piston displacement of the engine. Various factors cause departure from a 100% volumetric efficiency.

The pistons of an unsupercharged engine displace the same volume each time they sweep the cylinders from top center to bottom center. The amount of charge that fills this volume on the intake stroke depends on the existing pressure and temperature of the surrounding atmosphere. Therefore, to find the volumetric efficiency of an engine, standards for atmospheric pressure and temperature had to be established. The U.S. standard atmosphere was established in 1958 and provides the necessary pressure and temperature values to calculate volumetric efficiency.

The standard sea-level temperature is 59° F. or 15° C. At this temperature the pressure of one atmosphere is 14.69 lbs./sq. in., and this pressure will support a column of mercury 29.92 in. high. These standard sea-level conditions determine a standard density, and if the engine draws in a volume of charge of this density exactly equal to its piston displacement, it is said to be operating at 100% volumetric efficiency. An engine drawing in less volume than this has a volumetric efficiency lower than 100%. An engine equipped with a high-speed internal or external blower may have a volumetric efficiency greater than 100%. The equation for volumetric efficiency is:

$$\text{Volumetric efficiency} = \frac{\text{Volume of charge (corrected for temperature and pressure)}}{\text{Piston displacement}}.$$

Many factors decrease volumetric efficiency; some of these are:

(1) Part-throttle operation.
(2) Long intake pipes of small diameter.
(3) Sharp bends in the induction system.
(4) Carburetor air temperature too high.
(5) Cylinder-head temperature too high.
(6) Incomplete scavenging.
(7) Improper valve timing.

Propulsive Efficiency

A propeller is used with an engine to provide thrust. The engine supplies b.hp. through a rotating shaft, and the propeller absorbs the b.hp. and converts it into thrust hp. In this conversion, some power is wasted. Since the efficiency of any machine is the ratio of useful power output to the power input, propulsive efficiency (in this case, propeller efficiency) is the ratio of thrust hp. to b.hp. On the average, thrust hp. constitutes approximately 80% of the b.hp. The other 20% is lost in friction and slippage. Controlling the blade angle of the propeller is the best method of obtaining maximum propulsive efficiency for all conditions encountered in flight.

During takeoff, when the aircraft is moving at low speeds and when maximum power and thrust are required, a low propeller blade angle will give maximum thrust. For high-speed flying or diving, the blade angle is increased to obtain maximum thrust and efficiency. The constant-speed propeller is used to give required thrust at maximum efficiency for all flight conditions.

TURBINE ENGINE CONSTRUCTION

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

A typical gas turbine engine consists of:

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

The major components of all turbine engines are basically the same; however, the nomenclature of the component parts of various engines currently in use will vary slightly due to the difference in each manufacturer's terminology. These differences are reflected in the applicable maintenance manuals.

The greatest single factor influencing the construction features of any gas turbine engine is the type compressor (axial flow or centrifugal flow) for which the engine is designed. Later in the chapter a detailed description of compressors is given, but for the time being examine figures 1–32 and 1–33. Notice the physical effect the two types of compressors have on engine construction features. It is obvious that there is a difference in their length and diameter.

Note that in the axial-flow engine the air inlet

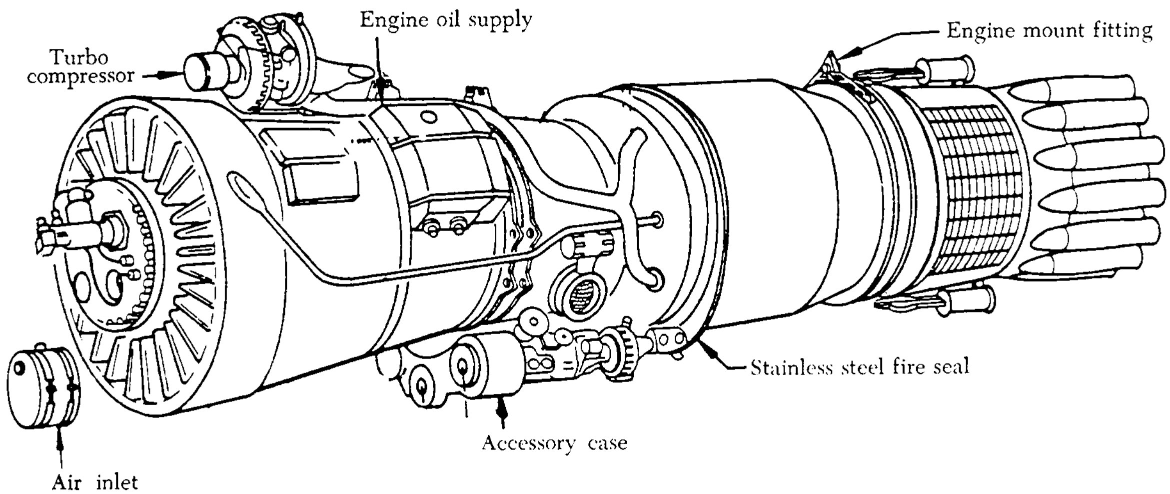


FIGURE 1–32. Axial-flow engine.

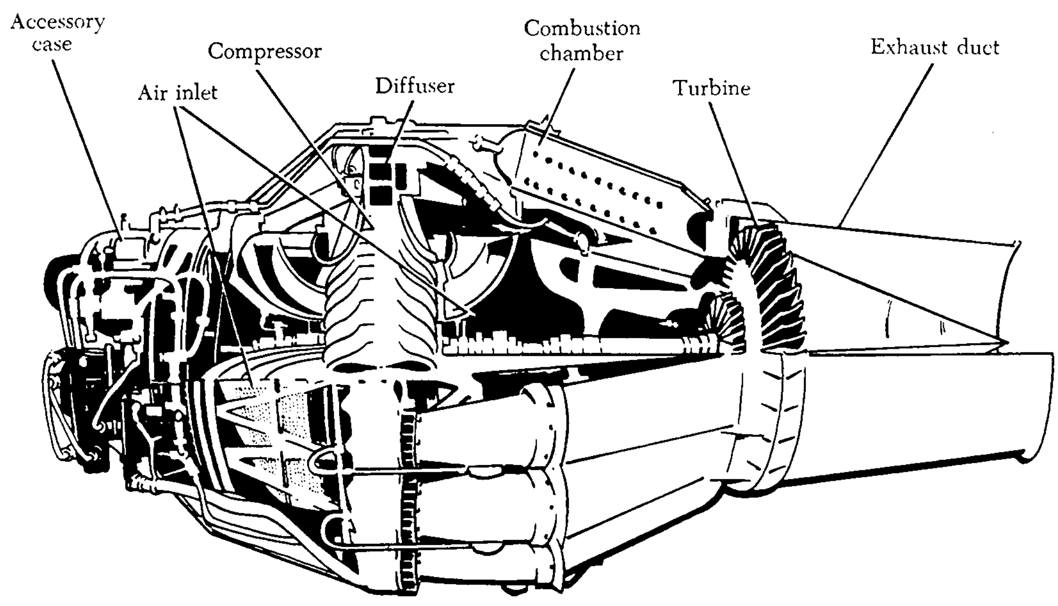


FIGURE 1–33. Centrifugal-flow engine.

duct is one of the major engine components; on the other hand, in the centrifugal-flow engine, air enters the air inlet and is directed to the compressor inducer vanes through circumferential inlets located in front and back of the impeller. The inlets are screened to prevent entry of foreign objects that could cause serious damage to the metal components if allowed to enter the compressor.

The accessories of the two types of engines are located at different points on the engines. This is necessary because of engine construction. The front of the axial-flow engine is utilized for air entrance; consequently, the accessories must be located elsewhere.

Other than the features previously mentioned, there is little visual dissimilarity between the remaining major components of the two engines.

AIR ENTRANCE

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

The amount of air passing through the engine is dependent upon three factors:

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

Inlets may be classified as:

(1) *Nose* inlets, located in the nose of the fuselage, or powerplant pod or nacelle.
(2) *Wing* inlets, located along the leading edge of the wing, usually at the root for single-engine installations.
(3) *Annular* inlets, encircling, in whole or in part, the fuselage or powerplant pod or nacelle.
(4) *Scoop* inlets, which project beyond the immediate surface of the fuselage or nacelle.
(5) *Flush* inlets, which are recessed in the side of the fuselage, powerplant pod, or nacelle.

There are two basic types of air entrances in use: the single entrance and the divided entrance. Generally, it is advantageous to use a single entrance with an axial-flow engine to obtain maximum ram pressure through straight flow. It is used almost exclusively on wing or external installations where the unobstructed entrance lends itself readily to a single, short, straight duct.

A divided entrance offers greater opportunity to diffuse the incoming air and enter the plenum chamber with the low velocity required to utilize efficiently a double-entry compressor. (The plenum chamber is a storage place for ram air, usually asso-

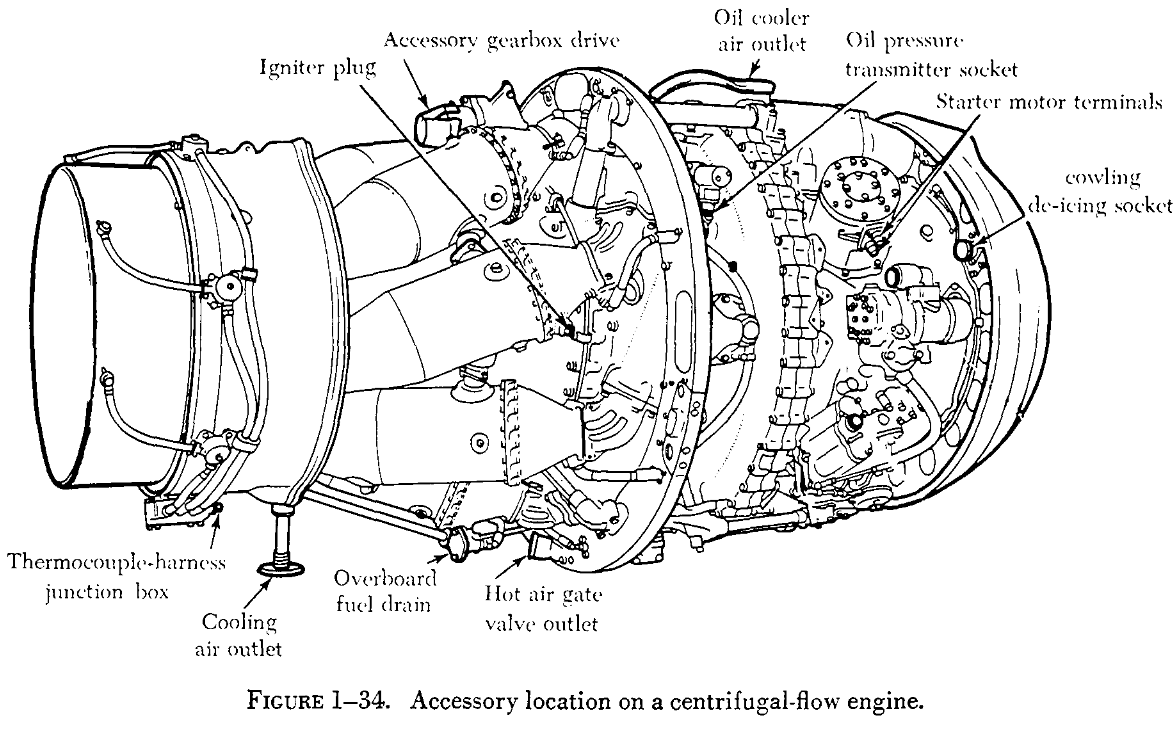


FIGURE 1–34. Accessory location on a centrifugal-flow engine.

ciated with fuselage installations.) It is also advantageous when the equipment installation or pilot location makes the use of a single or straight duct impractical. In most cases the divided entrance permits the use of very short ducts with a resultant small pressure drop through skin friction.

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 operation and control of the engine. Generally, it also includes accessories concerned with the aircraft, such as electric generators and fluid power-pumps. Secondary functions include acting as an oil reservoir and/or oil sump, and housing the accessory drive gears and reduction gears.

The arrangement and driving of accessories have always been major problems on gas turbine engines. Driven accessories are usually mounted on common pads either ahead of or adjacent to the compressor section, depending on whether the engine is centrifugal flow or axial flow. Figures 1–34 and 1–35 illustrate the accessory arrangement of a centrifugal-flow engine and an axial-flow engine, respectively.

The components of the accessory section of all centrifugal- and axial-flow engines have essentially the same purpose even though they often differ quite extensively in construction details and nomenclature.

The basic elements of the centrifugal-flow engine accessory section are (1) the accessory case, which has machined mounting pads for the engine-driven accessories, and (2) the gear train, which is housed within the accessory case.

The accessory case may be designed to act as an oil reservoir. If an oil tank is utilized, a sump is usually provided below the front bearing support for the drainage and scavenging of oil used to lubricate bearings and drive gears.

The accessory case is also provided with adequate tubing or cored passages for spraying lubricating oil on the gear train and supporting bearings.

The gear train is driven by the engine rotor through an accessory drive shaft gear coupling, which splines with a shaft gear and the rotor assembly compressor hub. The reduction gearing within the case provides suitable drive speeds for each engine accessory or component. Because the rotor

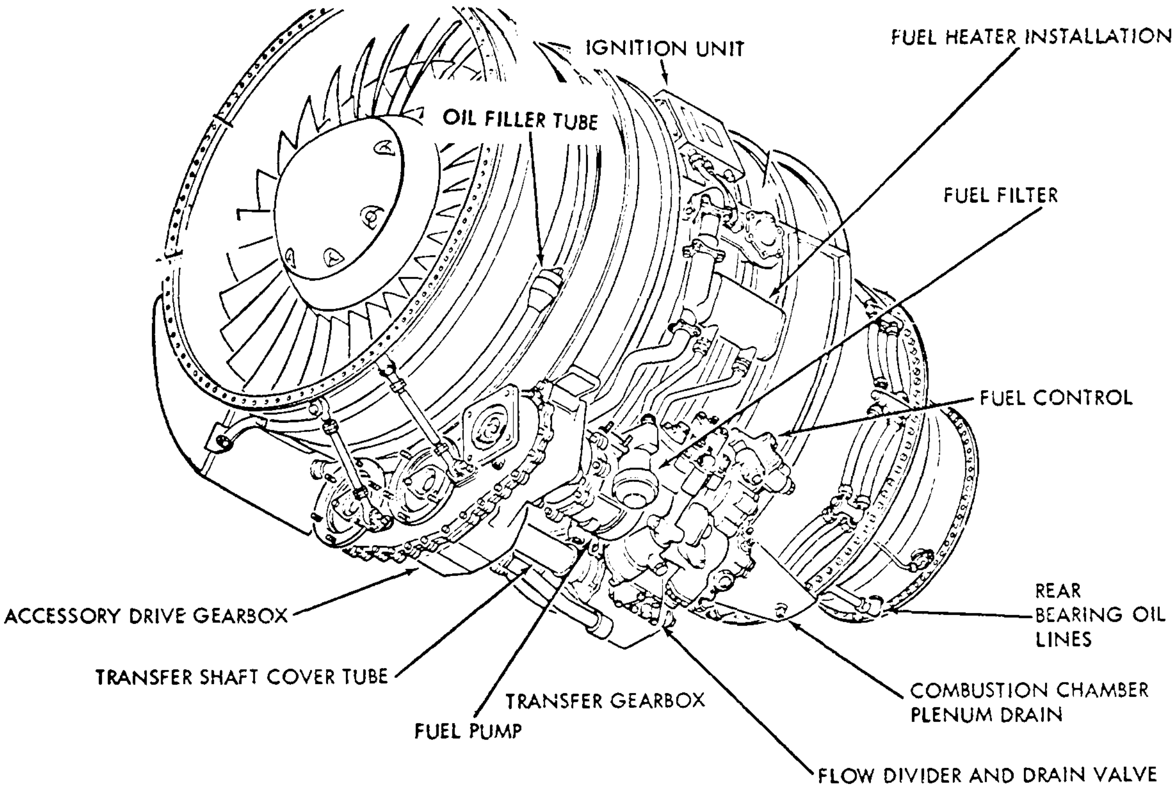


FIGURE 1–35. Accessory arrangement on an axial-flow engine.

operating r.p.m. is so high, the accessory reduction gear ratios are relatively high. The accessory drives are supported by ball bearings assembled in the mounting pad bores of the accessory case.

The components of an axial-flow engine accessory section are an accessory gearbox and a power take-off assembly, housing the necessary drive shafts and reduction gears. Figure 1–36 shows the location of the accessory gearbox.

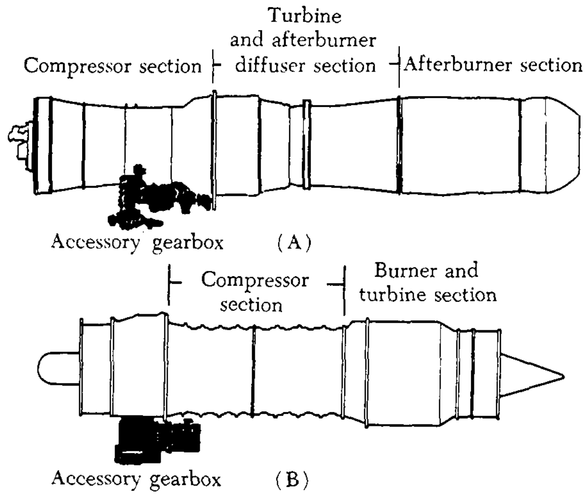


FIGURE 1–36. (A) Accessory gearbox mounted beneath the compressor; (B) Accessory gearbox mounted beneath the front bearing support.

Although the close relationship of the accessory gearbox and the power takeoff necessitates their being located near each other, two factors affect the location of gearboxes. They are engine diameter and engine installation.

Designers are forever striving to reduce engine diameter to make the engine more streamlined, thereby increasing aircraft performance by reducing drag. Also, engine installation in a particular aircraft may dictate the location or re-arrangement of the accessory gearboxes.

The accessory gearbox has basically the same functions as the accessory case of the centrifugal-flow engine. It has the usual machined mounting pads for the engine accessories, and it houses and supports the accessory drive gear trains. Also included are adequate tubing and cored passages for lubricating the gear trains and their supporting bearings.

The accessories usually provided on engines are the fuel control with its governing device; the high-pressure fuel pump(s); oil pressure pump and scavenge pump(s); auxiliary fuel pump and sometimes a starting fuel pump; and several engine accessories including starter, generator, and tachometer. Although these accessories are for the most part 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 the engine-driven type. Also associated with the engine systems are the nondriven accessories, such as ignition exciters, fuel or oil filters, barometric units, drip valves, compressor bleed valves, and relief valves.

COMPRESSOR SECTION

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

A secondary function of the compressor is to supply bleed-air for various purposes in the engine and aircraft.

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

Bleed air is utilized in a wide variety of ways, including driving the previously mentioned remote-driven accessories. Some of the current applications of bleed air are:

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

(5) Control-booster servosystems.

(6) Power for running instruments.

The compressor section's location depends on the type of compressor. Figures 1–32 and 1–33 have already illustrated how the arrangement of engine components varies with compressor type. In the centrifugal-flow engine, the compressor is located between the accessory section and the combustion section; in the axial-flow engine the compressor is located between the air inlet duct and the combustion section.

Compressor Types

The two principal types of compressors currently being used in turbojet aircraft engines are centrifugal flow and axial flow. The compressor type is a means of engine classification.

Much use has been made of the terms "centrifugal flow" and "axial flow" to describe the engine and compressor. However, the terms are applicable to the flow of air through the compressor.

In the centrifugal-flow engine, the compressor achieves its purpose by picking up the entering air and accelerating it outwardly by centrifugal action. In the axial-flow engine, the air is compressed while continuing in its original direction of flow, thus avoiding the energy loss caused by turns. From inlet to exit the air flows along an axial path and is compressed at a ratio of approximately 1.25:1 per stage. The components of each of these two types of compressors have their individual functions in the compression of air for the combustion section.

Centrifugal-flow Compressors

The centrifugal-flow compressor consists basically of an impeller (rotor), a diffuser (stator), and a compressor manifold, illustrated in figure 1–37. The two main functional elements are the impeller and the diffuser. Although the diffuser is a separate unit and is placed inside and bolted to the manifold; the entire assembly (diffuser and manifold) is often referred to as the diffuser. For clarification during compressor familiarization, the units are treated individually.

The impeller is usually made from forged aluminum alloy, heat-treated, machined, and smoothed for minimum flow restriction and turbulence.

In some types the impeller is fabricated from a single forging. This type impeller is shown in figure 1–37 (A). In other types the curved inducer vanes are separate pieces as illustrated in figure 1–38.

The impeller, whose function is to pick up and accelerate the air outwardly to the diffuser, may be either of two types—single entry or double entry. Both are similar in construction to the reciprocating engine supercharger impeller, the double-entry type being similar to two impellers back to back. However, because of the much greater combustion air requirements in turbojet engines, the impellers are larger than supercharger impellers.

The principal differences between the two types of impellers are the size and the ducting arrangement. The double-entry type has a smaller diameter, but is usually operated at a higher rotational speed to assure sufficient airflow. The single-entry impeller permits convenient ducting directly to the impeller eye (inducer vanes) as opposed to the more complicated ducting necessary to reach the rear side of the double-entry type. Although slightly more efficient in receiving air, the single-entry impeller must be large in diameter to deliver the same quantity of air as the double-entry type. This, of course, increases the overall diameter of the engine.

Included in the ducting for double-entry compressor engines is the plenum chamber. This chamber is necessary for a double-entry compressor because the air must enter the engine at almost right angles to the engine axis. Therefore, the air must, in order to give a positive flow, surround the engine compressor at a positive pressure before entering the compressor.

Included in some installations, as a necessary part of the plenum chamber, are the auxiliary air-intake doors (blow-in doors). These blow-in doors admit air to the engine compartment during ground operation, when air requirements for the engine are in excess of the airflow through the inlet ducts. The doors are held closed by spring action when the engine is not operating. During operation, however, the doors open automatically whenever engine compartment pressure drops below atmospheric pressure. During takeoff and flight, ram air pressure in the engine compartment aids the springs in holding the doors closed.

The diffuser is an annular chamber provided with a number of vanes forming a series of divergent passages into the manifold. The diffuser vanes direct the flow of air from the impeller to the manifold at an angle designed to retain the maximum amount of energy imparted by the impeller. They also deliver the air to the manifold at a velocity and pressure satisfactory for use in the combustion

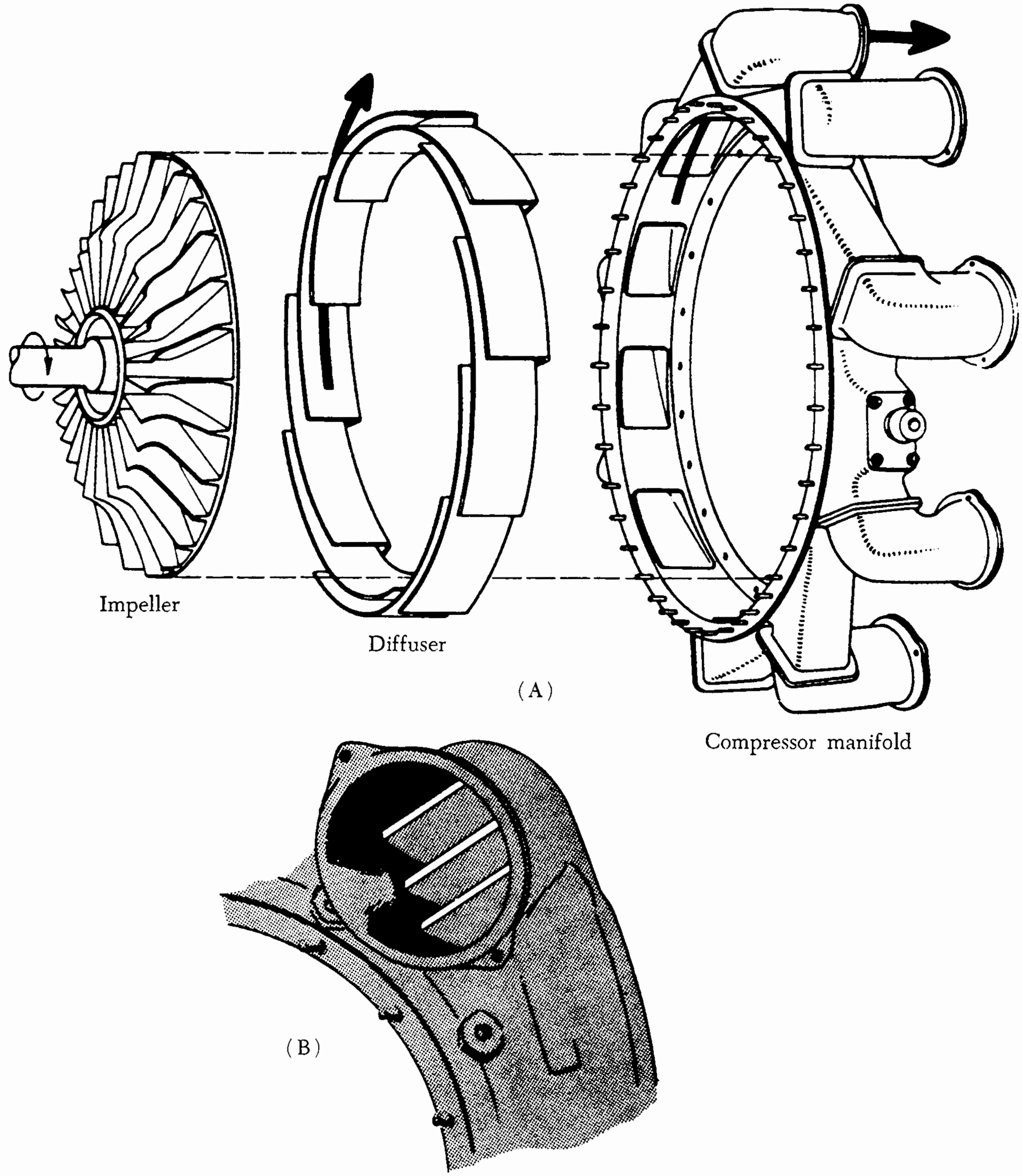


FIGURE 1–37. (A) Components of a centrifugal compressor; (B) Air outlet elbow with turning vanes for reducing air pressure losses.

chambers. Refer to figure 1–37 (A) and notice the arrow indicating the path of airflow through the diffuser, then through the manifold.

The compressor manifold shown in figure 1–37 (A) diverts the flow of air from the diffuser, which is an integral part of the manifold, into the combustion chambers. The manifold will have one outlet port for each chamber so that the air is evenly divided. A compressor outlet elbow is bolted to each of the outlet ports. These air outlets are constructed in the form of ducts and are known by a variety of names, such as air outlet ducts, outlet elbows, or

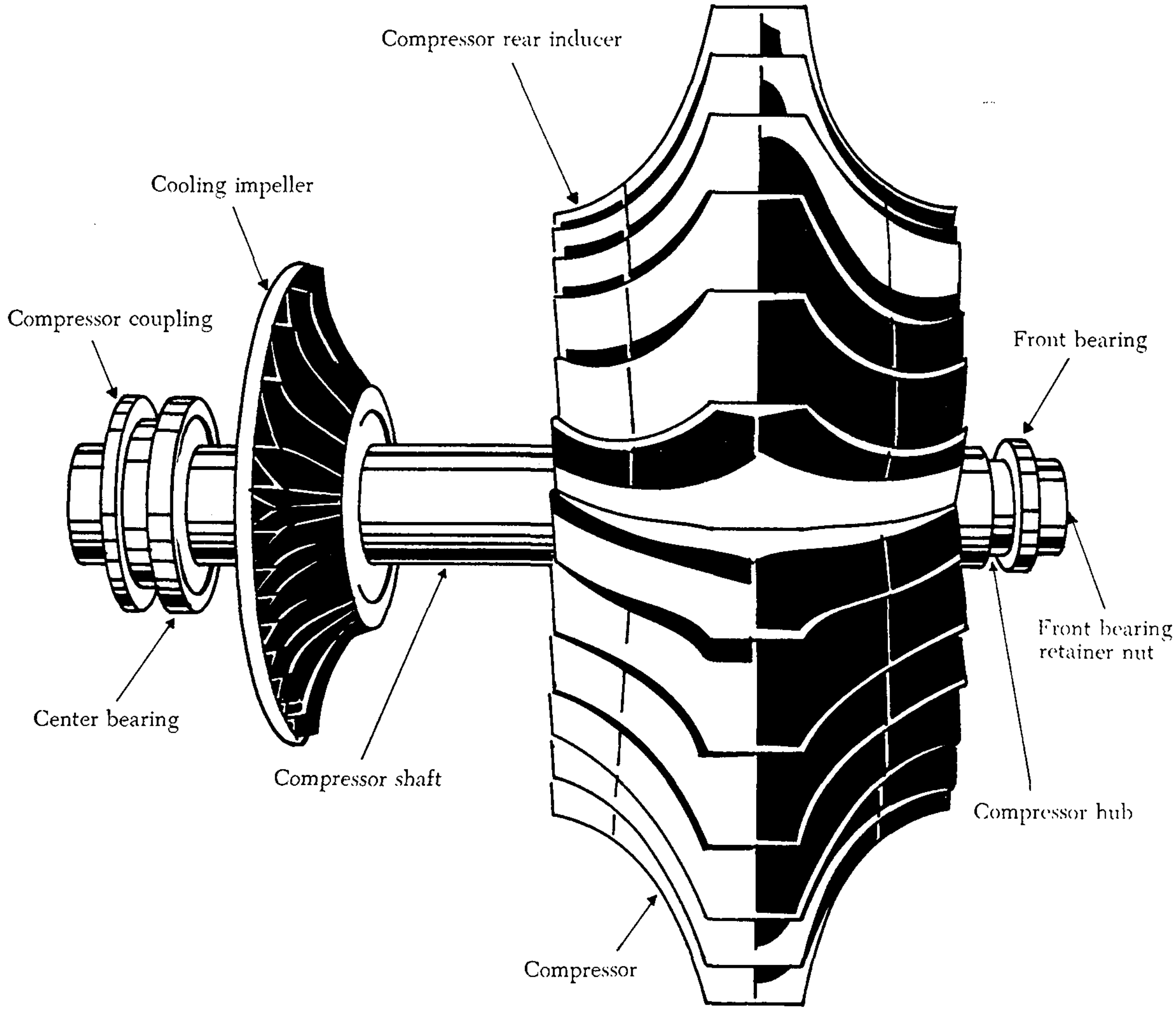


FIGURE 1–38. Double entry impeller with inducer vanes as separate pieces.

combustion chamber inlet ducts. Regardless of the terminology used, these outlet ducts perform a very important part of the diffusion process; that is, they change the radial direction of the airflow to an axial direction, where the diffusion process is completed after the turn. To help the elbows perform this function in an efficient manner, turning vanes (cascade vanes) are sometimes fitted inside the elbows. These vanes reduce air pressure losses by presenting a smooth, turning surface. (See figure 1–37 (B).)

Axial-flow Compressor

The axial-flow compressor has two main elements, a rotor and a stator. The rotor has blades fixed on a spindle. These blades impel air rearward in the same manner as a propeller because of their angle and airfoil contour. The rotor, turning at high speed, takes in air at the compressor inlet and impels it through a series of stages. The action of the rotor increases the compression of the air at each stage and accelerates it rearward through several stages. With this increased velocity, energy is transferred from the compressor to the air in the form of velocity energy. The stator blades act as diffusers at each stage, partially converting high velocity to pressure. Each consecutive pair of rotor and stator blades constitutes a pressure stage. The number of rows of blades (stages) is determined by the amount of air and total pressure rise required. The greater the number of stages, the higher the compression ratio. Most present-day engines utilize from 10 to 16 stages.

The stator has rows of blades, or vanes, dovetailed into split rings, which are in turn 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 are fitted, is horizontally divided into halves. Either the upper or lower half may be removed for inspection or maintenance of rotor and stator blades.

The function of the vanes is twofold. They are designed to receive air from the air inlet duct or from each preceding stage of the compressor and deliver it 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 obtain the maximum possible compressor blade efficiency. Shown in figure 1–39 are the rotor and stator elements of a typical axial-flow compressor.

The rotor blades are usually preceded by an inlet guide vane assembly. The guide vanes direct the airflow into the first stage rotor blades at the proper angle and impart a swirling motion to the air entering the compressor. This pre-swirl, in the direction of engine rotation, improves the aerodynamic characteristics of the compressor by reducing the drag on the first-stage rotor blades. The inlet guide vanes are curved steel vanes usually welded to steel inner and outer shrouds. The inlet guide vanes may be preceded by a protective inlet screen. This screen reduces the chance of accidental entry of foreign bodies, such as stones, dirt, clothing, or other debris, into the compressor.

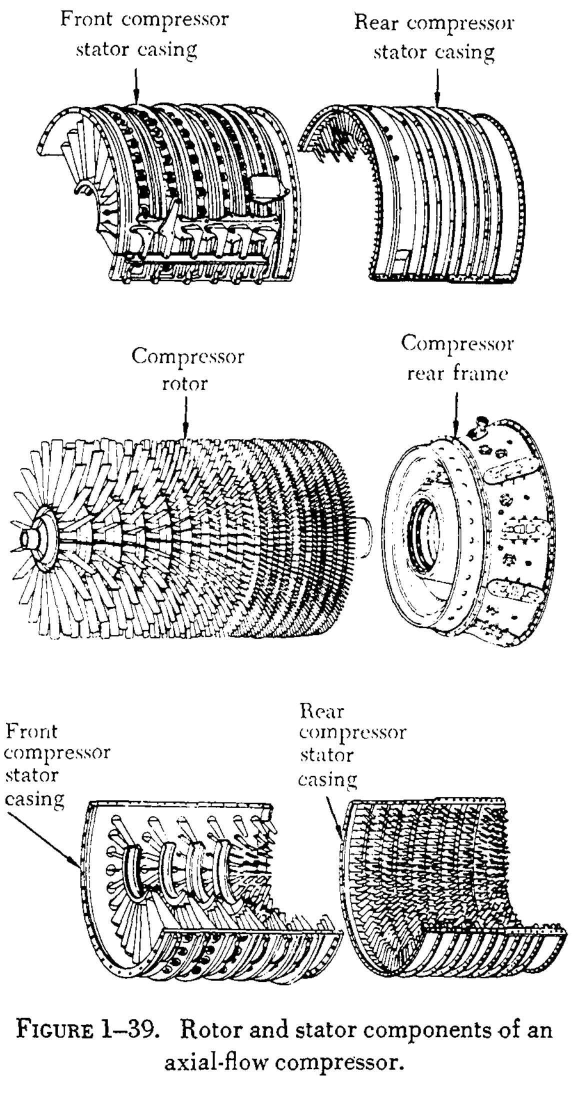


FIGURE 1–39. Rotor and stator components of an axial-flow compressor.

At the discharge end of the compressor, the stator vanes are constructed to straighten the airflow to eliminate turbulence. These vanes are called straightening vanes or the outlet vane assembly.

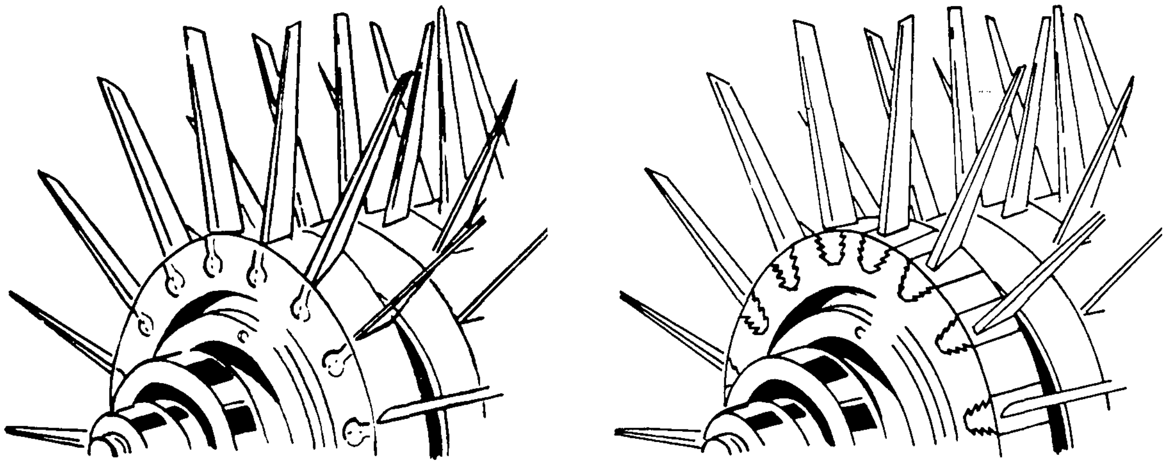
The casings of axial-flow compressors not only support the stator vanes and provide the outer wall of the axial path the air follows, but they also provide the means for extracting compressor air for various purposes.

The stator vanes are usually made of steel with corrosion- and erosion-resistant qualities. Quite frequently they are shrouded (or enclosed) by a band of suitable material to simplify the fastening problem. The vanes are welded into the shrouds, and the outer shroud is secured to the compressor housing inner wall by radial retaining screws.

The rotor blades are usually made of stainless steel. Methods of attaching the blades in the rotor disk rims vary in different designs, but they are commonly fitted into disks by either bulb-type or fir-tree-type roots. (See figure 1–40.) The blades are then locked by means of screws, peening, locking wires, pins, or keys.

Compressor blade tips are reduced in thickness by cutouts, referred to as blade "profiles." These profiles prevent serious damage to the blade or housing should the blades contact the compressor housing. This condition can occur if rotor blades become excessively loose or if rotor support is reduced by a malfunctioning bearing. Even though blade profiles greatly reduce such possibilities, occasionally a blade may break under stress of rubbing and cause considerable damage to compressor blades and stator vane assemblies.

The blades vary in length from entry to discharge because the annular working space (drum to casing) is reduced progressively toward the rear by the decrease in the casing diameter (see figure 1–41).



(A) Bulb root (B) Fir-tree root

FIGURE 1–40. Common retention methods used on compressor rotor blades.

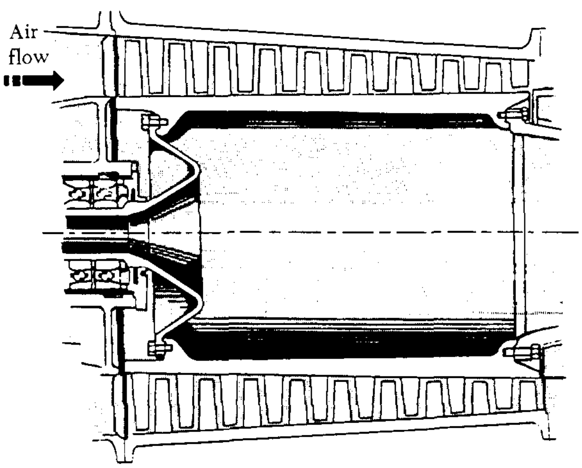


FIGURE 1–41. Drum-type compressor rotor.

Before leaving the subject of rotor familiarization, it may be well to mention that the rotor features either drum-type or disk-type construction.

The drum-type rotor consists of rings that are flanged to fit one against the other, wherein the entire assembly can then be held together by through bolts. This type of construction is satisfactory for low-speed compressors where centrifugal stresses are low.

The disk-type rotor consists of a series of disks machined from aluminum forgings, shrunk over a steel shaft, with rotor blades dovetailed into the disk rims. Another method of rotor construction is to machine the disks and shaft from a single aluminum forging, and then to bolt steel stub shafts on the front and rear of the assembly to provide bearing support surfaces and splines for joining the turbine shaft. The disk-type rotors are used almost exclusively in all present-day, high-speed engines and are the type referred to in this text. The drum-type and disk-type rotors are illustrated in figures 1–41 and 1–42, respectively.

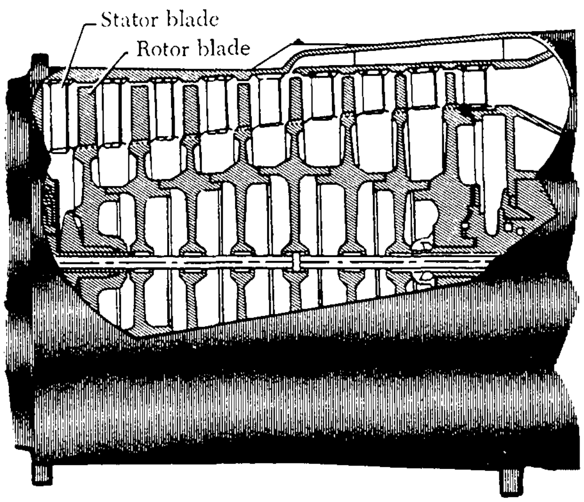


FIGURE 1–42. Disk-type compressor rotor.

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 currently in use, the single rotor and the dual rotor, sometimes referred to as solid spool and split spool, respectively.

One version of the solid-spool compressor uses variable inlet guide vanes. Also, the first few rows of stator vanes are variable. This is the arrangement on the General Electric CJ805 engine. It incorporates a 17-stage compressor, and 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 and 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 which extends into each combustion liner atomizes the fuel for combustion.

These variables are controlled in direct relation to the amount of power the engine is required to produce by the pilot's power lever position.

One version of the split-spool compressor is found in Pratt and Whitney's JT3C engine. It incorporates two compressors with their respective turbines and interconnecting shafts, which form two physically independent rotor systems.

As previously mentioned, centrifugal- and axial-flow engines dominate the gas-turbine field. There are, however, several possible configurations of these engine types, some of which have been tried experimentally, while others are still in the design or laboratory stage of development.

From an analysis of the centrifugal- and axial-flow engine compressors at their present stage of development, the axial-flow type appears to have 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.

The advantages and disadvantages of both types of compressors are included in the following list. Bear in mind that even though each compressor type has merits and limitations, the performance potential is the key to further development and use.

The centrifugal-flow compressor's advantages are:

(1) High pressure rise per stage.
(2) Good efficiencies over wide rotational speed range.
(3) Simplicity of manufacture, thus low cost.
(4) Low weight.
(5) Low starting power requirements.

The centrifugal-flow compressor's disadvantages are:

(1) Large frontal area for given airflow.
(2) More than two stages are not practical because of losses in turns between stages.

The axial-flow compressor's advantages are:

(1) High peak efficiencies.
(2) Small frontal area for given airflow.
(3) Straight-through flow, allowing high ram efficiency.
(4) Increased pressure rise by increasing number of stages with negligible losses.

The axial-flow compressor's disadvantages are:

(1) Good efficiencies over only narrow rotational speed range.
(2) Difficulty of manufacture and high cost.
(3) Relatively high weight.
(4) High starting power requirements. (This has been partially overcome by split compressors.)

COMBUSTION SECTION

The combustion section houses the combustion process, which raises the temperature of the air passing through the engine. This process releases energy contained in the air/fuel mixture. The major part of this energy is required at the turbine to drive 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 function of the combustion section is, of course, to burn the fuel/air mixture, thereby adding heat energy to the air. To do this efficiently the combustion chamber must:

(1) Provide the means for proper mixing of the fuel and air to assure good combustion.
(2) Burn this mixture efficiently.
(3) Cool the hot combustion products to a temperature which the turbine blades can withstand under operating conditions.
(4) Deliver the hot gases to the turbine section.

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

All combustion chambers contain the same basic elements:

(1) A casing.
(2) A perforated inner liner.
(3) A fuel injection system.
(4) Some means for initial ignition.
(5) A fuel drainage system to drain off unburned fuel after engine shutdown.

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

(1) The multiple-chamber or can type.
(2) The annular or basket type.
(3) The can-annular type.

The can-type combustion chamber is typical of the type used on both centrifugal- and axial-flow engines. It is particularly well suited for the centrifugal compressor engine, since the air leaving the compressor is already divided into equal portions as it leaves the diffuser vanes. It is then a simple matter to duct the air from the diffuser into the respective combustion chambers, arranged radially around the axis of the engine. The number of chambers will vary, since in the past (or development years) as few as two and as many as 16 chambers have been used. The present trend indicates the use of about eight or 10 combustion chambers. Figure 1–43 illustrates the arrangement for can-type combustion chambers. On American-built engines these chambers are numbered in a clockwise direction facing the rear of the engine with the No. 1 chamber at the top.

Each of the can-type combustion chambers consists of an outer case or housing, within which there is a perforated stainless steel (highly heat-resistant) combustion chamber liner or inner liner. (See figure 1–44.) The outer case is divided to facilitate liner replacement. The larger section or chamber body encases the liner at the exit end, and the smaller chamber cover encases the front or inlet end of the liner.

The interconnector (flame propagation) tubes are a necessary part of the can-type combustion chambers. Since each can is a separate burner operating independently of the other cans, there must be some way to spread combustion during the initial starting operation. This is accomplished by interconnecting all the chambers so that as the flame is started by the spark igniter plugs in two of the lower chambers, it will pass through the tubes and ignite the combustible mixture in the adjacent chamber, and continue on until all the chambers are burning.

The flame tubes will vary in construction details from one engine to another, although the basic components are almost identical.

The interconnector tubes are shown in figure 1–45. Bear in mind that not only must the chambers be interconnected by an outer tube (in this case a ferrule), but there must also be a slightly longer tube inside the outer one to interconnect the chamber liners where the flame is located. The outer tubes or jackets around the interconnecting flame tubes not only afford airflow between the chambers, but they also fulfill an insulating function around the hot flame tubes.

The spark igniters previously mentioned are normally two in number, and are located in two

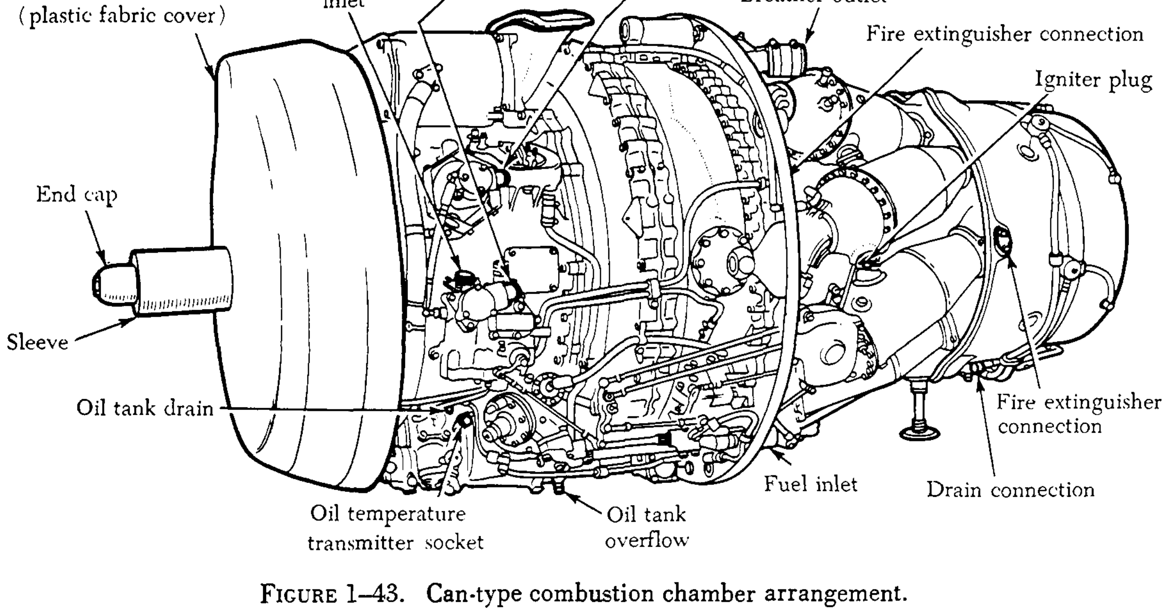


FIGURE 1–43. Can-type combustion chamber arrangement.

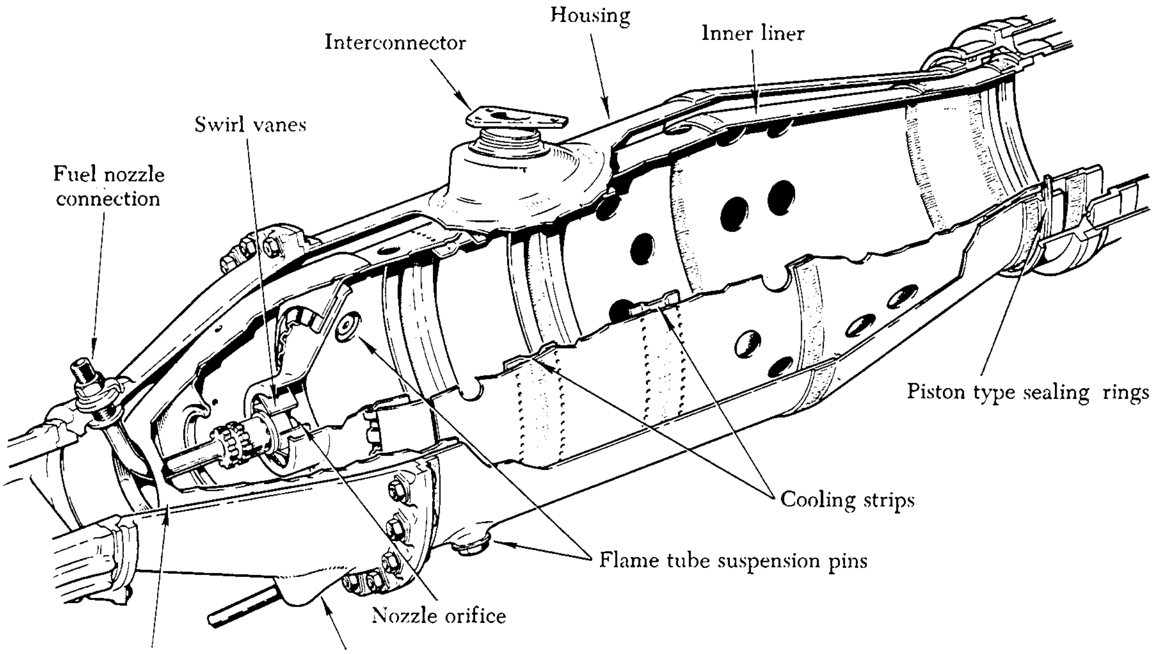


FIGURE 1–44. Can-type combustion chamber.

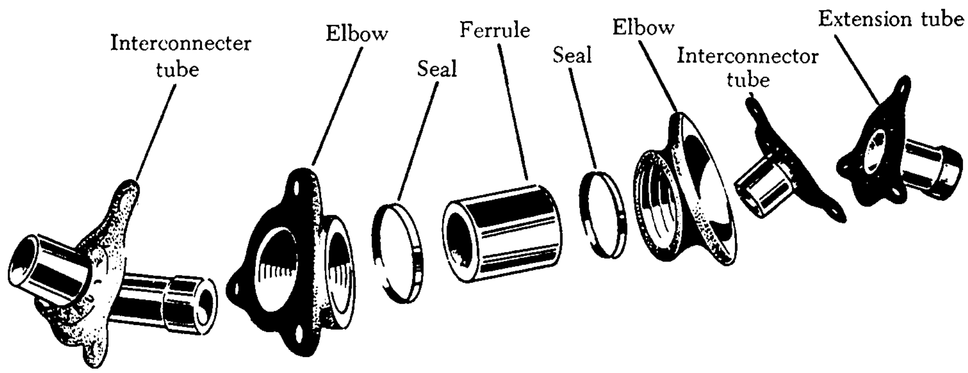


FIGURE 1–45. Interconnecting flame tubes for can-type combustion chambers.

of the can-type combustion chambers.

Another very important requirement in the construction of combustion chambers is providing the means for draining unburned fuel. This drainage prevents gum deposits in the fuel manifold, nozzles, and combustion chambers. These deposits are caused by the residue left when the fuel evaporates. Probably most important is the danger of afterfire if the fuel is allowed to accumulate after shutdown. If the fuel is not drained, a great possibility exists, that at the next starting attempt, the excess fuel in the combustion chamber will ignite, and tailpipe temperature will go beyond safe operating limits.

The liners of the can-type combustors (figure 1–44) have perforations of various sizes and shapes, each hole having 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 into two main streams—primary and secondary air. The primary or combustion air is directed inside the liner at the front end, where it mixes with the fuel and is burned. Secondary or cooling air passes between the outer casing and the liner and joins the combustion gases through larger holes toward the rear of the liner, cooling the combustion gases from about 3,500° F. to near 1,500° F. To aid in atomization of the fuel, holes are provided around the fuel nozzle in the dome or inlet end of the can-type combustor liner. Louvers are also provided along the axial length of the liners to direct a cooling layer of air along the inside wall of the liner. This layer of air also tends to control the flame pattern by keeping it centered in the liner, thereby preventing burning of the liner walls.

Figure 1–46 illustrates the flow of air through the louvers in the double-annular combustion chamber.

Some provision is always made in the combustion chamber case, or in the compressor air outlet elbow, for 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.

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

The annular combustion chamber consists basically of a housing and a liner, as does the can type. The liner consists of an undivided circular shroud extending all the way around the outside of the turbine shaft housing. The chamber may be constructed of one or more baskets; that is, if two or more chambers are used, they are placed one outside the other in the same radial plane, hence, the double-annular chamber. The double-annular chamber is illustrated in figure 1–47.

The spark igniter plugs of the annular combustion chamber are the same basic type used in the can combustion chambers, although construction details may vary. 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.

The can-annular type combustion chamber is a development by Pratt and Whitney for use in their JT3 axial-flow turbojet engine. Since this engine was to feature the split-spool compressor, it required a combustion chamber capable of meeting the stringent requirements of maximum strength and limited length with a high overall efficiency. These requirements were necessary because of the high air pressures and velocities present in a split-spool compressor, along with the shaft length limitations explained in the following two paragraphs.

The split 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. Because this shaft is inside the other, a limitation of diameter is imposed, with the result that the distance between the front compressor and the rear

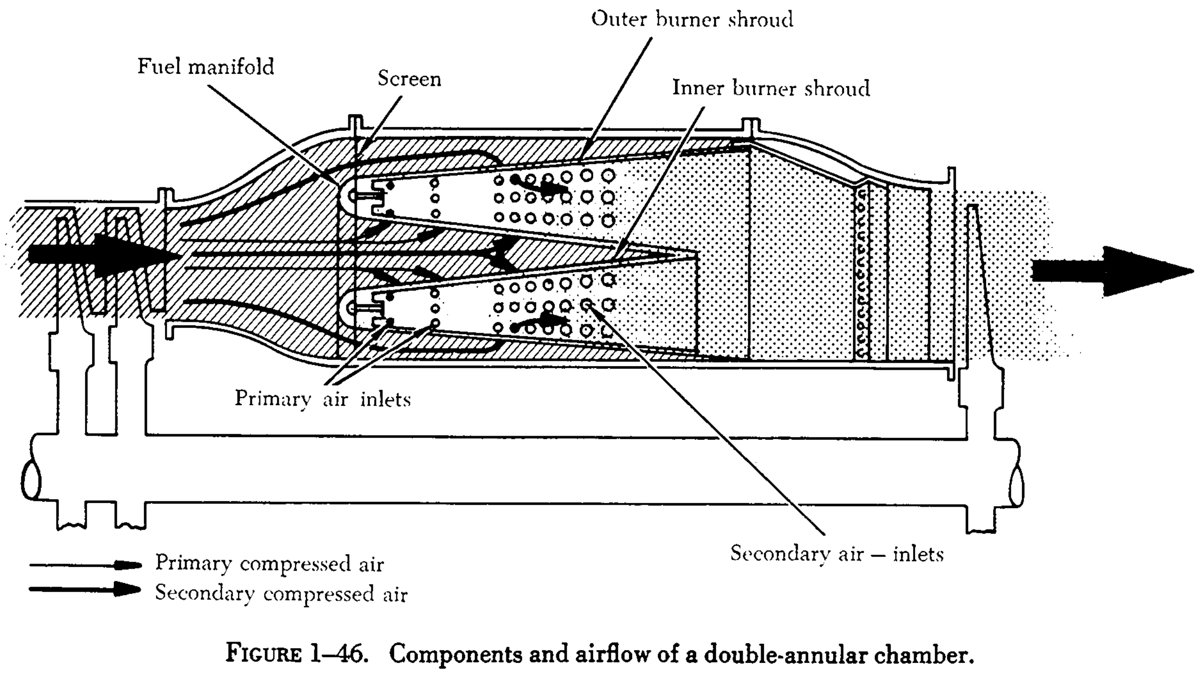


FIGURE 1–46. Components and airflow of a double-annular chamber.

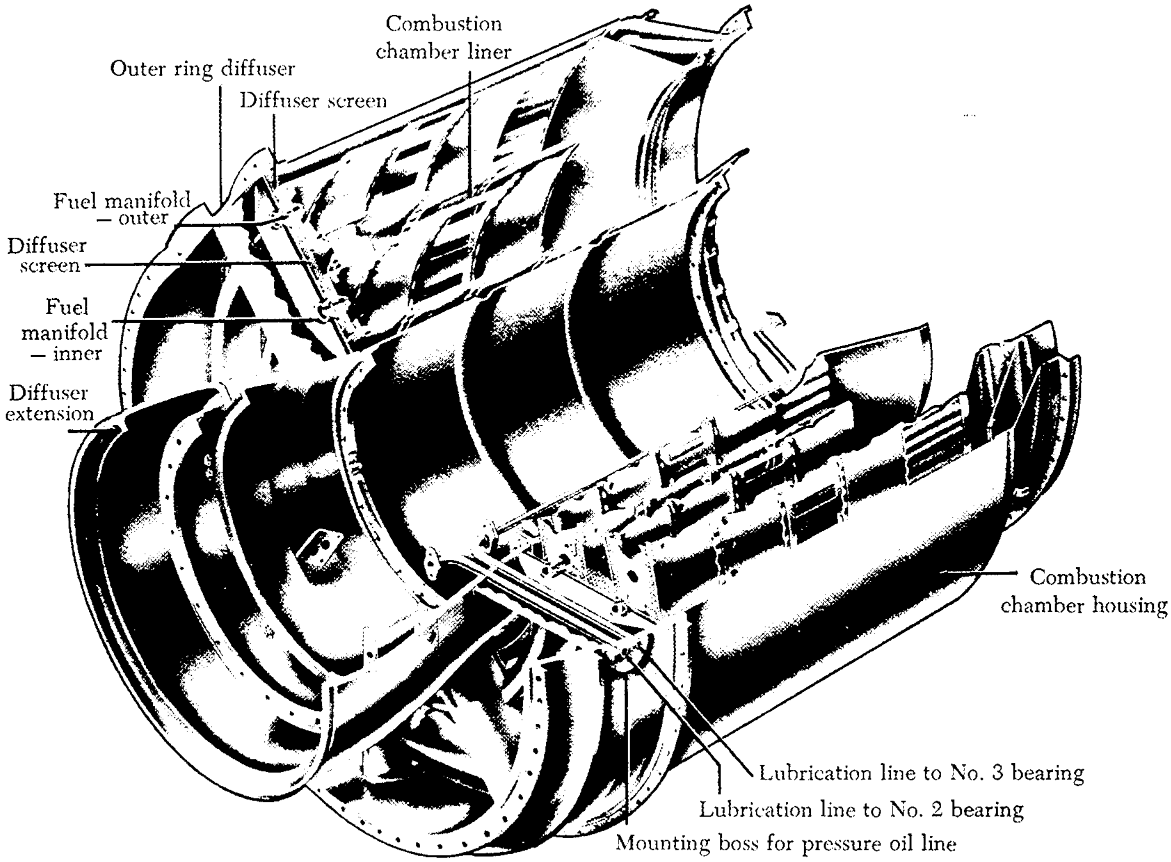


FIGURE 1–47. Double-annular combustion chamber.

turbine must be limited if critical shaft lengths are to be avoided.

Since the compressor and turbine are not susceptible to appreciable shortening, the necessary shaft length limitation had to be absorbed by developing a new type of burner. The designers had to develop a design that would give the desired performance in much less relative distance than had been previously assigned for this purpose.

The can-annular combustion chambers are arranged radially around the axis of the engine, the axis in this instance being the rotor shaft housing. Figure 1–48 shows this arrangement to advantage.

The combustion chambers are enclosed in 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 facilitate the engine-starting process as mentioned previously in the can-type combustion chamber familiarization. These flame tubes function identically with those previously discussed, but they differ in construction details.

Figure 1–48 also shows that each combustion chamber contains a central bullet-shaped perforated liner. The size and shape of the holes are designed to admit the correct quantity of air at the proper velocity and angle required. Cutouts are provided in two of the bottom chambers for installation of the spark igniters. Notice also in figure 1–48 how the combustion chambers are supported at the aft end by outlet duct clamps which secure them to the turbine nozzle assembly.

Again refer to figure 1–48 and notice how the forward face of each chamber presents six apertures which align with the six fuel nozzles of the corresponding fuel nozzle cluster. These nozzles are the dual-orifice (duplex) type requiring the use of a flow-divider (pressurizing valve), as mentioned in the can-type combustion chamber discussion. Around each nozzle are pre-swirl vanes for imparting a swirling motion to the fuel spray, which results in better atomization of the fuel, better burning and efficiency.

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

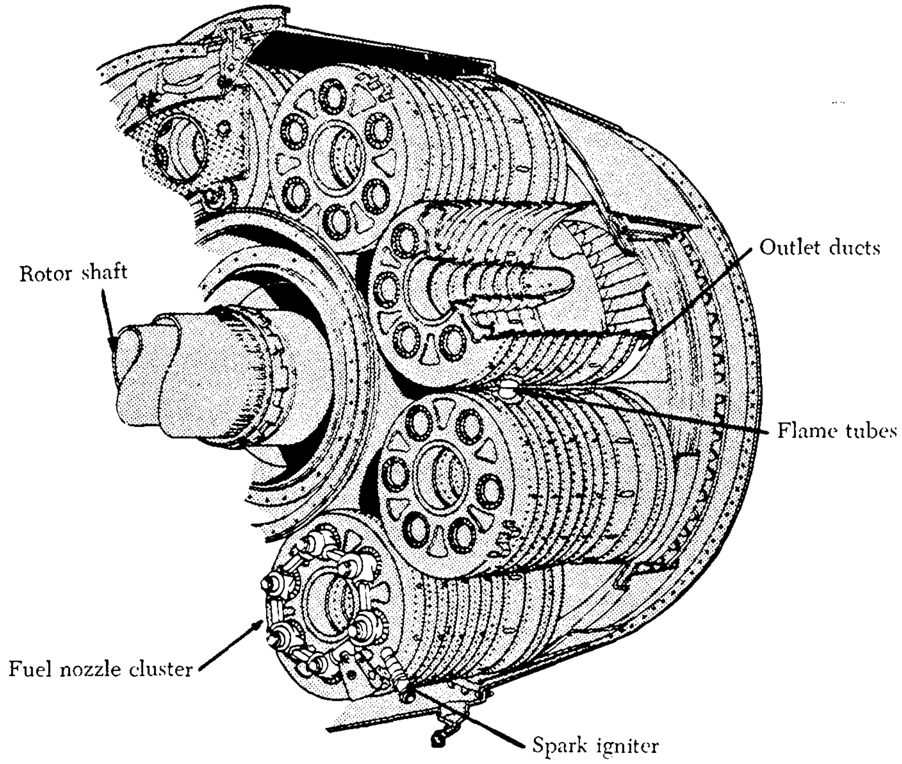


FIGURE 1–48. Can-annular combustion chamber components and arrangement.

(1) High flame speed: Better mixing of air and fuel, ensuring spontaneous burning.
(2) Low air velocity axially: Swirling eliminates flame moving axially too rapidly.

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, assuring proper drainage and elimination of residual fuel burning at the next start.

The flow of air through the holes and louvers of the can-annular chambers is almost identical with the flow through other types of burners. Special baffling is used to swirl the combustion airflow and to give it turbulence. Figure 1–49 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 accessories. This is the sole purpose of the turbine and this function absorbs approximately 60 to 80% 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; that is, the compressor size and type, number of accessories, and a propeller and its reduction gears if the engine is a turbo-propeller type.

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 1–50 and 1–51, respectively.

The stator element is known by a variety of names, of which turbine nozzle vanes, turbine 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.

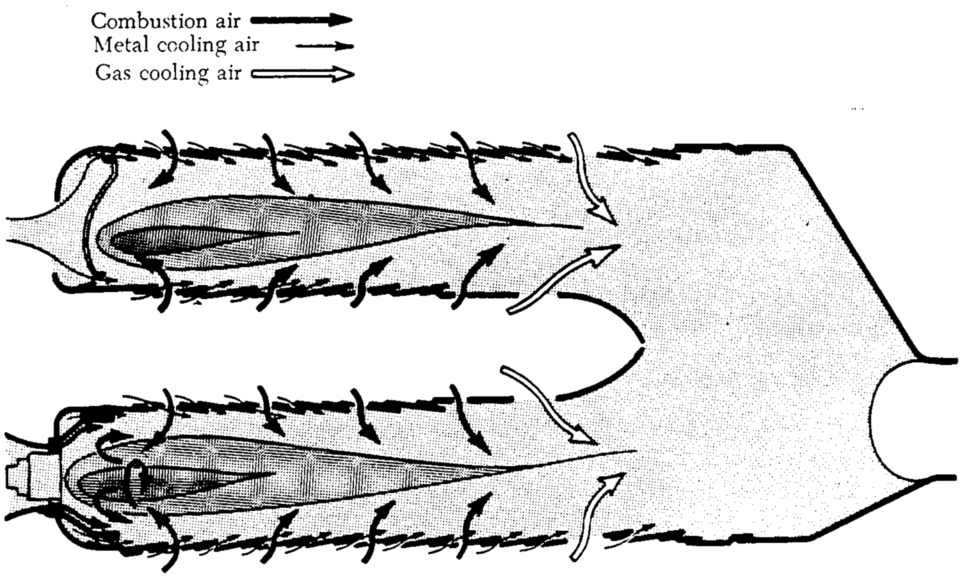


FIGURE 1–49. Airflow through a can-annular chamber.

The function of the turbine nozzles is twofold. First, after the combustion chamber has introduced the heat energy into the mass airflow and delivered it evenly to the turbine nozzles, it becomes the job of the nozzles to prepare the mass air flow for driving the turbine rotor. The stationary blades or vanes of the turbine nozzles are contoured and set at such an angle that they form a number of small nozzles discharging the gas at extremely high speed; thus, the nozzle converts a varying portion of the heat and pressure energy to velocity energy which

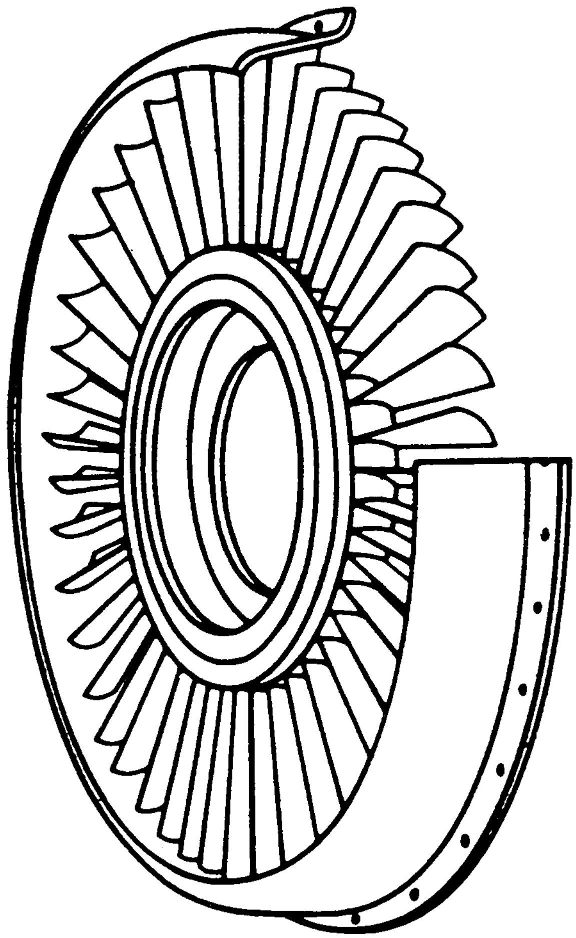


FIGURE 1–50. Stator element of the turbine assembly.

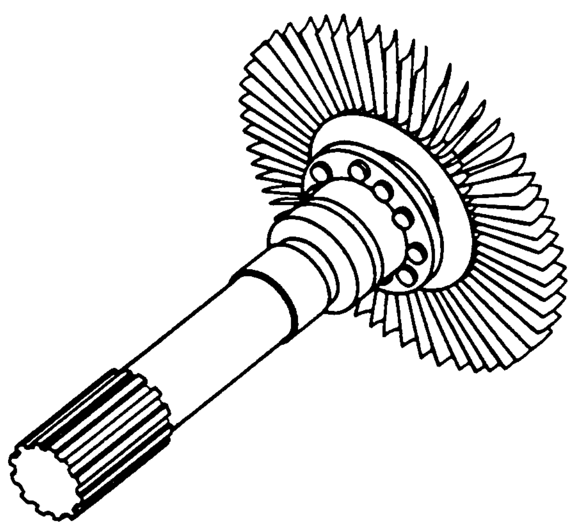
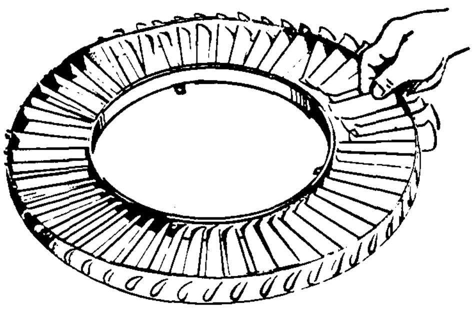


FIGURE 1–51. Rotor element of the turbine assembly.

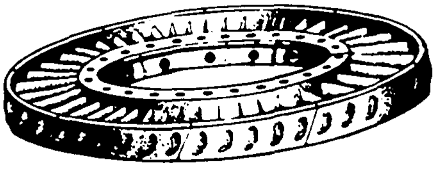
can then be converted to mechanical energy through the rotor blades.

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

The turbine nozzle assembly consists of an inner shroud and an outer shroud between which are fixed the nozzle vanes. The number of vanes employed vary with different types and sizes of engines. Figure 1–52 illustrates typical turbine nozzles featuring loose and welded vanes.



(A) Turbine nozzle vane assembly with loose fitting vanes;



(B) Turbine nozzle vane assembly with welded vanes.

FIGURE 1–52. Typical turbine nozzles.

The blades or vanes of the turbine nozzle may be assembled between the outer and inner shrouds or rings in a variety of ways. Although the actual elements may vary slightly in their configuration and construction features, there is one characteristic peculiar to all turbine nozzles; that is, the nozzle vanes must be constructed to allow for thermal expansion. Otherwise, there would be severe distortion or warping of the metal components because of rapid temperature changes.

The thermal expansion of turbine nozzles is accomplished by one of several methods. One method necessitates the vanes being assembled loosely in the supporting inner and outer shrouds. (See figure 1–52(A).)

Each vane fits into a contoured slot in the shrouds, which conforms with the airfoil shape of the vane. These slots are slightly larger than the vanes to give a loose fit. For further support the inner and outer shrouds are encased by an inner and an outer support ring, which give increased strength and rigidity. These support rings also facilitate removal of the nozzle vanes as a unit; otherwise, the vanes could fall out as the shrouds were removed.

Another method of thermal expansion construction is to fit the vanes into inner and outer shrouds; however, in this method the vanes are welded or riveted into position. (See figure 1–52(B).) Some means must be provided to allow for thermal expansion; therefore, either the inner or the outer shroud ring is cut into segments. These saw cuts dividing the segments will allow sufficient expansion to prevent stress and warping of the vanes.

The rotor element of the turbine section consists essentially of a shaft and a wheel. (See figure 1–51.)

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

The turbine disk is referred to as such when in an unbladed form. When the turbine blades are installed, the disk then becomes the turbine wheel. The disk acts as an anchoring component for the turbine blades. Since the disk is bolted or welded to the shaft, the blades can transmit to the rotor shaft the energy they extract from the exhaust gases.

The disk rim is exposed to the hot gases passing through the blades and absorbs considerable heat from these gases. In addition, the rim also absorbs heat from the turbine buckets (blades) by conduction. Hence, disk rim temperatures normally are high and well above the temperatures of the more remote inner portion of the disk. As a result of these temperature gradients, thermal stresses are added to the rotational stresses.

There are various means to relieve, at least partially, the aforementioned stresses. One such means is to bleed cooling air back onto the face of the disk.

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

The turbine shaft, illustrated in figure 1–51, is usually fabricated from alloy steel. It must be capable of absorbing the high torque loads that are exerted when a heavy axial-flow compressor is started.

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

The turbine shaft must have some means for attachment to the compressor rotor hub. This is usually accomplished by a spline cut on the forward end of the shaft. The spline fits into a coupling device between the compressor and turbine shafts. If a coupling is not used, the splined end of the turbine shaft may fit into a splined recess in the compressor rotor hub. This splined coupling arrangement is used almost exclusively with centrifugal compressor engines, while the axial compressor engine may use either of these described 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 1–53.

The blades are retained in their respective grooves by a variety of methods; some of the more common ones are peening, welding, locktabs, and riveting. Figure 1–54 shows a typical turbine wheel using rivets for blade retention.

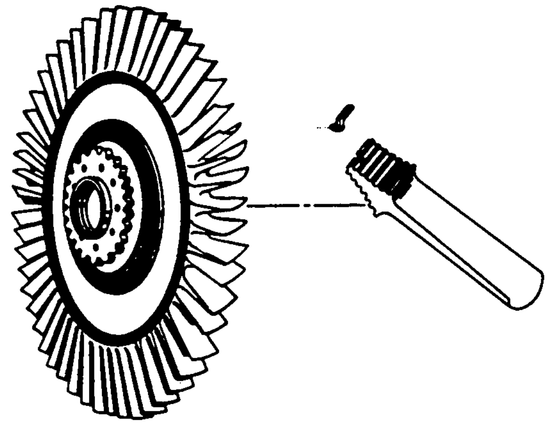


FIGURE 1–53. Turbine blade with fir-tree design and lock-tab method of blade retention.

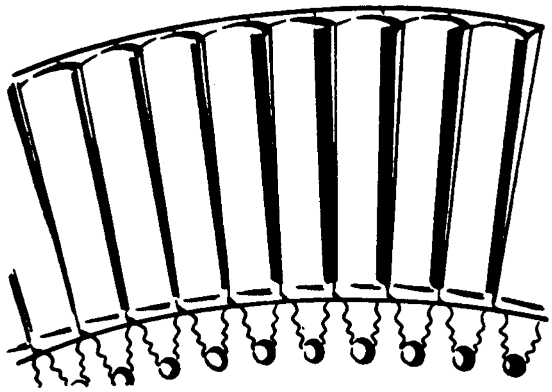


FIGURE 1–54. Riveting method of turbine blade retention.

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

Another method of blade retention is to construct the root of the blade so that it will contain all the elements necessary for its retention. This method, illustrated in figure 1–55, shows that the blade root has a stop made on one end of the root so that the blade can be inserted and removed in one direction only, while on the opposite end is a tang. This tang is bent to secure the blade in the disk.

Turbine blades may be either forged or cast, depending on the composition of the alloys. Most

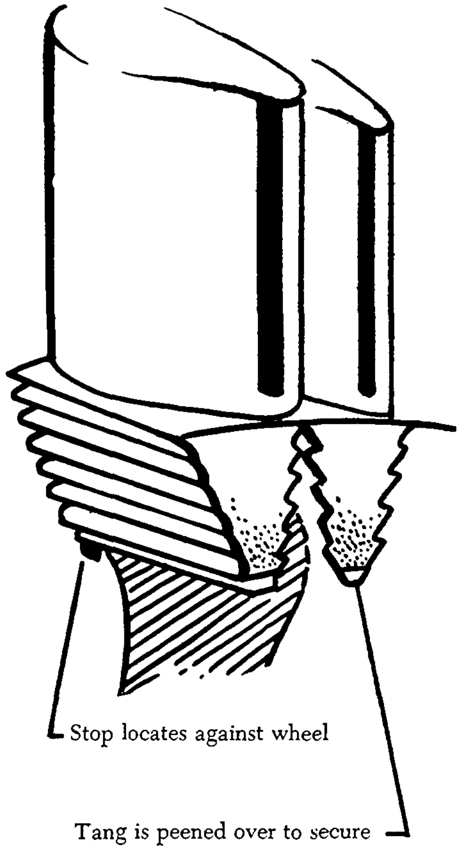


FIGURE 1–55. Turbine bucket, featuring tang method of blade retention.

blades are precision-cast and finish-ground to the desired shape.

Most turbines are open at the outer perimeter of the blades; however, a second type called the shrouded turbine is sometimes used. The shrouded turbine blades, in effect, form a band around the outer perimeter of the turbine wheel. This improves efficiency and vibration characteristics, and permits lighter stage weights; on the other hand, it limits turbine speed and requires more blades (see figure 1–56).

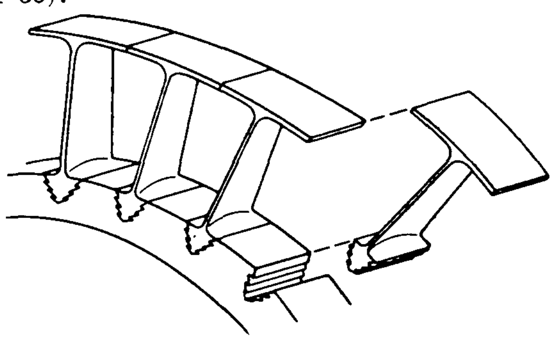


FIGURE 1–56. Shrouded turbine blades.

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

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

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

In the single-stage rotor turbine (figure 1–57), the power is developed by one rotor, and all engine-driven parts are driven by this single wheel. This arrangement is used on engines where the need for low weight and compactness predominates.

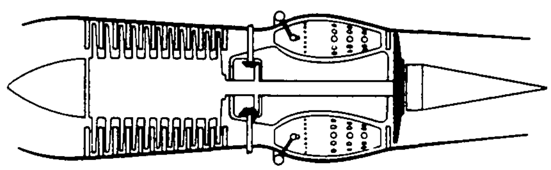


FIGURE 1–57. Single-stage rotor turbine.

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 can 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. (See figure 1–58.)

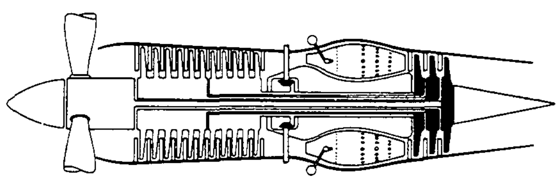


FIGURE 1–58. Multiple-rotor turbine.

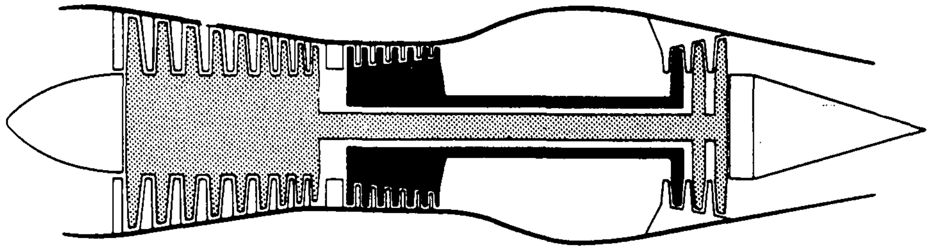


FIGURE 1–59. Dual-rotor turbine for split-spool compressor.

The turbine rotor arrangement for a dual-rotor turbine, such as required for a split-spool compressor, is similar to the arrangement in figure 1–58. The difference is that where the third turbine is used for a propeller in figure 1–58, it would be joined with the second turbine to make a two-stage turbine for driving the front compressor. This arrangement is shown in figure 1–59.

The remaining element to be discussed concerning turbine familiarization is the turbine casing or housing. The turbine casing encloses the turbine wheel and the nozzle vane assembly, and at the same time gives either direct or indirect support to the stator elements of the turbine section. It always has flanges provided front and rear for bolting the assembly to the combustion chamber housing and the exhaust cone assembly, respectively. A turbine casing is illustrated in figure 1–60.

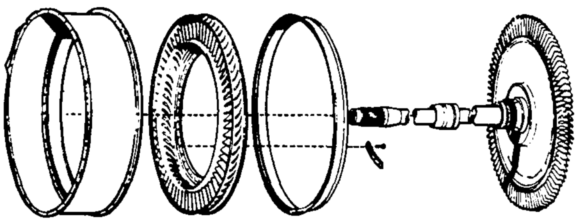


FIGURE 1–60. Turbine casing assembly.

Exhaust Section

The exhaust section of the turbojet engine is made up of several components, each of which has its individual functions. Although the components have individual purposes, they also have one common function: They must direct the flow of hot gases rearward in such a manner as to prevent turbulence and at the same time impart a high final or exit velocity to the gases.

In performing the various functions, each of the components affects the flow of gases in different ways as described in the following paragraphs.

The exhaust section is located directly behind the turbine section and ends when the gases are ejected at the rear in the form of a high-velocity jet. The components of the exhaust section include the exhaust cone, tailpipe (if required), and the exhaust or jet nozzle. Each component is discussed individually.

The exhaust cone collects the exhaust gases discharged from the turbine buckets and gradually converts them into a solid jet. In performing this, the velocity of the gases is decreased slightly and the pressure increased. This is due to the diverging passage between the outer duct and the inner cone; that is, the annular area between the two units increases rearward.

The exhaust cone assembly consists of an outer shell or duct, an inner cone, three or four radial hollow struts or fins, and the necessary number of tie rods to aid the struts in supporting the inner cone from the outer duct.

The outer shell or duct is usually made of stainless steel and is attached to the rear flange of the turbine case. This element collects the exhaust gases and delivers them either directly or via a tailpipe to the jet nozzle, depending, of course, on whether or not a tailpipe is required. In some engine installations a tailpipe is not needed. For instance, when the engine is installed in nacelles or pods, a short tailpipe is all that is required, in which case the exhaust duct and exhaust nozzle will suffice. The duct must be constructed to include such features as a predetermined number of thermocouple bosses for installing tailpipe temperature thermocouples, and there must also be the insertion holes for the supporting tie rods. In some cases, tie rods are not used for supporting the inner cone. If such is the case, the hollow struts provide the sole support of the inner cone, the struts being spot-welded in position to the inside surface of the duct and to the inner cone, respectively (see figure 1–61).

The radial struts actually have a twofold function. They not only support the inner cone in the exhaust

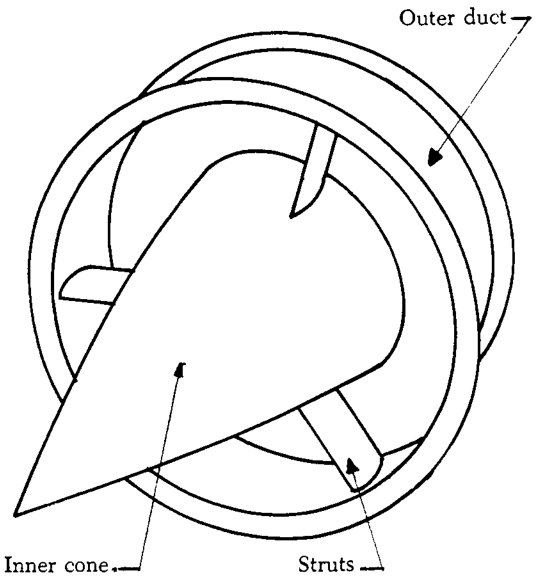


FIGURE 1–61. Exhaust collector with welded support struts.

duct, but they also perform the important function of straightening the swirling exhaust gases that would otherwise leave the turbine at an angle of approximately 45°.

The centrally located inner cone fits rather closely against the rear face of the turbine disk, preventing turbulence of the gases as they leave the turbine wheel. The cone is supported by the radial struts. In some configurations a small hole is located in the exit tip of the cone. This hole allows cooling air to be circulated from the aft end of the cone, where the pressure of the gases is relatively high, into the interior of the cone and consequently against the face of the turbine wheel. The flow of air is positive, since the air pressure at the turbine wheel is relatively low due to rotation of the wheel; thus air circulation is assured. The gases used for cooling the turbine wheel will return to the main path of flow by passing through the clearance between the turbine disk and the inner cone.

The exhaust cone assembly is the terminating component of the basic engine. The remaining components (the tailpipe and jet nozzle) are usually considered airframe components.

The tailpipe is used primarily to pipe the exhaust gases out of the airframe. The use of a 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.

The tailpipe terminates in a jet nozzle located just forward of the end of the fuselage. Most installations use a single direct exhaust as opposed to a dual exit exhaust to obtain the advantages of low-weight, simplicity, and minimum duct losses (see figure 1–62).

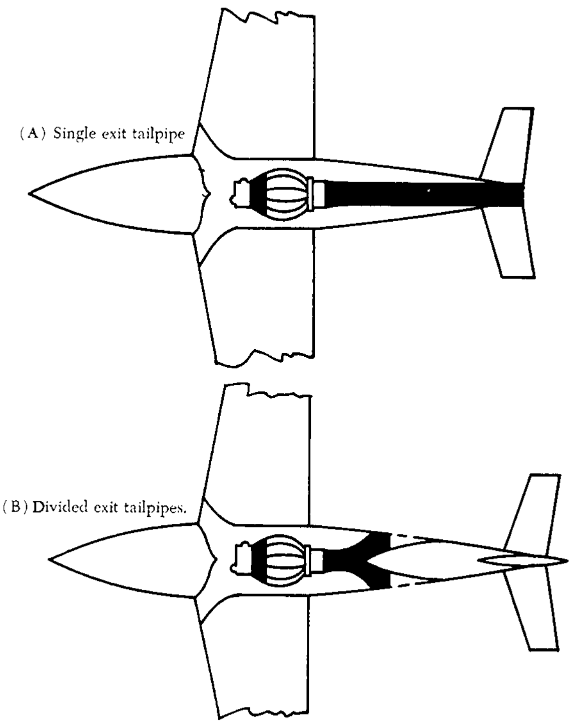


FIGURE 1–62. (A) Single exit tailpipe, (B) Divided exit tailpipes.

The tailpipe is usually constructed so that it is semiflexible. Again the necessity for this feature is dependent on its length. On extremely long tailpipes, a bellows arrangement is incorporated in its construction, allowing movement both in installation and maintenance, and in thermal expansion. This eliminates stress and warping which would otherwise be present.

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

The insulation blanket, illustrated in figures 1–63 and 1–64, consists of several layers of aluminum foil, each separated by a layer of fiber glass or some other suitable material. Although these blankets protect the fuselage from heat radiation, they are primarily used to reduce heat losses from the exhaust system. The reduction of heat losses improves engine performance. A typical insulation blanket

slowly. This breakdown in r.p.m. drop provides a means of pinpointing certain troubles in the ignition system. It can save a lot of time and unnecessary work by confining maintenance to the specific part of the ignition system which is responsible for the trouble.

Fast r.p.m. drop is usually the result of either faulty spark plugs or faulty ignition harness. This is true because faulty plugs or leads take effect at once. The cylinder goes dead or starts firing intermittently the instant the switch is moved from "both" to the "right" or "left" position.

Slow r.p.m. drop usually is caused by incorrect ignition timing or faulty valve adjustment. With late ignition timing, the charge is fired too late with relation to piston travel for the combustion pressures to build up to the maximum at the proper time. The result is a power loss greater than normal for single ignition because of the lower peak pressures obtained in the cylinder. However, this power loss does not occur as rapidly as that which accompanies a dead spark plug. This explains the slow r.p.m. drop as compared to the instantaneous drop with a dead plug or defective lead. Incorrect valve clearances, through their effect on valve overlap, can cause the mixture to be too rich or too lean. The too-rich or too-lean mixture may affect one plug more than another, because of the plug location, and show up as a slow r.p.m. drop on the ignition check.

Cruise Mixture Check

The cruise mixture check is a check of carburetor metering. Checking the carburetor metering characteristics at 200- to 300-r.p.m. intervals, from 800 r.p.m. to the ignition system check speed, gives a complete pattern for the basic carburetor performance.

To perform this test, set up a specified engine speed with the propeller in full low pitch. The first check is made at 800 r.p.m. With the carburetor mixture control in the "automatic-rich" position, read the manifold pressure. With the throttle remaining in the same position, move the mixture control to the "automatic lean" position. Read and record the engine speed and manifold pressure readings. Repeat this check at 1,000, 1,200, 1,500, 1,700, and 2,000 r.p.m. or at the r.p.m.'s specified by the manufacturer. Guard against a sticking instrument by tapping the tachometer.

Moving the mixture control from the "auto-rich" position to the "auto-lean" position checks the cruise mixture. In general, the speed should not increase more than 25 r.p.m. or decrease more than 75 r.p.m. during the change from "auto-rich" to "auto-lean."

For example, suppose that the r.p.m. change is above 100 for the 800 to 1,500 r.p.m. checks; it is obvious that the probable cause is an incorrect idle mixture. When the idle is adjusted properly, carburetion will be correct throughout the range.

Idle Speed and Idle Mixture Checks

Plug fouling difficulty is the inevitable result of failure to provide a proper idle mixture setting. The tendency seems to be to adjust the idle mixture on the extremely rich side and to compensate for this by adjusting the throttle stop to a relatively high r.p.m. for minimum idling. With a properly adjusted idle mixture setting, it is possible to run the engine at idle r.p.m. for long periods. Such a setting will result in a minimum of plug fouling and exhaust smoking and it will pay dividends from the savings on the aircraft brakes after landing and while taxiing.

If the wind is not too strong, the idle mixture setting can be checked easily during the ground check as follows:

(1) Close throttle.

(2) Move the mixture control to the "idle cutoff" position and observe the change in r.p.m. Return the mixture control back to the "rich" position before engine cutoff.

As the mixture control lever is moved into idle cutoff, and before normal dropoff, one of two things may occur momentarily:

(1) The engine speed may increase. An increase in r.p.m., but less than that recommended by the manufacturer (usually 20 r.p.m.), indicates proper mixture strength. A greater increase indicates that the mixture is too rich.

(2) The engine speed may not increase or may drop immediately. This indicates that the idle mixture is too lean.

The idle mixture should be set to give a mixture slightly richer than best power, resulting in a 10- to 20-r.p.m. rise after idle cutoff.

The idle mixture of engines equipped with electric primers can be checked by flicking the primer switch momentarily and noting any change in manifold pressure and r.p.m. A decrease in r.p.m. and an increase in manifold pressure will occur when the primer is energized if the idle mixture is too rich. If the idle mixture is adjusted too lean, the r.p.m. will increase and manifold pressure will decrease.

Two-Speed Supercharger Check

To check the operation of the two-speed blower mechanism, set the engine speed to a sufficiently high r.p.m. to obtain the minimum oil pressure required for clutch operation. Move the supercharger control to the "high" position. A momentary drop in oil pressure should accompany the shift. Open the throttle to obtain not more than 30 in. Hg manifold pressure. When the engine speed has stabilized, observe the manifold pressure, and shift the supercharger control to the "low" position without moving the throttle. A sudden decrease in manifold pressure indicates that the two-speed supercharger drive is functioning properly. If no decrease occurs, the clutch may be inoperative.

As soon as the change in manifold pressure has been checked, reduce the engine speed to 1,000 r.p.m., or less. If the shift of the supercharger did not appear to be satisfactory, operate the engine at 1,000 r.p.m. for 2 or 3 min. to permit heat generated during the shift to dissipate from the clutches, and then repeat the shifting procedure. Blower shifts should be made without hesitation or dwelling between the control positions to avoid dragging or slipping the clutches. Make sure the supercharger control is in the "low" position when the ground check is completed.

Acceleration and Deceleration Checks

The acceleration check is made with the mixture control in both auto-rich and auto-lean. Move the throttle from idle to takeoff smoothly and rapidly. The engine r.p.m. should increase without hesitation and with no evidence of engine backfire.

This check will, in many cases, show up borderline conditions that will not be revealed by any of the other checks. This is true because the high cylinder pressures developed during this check put added strain on both the ignition system and the fuel metering system. This added strain is sufficient to point out certain defects that otherwise go unnoticed. Engines must be capable of rapid acceleration, since in an emergency, such as a go-around during landing, the ability of an engine to accelerate rapidly is sometimes the difference between a successful go-around and a crash landing.

The deceleration check is made while retarding the throttle from the acceleration check. Note the engine behavior. The r.p.m. should decrease smoothly and evenly. There should be little or no tendency for the engine to afterfire.

Engine Stopping

With each type of carburetor installation, specific procedures are used in stopping the engine. The general procedure outlined in the following paragraphs reduces the time required for stopping, minimizes backfiring tendencies, and, most important, prevents overheating of tightly baffled air-cooled engines during operation on the ground.

In stopping any aircraft engine, the controls are set as follows, irrespective of carburetor type or fuel system installation.

(1) Cowl flaps are always placed in the "full open" position to avoid overheating the engine, and are left in that position after the engine is stopped to prevent engine residual heat from deteriorating the ignition system.

(2) Oil cooler shutters should be "full open" to allow the oil temperature to return to normal.

(3) Intercooler shutters are kept in the "full open" position.

(4) Carburetor air-heater control is left in the "cold" position to prevent damage which may occur from backfire.

(5) Turbocharger waste gates are set in the "full open" position.

(6) Two-speed supercharger control is placed in the "low blower" position.

(7) A two-position propeller will usually be stopped with the control set in the "high pitch" (decrease r.p.m.) position. Open the throttle to approximately 1,200 r.p.m. and shift the propeller control to "high pitch" position. Allow the engine to operate approximately 1 minute before stopping, so that the oil dumped into the engine from the propeller may be scavenged and returned to the oil tank. However, to inspect the propeller piston for galling and wear and for other special purposes, this propeller may be stopped with the propeller control in "low pitch" (increase r.p.m.) position when the engine is stopped.

No mention is made of the throttle, mixture control, fuel selector valve, and ignition switches in the preceding set of directions because the operation of these controls varies with the type of carburetor used with the engine.

Engines equipped with a float-type carburetor without an idle cutoff unit are stopped as follows:

(1) Adjust the throttle to obtain an idling speed of approximately 600 to 800 r.p.m., depending on the type of engine.

(2) Close the fuel selector valve.
(3) Open the throttle slowly until the engine is operating at approximately 800 to 1,000 r.p.m.
(4) Observe the fuel pressure. When it drops to zero, turn the ignition switch to the "off" position and simultaneously move the throttle slowly to the "full open" position. This operation will remove the accelerating charge from the induction system and avoid the possibility of accidental starting.
(5) When the engine has stopped, place the fuel selector valve in the "on" position and refill the carburetor and fuel lines by using the auxiliary pump.

An engine equipped with a carburetor incorporating an idle cutoff is stopped as follows:

(1) Idle the engine by setting the throttle for 800 to 1,000 r.p.m.
(2) Move the mixture control to the "idle cutoff" position. In a pressure-type carburetor, this causes the cloverleaf valve to stop the discharge of fuel through the discharge nozzle. In a float-type carburetor, it equalizes the pressure in the float chamber and at the discharge nozzle.
(3) After the propeller has stopped rotating, place the ignition switch in the "off" position.

BASIC ENGINE OPERATING PRINCIPLES

A thorough understanding of the basic principles on which a reciprocating engine operates and the many factors which affect its operation is necessary to diagnose engine malfunctions. Some of these basic principles are reviewed not as a mere repetition of basic theory, but as a concrete, practical discussion of what makes for good or bad engine performance.

The conventional reciprocating aircraft engine operates on the four-stroke-cycle principle. Pressure from burning gases acts upon a piston, causing it to reciprocate back and forth in an enclosed cylinder. This reciprocating motion of the piston is changed into rotary motion by a crankshaft, to which the piston is coupled by means of a connecting rod. The crankshaft, in turn, is attached or geared to the aircraft propeller. Therefore, the rotary motion of the crankshaft causes the propeller to revolve. Thus, the motion of the propeller is a direct result of the forces acting upon the piston as it moves back and forth in the cylinder.

Four strokes of the piston, two up and two down, are required to provide one power impulse to the crankshaft. Each of these strokes is considered an event in the cycle of engine operation. Ignition of the gases (fuel/air mixture) at the end of the second, or compression, stroke makes a fifth event. Thus, the five events which make up a cycle of operation occur in four strokes of the piston.

As the piston moves downward on the first stroke (intake), the intake valve is open and the exhaust valve is closed. As air is drawn through the carburetor gasoline is introduced into the stream of air forming a combustible mixture.

On the second stroke, the intake closes and the combustible mixture is compressed as the piston moves upward. This is the compression stroke.

At the correct instant, an electric spark jumps across the terminals of the spark plug and ignites the fuel/air mixture. The ignition of the fuel/air mixture is timed to occur just slightly before the piston reaches top dead center.

As the mixture burns, temperature and pressure rise rapidly. The pressure reaches maximum just after the piston has passed top center. The expanding and burning gas forces the piston downward, transmitting energy to the crankshaft. This is the power stroke. Both intake and exhaust valves are closed at the start of the power stroke.

Near the end of the power stroke, the exhaust valve opens, and the burned gases start to escape through the exhaust port. On its return stroke, the piston forces out the remaining gases. This stroke, the exhaust stroke, ends the cycle. With the introduction of a new charge through the intake port, the action is repeated and the cycle of events occurs over and over again as long as the engine is in operation.

Ignition of the fuel charge must occur at a specific time in relation to crankshaft travel. The igniting device is timed to ignite the charge just before the piston reaches top center on the compression stroke. Igniting the charge at this point permits maximum pressure to build up at a point slightly after the piston passes over top dead center. For ideal combustion, the point of ignition should vary with engine speed and with degree of compression, mixture strength, and other factors governing the rate of burning. However, certain factors, such as the limited range of operating r.p.m. and the dangers of operating with incorrect spark settings, prohibit the use of variable spark control in most instances. Therefore, most aircraft ignition system units are timed to ignite the fuel/air charge at one fixed position (advanced).

On early models of the four-stroke-cycle engine, the intake valve opened at top center (beginning of the intake stroke). It closed at bottom center (end of intake stroke). The exhaust valve opened at bottom center (end of power stroke) and closed at top center (end of exhaust stroke). More efficient engine operation can be obtained by opening the intake valve several degrees before top center and closing it several degrees after bottom center. Opening the exhaust valve before bottom center, and closing it after top center, also improves engine performance. Since the intake valve opens before top-center exhaust stroke and the exhaust valve closes after top-center intake stroke, there is a period where both the intake and exhaust valves are open at the same time. This is known as valve lap or valve overlap. In valve timing, reference to piston or crankshaft position is always made in terms of before or after the top and bottom center points, *e.g.*, ATC, BTC, ABC, and BBC.

Opening the intake valve before the piston reaches top center starts the intake event while the piston is still moving up on the exhaust stroke. This aids in increasing the volume of charge admitted into the cylinder. The selected point at which the intake valve opens depends on the r.p.m. at which the engine normally operates. At low r.p.m., this early timing results in poor efficiency since the incoming charge is not drawn into and the exhaust gases are not expelled out of the cylinder with sufficient speed to develop the necessary momentum. Also, at low r.p.m. the cylinder is not well scavenged, and residual gases mix with the incoming fuel and are trapped during the compression stroke. Some of the incoming mixture is also lost through the open exhaust port. However, the advantages obtained at normal operating r.p.m. more than make up for the poor efficiency at low r.p.m. Another advantage of this valve timing is the increased fuel vaporization and beneficial cooling of the piston and cylinder.

Delaying the closing of the intake valve takes advantage of the inertia of the rapidly moving fuel/air mixture entering the cylinder. This ramming effect increases the charge over that which would be taken in if the intake valve closed at bottom center (end of intake stroke). The intake valve is actually open during the latter part of the exhaust stroke, all of the intake stroke, and the first part of the compression stroke. Fuel/air mixture is taken in during all this time.

The early opening and late closing of the exhaust valve goes along with the intake valve timing to improve engine efficiency. The exhaust valve opens on the power stroke, several crankshaft degrees before the piston reaches bottom center. This early opening aids in obtaining better scavenging of the burned gases. It also results in improved cooling of the cylinders, because of the early escape of the hot gases. Actually, on aircraft engines, the major portion of the exhaust gases, and the unused heat, escapes before the piston reaches bottom center. The burned gases continue to escape as the piston passes bottom center, moves upward on the exhaust stroke, and starts the next intake stroke. The late closing of the exhaust valve still further improves scavenging by taking advantage of the inertia of the rapidly moving outgoing gases. The exhaust valve is actually open during the latter part of the power stroke, all of the exhaust stroke, and the first part of the intake stroke.

From this description of valve timing, it can be seen that the intake and exhaust valves are open at the same time on the latter part of the exhaust stroke and the first part of the intake stroke. During this valve overlap period, the last of the burned gases are escaping through the exhaust port while the fresh charge is entering through the intake port.

Many aircraft engines are supercharged. Supercharging increases the pressure of the air or fuel/air mixture before it enters the cylinder. In other words, the air or fuel/air mixture is forced into the cylinder rather than being drawn in. Supercharging increases engine efficiency and makes it possible for an engine to maintain its efficiency at high altitudes. This is true because the higher pressure packs more charge into the cylinder during the intake event. This increase in weight of charge results in corresponding increase in power. In addition, the higher pressure of the incoming gases more forcibly ejects the burned gases out through the exhaust port. This results in better scavenging of the cylinder.

Combustion Process

Normal combustion occurs when the fuel/air mixture ignites in the cylinder and burns progressively at a fairly uniform rate across the combustion chamber. When ignition is properly timed, maximum pressure is built up just after the piston has passed top dead center at the end of the compression stroke.

The flame fronts start at each spark plug and burn in more or less wavelike forms (figure 10–32). The velocity of the flame travel is influenced by the type of fuel, the ratio of the fuel/air mixture, and the pressure and temperature of the fuel mixture. With normal combustion, the flame travel is about 100 ft./sec. The temperature and pressure within the cylinder rises at a normal rate as the fuel/air mixture burns.

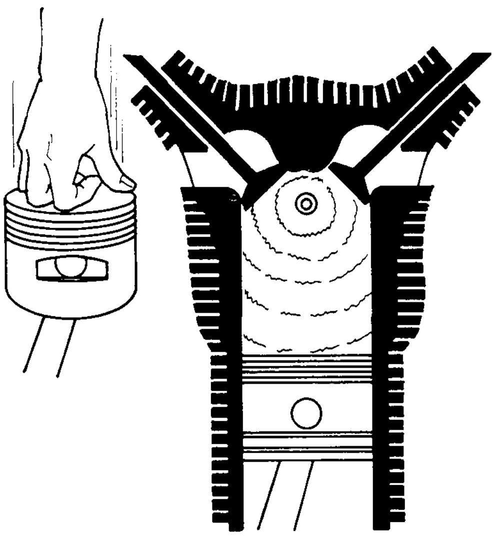


FIGURE 10–32. Normal combustion within a cylinder.

There is a limit, however, to the amount of compression and the degree of temperature rise that can be tolerated within an engine cylinder and still permit normal combustion. All fuels have critical limits of temperature and compression. Beyond this limit, they will ignite spontaneously and burn with explosive violence. This instantaneous and explosive burning of the fuel/air mixture or, more accurately, of the latter portion of the charge, is called detonation.

As previously mentioned, during normal combustion the flame fronts progress from the point of ignition across the cylinder. These flame fronts compress the gases ahead of them. At the same time, the gases are being compressed by the upward movement of the piston. If the total compression on the remaining unburned gases exceeds the critical point, detonation occurs. Detonation (figure 10–33) then, is the spontaneous combustion of the unburned charge ahead of the flame fronts after ignition of the charge.

The explosive burning during detonation results in an extremely rapid pressure rise. This rapid pressure rise and the high instantaneous temperature, combined with the high turbulence generated,

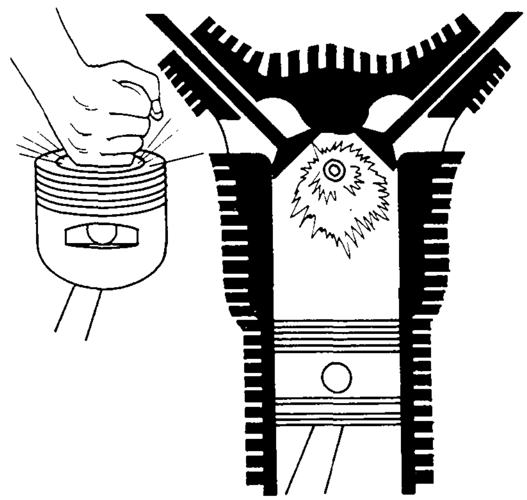


FIGURE 10–33. Detonation within a cylinder.

cause a "scrubbing" action on the cylinder and the piston. This can burn a hole completely through the piston.

The critical point of detonation varies with the ratio of fuel to air in the mixture. Therefore, the detonation characteristic of the mixture can be controlled by varying the fuel/air ratio. At high power output, combustion pressures and temperatures are higher than they are at low or medium power. Therefore, at high power the fuel/air ratio is made richer than is needed for good combustion at medium or low power output. This is done because, in general, a rich mixture will not detonate as readily as a lean mixture.

Unless detonation is heavy, there is no cockpit evidence of its presence. Light to medium detonation does not cause noticeable roughness, temperature increase, or loss of power. As a result, it can be present during takeoff and high-power climb without being known to the crew.

In fact, the effects of detonation are often not discovered until after teardown of the engine. When the engine is overhauled, however, the presence of severe detonation during its operation is indicated by dished piston heads, collapsed valve heads, broken ring lands, or eroded portions of valves, pistons, or cylinder heads.

The basic protection from detonation is provided in the design of the engine carburetor setting, which automatically supplies the rich mixtures required for detonation suppression at high power; the rating limitations, which include the maximum operating temperatures; and selection of the correct grade of fuel. The design factors, cylinder cooling, magneto timing, mixture distribution, supercharging, and carburetor setting are taken care of in the design and development of the engine and its method of installation in the aircraft.

The remaining responsibility for prevention of detonation rests squarely in the hands of the ground and flight crews. They are responsible for observance of r.p.m. and manifold pressure limits. Proper use of supercharger and fuel mixture, and maintenance of suitable cylinder head and carburetor-air temperatures are entirely in their control.

Pre-ignition, as the name implies, means that combustion takes place within the cylinder before the timed spark jumps across the spark plug terminals. This condition can often be traced to excessive carbon or other deposits which cause local hot spots. Detonation often leads to pre-ignition. However, pre-ignition may also be caused by high-power operation on excessively lean mixtures. Pre-ignition is usually indicated in the cockpit by engine roughness, backfiring, and by a sudden increase in cylinder head temperature.

Any area within the combustion chamber which becomes incandescent will serve as an igniter in advance of normal timed ignition and cause combustion earlier than desired. Pre-ignition may be caused by an area roughened and heated by detonation erosion. A cracked valve or piston, or a broken spark plug insulator may furnish a hot point which serves as a "glow plug."

The hot spot can be caused by deposits on the chamber surfaces resulting from the use of leaded fuels. Normal carbon deposits can also cause pre-ignition. Specifically, pre-ignition is a condition similar to early timing of the spark. The charge in the cylinder is ignited before the required time for normal engine firing. However, do not confuse pre-ignition with the spark which occurs too early in the cycle. Pre-ignition is caused by a hot spot in the combustion chamber, not by incorrect ignition timing. The hot spot may be due to either an overheated cylinder or a defect within the cylinder.

The most obvious method of correcting pre-ignition is to reduce the cylinder temperature. The immediate step is to retard the throttle. This reduces the amount of fuel charge and the amount of heat generated. If a supercharger is in use and is in high ratio, it should be returned to low ratio to lower the charge temperature. Following this, the mixture should be enriched, if possible, to lower combustion temperature.

If the engine is at high power when pre-ignition occurs, retarding the throttle for a few seconds may provide enough cooling to chip off some of the lead, or other deposit, within the combustion chamber. These chipped-off particles pass out through the exhaust. They are visible at night as a shower of sparks. If retarding the throttle does not permit a return to uninterrupted normal power operation, deposits may be removed by a sudden cooling shock treatment. Such treatments are water injection, alcohol from the deicing system, full-cold carburetor air, or any other method that provides sudden cooling to the cylinder chamber.

Backfiring

When a fuel/air mixture does not contain enough fuel to consume all the oxygen, it is called a lean mixture. Conversely, a charge that contains more fuel than required is called a rich mixture. An extremely lean mixture either will not burn at all or will burn so slowly that combustion is not complete at the end of the exhaust stroke. The flame lingers in the cylinder and then ignites the contents in the intake manifold or the induction system when the intake valve opens. This causes an explosion known as backfiring, which can damage the carburetor and other parts of the induction system.

A point worth stressing is that backfiring rarely involves the whole engine. Therefore, it is seldom the fault of the carburetor. In practically all cases, backfiring is limited to one or two cylinders. Usually it is the result of faulty valve clearance setting, defective fuel injector nozzles, or other conditions which cause these cylinders to operate leaner than the engine as a whole. There can be no permanent cure until these defects are discovered and corrected. Because these backfiring cylinders will fire intermittently and therefore run cool, they can be detected by the cold cylinder check. The cold cylinder check is discussed later in this chapter.

In some instances, an engine backfires in the idle range, but operates satisfactorily at medium and high power settings. The most likely cause, in this case, is an excessively lean idle mixture. Proper adjustment of the idle fuel/air mixture usually corrects this difficulty.

Afterfiring

Afterfiring, sometimes called afterburning, often results when the fuel/air mixture is too rich. Overly rich mixtures are also slow burning. Therefore, charges of unburned fuel are present in the exhausted gases. Air from outside the exhaust stacks mixes with this unburned fuel which ignites. This causes an explosion in the exhaust system. Afterfiring is perhaps more common where long exhaust ducting retains greater amounts of unburned charges. As in the case of backfiring, the correction for afterfiring is the proper adjustment of the fuel/air mixture.

Afterfiring can also be caused by cylinders which are not firing because of faulty spark plugs, defective fuel-injection nozzles, or incorrect valve clearance. The unburned mixture from these dead cylinders passes into the exhaust system, where it ignites and burns. Unfortunately, the resultant torching or afterburning can easily be mistaken for evidence of a rich carburetor. Cylinders which are firing intermittently can cause a similar effect. Again, the malfunction can be remedied only by discovering the real cause and correcting the defect. Either dead or intermittent cylinders can be located by the cold cylinder check.

FACTORS AFFECTING ENGINE OPERATION

Compression

To prevent loss of power, all openings to the cylinder must close and seal completely on the compression and power strokes. In this respect, there are three items in the proper operation of the cylinder that must be right for maximum efficiency. First, the piston rings must be in good condition to provide maximum sealing during the stroke of the piston. There must be no leakage between the piston and the walls of the combustion chamber. Second, the intake and exhaust valves must close tightly so that there will be no loss of compression at these points. Third, and very important, the timing of the valves must be such that highest efficiency is obtained when the engine is operating at its normal rated r.p.m. A failure at any of these points results in greatly reduced engine efficiency.

Fuel Metering

The induction system is the distribution and fuel metering part of the engine. Obviously, any defect in the induction system seriously affects engine operation. For best operation, each cylinder of the engine must be provided with the proper fuel/air mixture, usually metered by the carburetor. On some fuel-injection engines, fuel is metered by the fuel injector flow divider and fuel-injection nozzles.

The relation between fuel/air ratio and power is illustrated in figure 10–34. Note that, as the fuel mixture is varied from lean to rich, the power output of the engine increases until it reaches a maximum. Beyond this point, the power output falls off as the mixture is further enriched. This is because the fuel mixture is now too rich to provide perfect combustion. Note that maximum engine power can be obtained by setting the carburetor for one point on the curve.

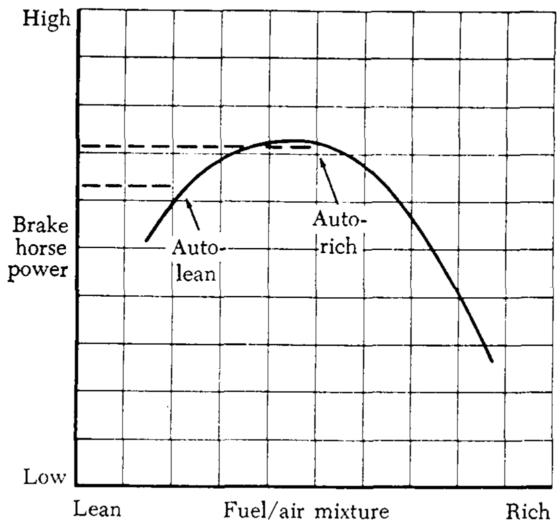


FIGURE 10–34. Power versus fuel/air mixture curve.

In establishing the carburetor settings for an aircraft engine, the design engineers run a series of curves similar to the one shown. A curve is run for each of several engine speeds. If, for example, the idle speed is 600 r.p.m., the first curve might be run at this speed. Another curve might be run at 700 r.p.m., another at 800 r.p.m., and so on, in 100-r.p.m. increments, up to takeoff r.p.m. The points of maximum power on the curves are then joined to obtain the best-power curve of the engine for all speeds. This best-power curve establishes the automatic rich setting of the carburetor.

In establishing the detailed engine requirements regarding carburetor setting, the fact that the cylinder head temperature varies with fuel/air ratio must be considered. This variation is illustrated in the curve shown in figure 10–35. Note that the cylinder head temperature is lower with the auto-lean setting than it is with the auto-rich mixture. This is exactly opposite common belief, but it is true. Furthermore, knowledge of this fact can be used to advantage by flight crews. If, during cruise, it becomes difficult to keep the cylinder head temperature within limits, the fuel/air mixture may be leaned out to get cooler operation. The desired cooling can then be obtained without going to auto-rich with its costly waste of fuel. The curve shows only the variation in cylinder head temperature. For a given r.p.m., the power output of the engine is less with the best-economy setting (auto-lean) than with the best-power mixture.

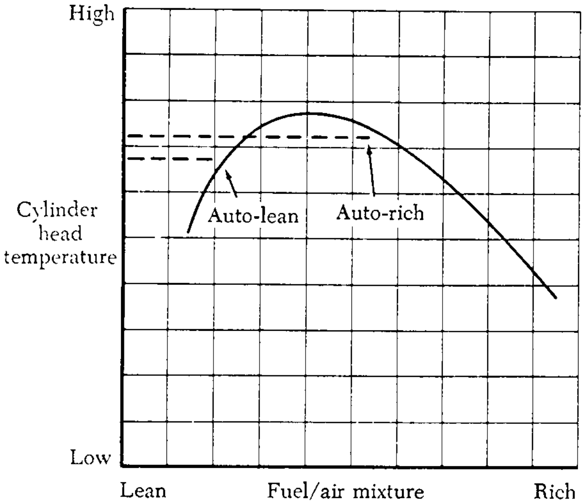


FIGURE 10–35. Variation in head temperature with fuel/air mixture (cruise power).

The decrease in cylinder head temperature with a leaner mixture holds true only through the normal cruise range. At higher power settings, cylinder temperatures are higher with the leaner mixtures. The reason for this reversal hinges on the cooling ability of the engine. As higher powers are approached, a point is reached where the airflow around the cylinders will not provide sufficient cooling. At this point, a secondary cooling method must be used. This secondary cooling is done by enriching the fuel/air mixture beyond the best-power point. Although enriching the mixture to this extent results in a power loss, both power and economy must be sacrificed for engine cooling purposes.

To further investigate the influence of cooling requirements on fuel/air mixture, the effects of water injection must be examined. Figure 10–36 shows a fuel/air curve for a water-injection engine. The dotted portion of the curve shows how the fuel/air mixture is leaned out during water injection. This leaning is possible because water, rather than extra fuel, is used as a cylinder coolant.

This permits leaning out to approximately best-power mixture without danger of overheating or

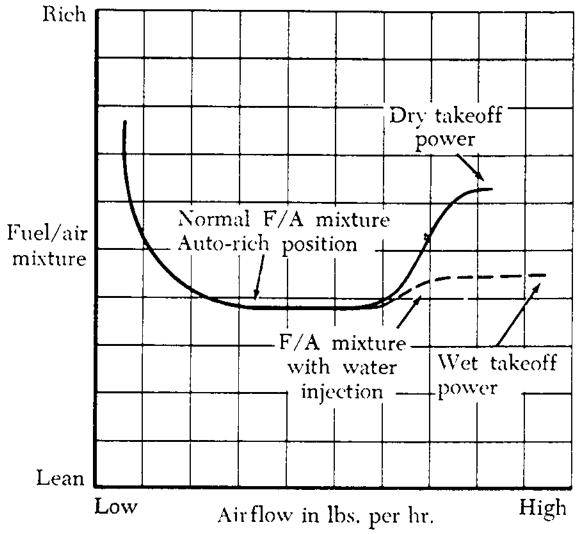


FIGURE 10–36. Fuel/air curve for a water-injection engine.

detonation. This leaning out gives an increase in power. The water does not alter the combustion characteristics of the mixture. Fuel added to the auto-rich mixture in the power range during "dry" operation is solely for cooling. A leaner mixture would give more power.

Actually, water or, more accurately, the antidetonant (water/alcohol) mixture is a better coolant than extra fuel. Therefore, water injection permits higher manifold pressures and a still further increase in power.

In establishing the final curve for engine operation, the engine's ability to cool itself at various power settings is, of course, taken into account. Sometimes the mixture must be altered for a given installation to compensate for the effect of cowl design, cooling airflow, or other factors on engine cooling.

The final fuel/air mixture curves take into account economy, power, engine cooling, idling characteristics, and all other factors which affect combustion.

The chart in figure 10–37 shows a typical final curve for injection-type carburetors. Note that the fuel/air mixture at idle and at takeoff power is the same in auto-rich and auto-lean. Beyond idle, a gradual spread occurs as cruise power is approached. This spread is maximum in the cruise range. The spread decreases toward takeoff power. This spread between the two curves in the cruise range is the basis for the cruise metering check.

Figure 10–38 shows a typical final curve for a float-type carburetor. Note that the fuel/air mixture at idle is the same in rich and in manual lean.

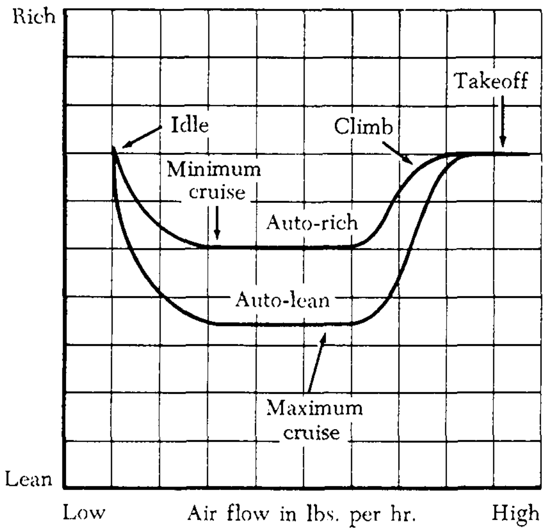


FIGURE 10–37. Typical fuel/air mixture curve for injection-type carburetor.

The mixture remains the same until the low cruise range is reached. At this point, the curves separate and then remain parallel through the cruise and power ranges.

Note the spread between the rich and lean setting in the cruise range of both curves. Because of this spread, there will be a decrease in power when the mixture control is moved from auto-rich to auto-lean with the engine operating in the cruise range. This is true because the auto-rich setting in the cruise range is very near the best-power mixture ratio. Therefore, any leaning out will give a mixture which is leaner than best power.

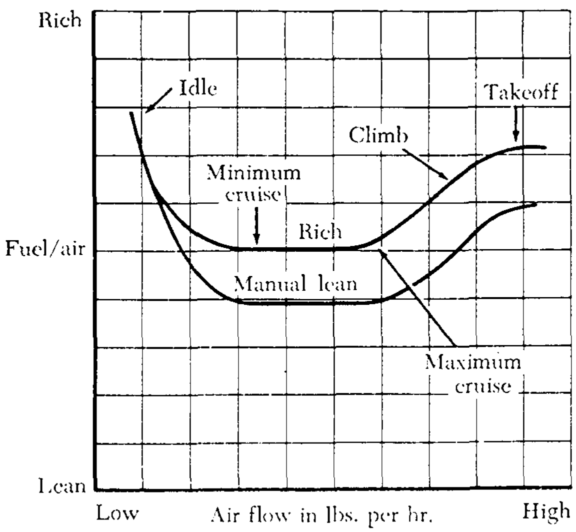


FIGURE 10–38. Typical fuel/air mixture curve for float-type carburetor.

Idle Mixture

The idle mixture curve (figure 10–39) shows how the mixture changes when the idle mixture adjustment is changed. Note that the greatest effect is at idling speeds. However, there is some effect on the mixture at airflows above idling. The airflow at which the idle adjustment effect cancels out varies from minimum cruise to maximum cruise. The exact point depends on the type of carburetor and the carburetor setting. In general, the idle adjustment affects the fuel/air mixture up to medium cruise on most engines having pressure-injection-type carburetors, and up to low cruise on engines equipped with float-type carburetors. This means that incorrect idle mixture adjustments can easily give faulty cruise performance as well as poor idling.

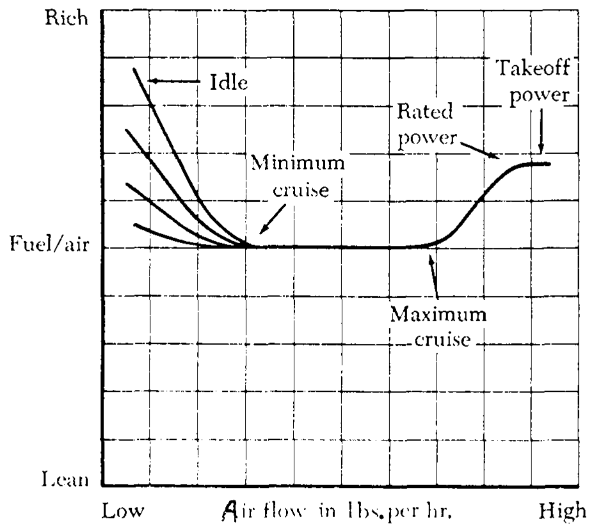


FIGURE 10–39. Idle mixture curve.

There are variations in mixture requirements between one engine and another because of the fuel distribution within the engine and the ability of the engine to cool. Remember that a carburetor setting must be rich enough to supply a combustible mixture for the leanest cylinder. If fuel distribution is poor, the overall mixture must be richer than would be required for the same engine if distribution were good. The engine's ability to cool depends on such factors as cylinder design (including the design of the cooling fins), compression ratio, accessories on the front of the engine which cause individual cylinders to run hot, and the design of the baffling used to deflect airflow around the cylinder. At takeoff power, the mixture must be rich enough to supply sufficient fuel to keep the hottest cylinder cool.

The Induction Manifold

The induction manifold provides the means of distributing air, or the fuel/air mixture, to the cylinders. Whether the manifold handles a fuel/air mixture or air alone depends on the type of fuel metering system used. On an engine equipped with a carburetor, the induction manifold distributes a fuel/air mixture from the carburetor to the cylinders. On a fuel-injection engine, the fuel is delivered to injection nozzles, one in each cylinder, which provide the proper spray pattern for efficient burning. Thus, the mixing of fuel and air takes place in the cylinders or at the inlet port to the cylinder. On a fuel-injection engine the induction manifold handles only air.

The induction manifold is an important item because of the effect it can have on the fuel/air mixture which finally reaches the cylinder. Fuel is introduced into the airstream by the carburetor in a liquid form. To become combustible, the fuel must be vaporized in the air. This vaporization takes place in the induction manifold, which includes the internal supercharger if one is used. Any fuel that does not vaporize will cling to the walls of the intake pipes. Obviously, this affects the effective fuel/air ratio of the mixture which finally reaches the cylinder in vapor form. This explains the reason for the apparently rich mixture required to start a cold engine. In a cold engine, some of the fuel in the airstream condenses out and clings to the walls of the manifold. This is in addition to that fuel which never vaporized in the first place. As the engine warms up, less fuel is required because less fuel is condensed out of the airstream and more of the fuel is vaporized, thus giving the cylinder the required fuel/air mixture for normal combustion.

Any leak in the induction system has an effect on the mixture reaching the cylinders. This is particularly true of a leak at the cylinder end of an intake pipe. At manifold pressures below atmospheric pressure, such a leak will lean out the mixture. This occurs because additional air is drawn in from the atmosphere at the leaky point. The affected cylinder may overheat, fire intermittently, or even cut out altogether.

Operational Effect of Valve Clearance

While considering the operational effect of valve clearance, keep in mind that all aircraft reciprocating engines of current design use valve overlap.

Figure 10–40 shows the pressures at the intake and exhaust ports under two different sets of operating conditions. In one case, the engine is operating at a manifold pressure of 35 in. Hg. Barometric pressure (exhaust back pressure) is 29 in. Hg. This gives a pressure differential of 6 in. Hg (3 p.s.i.) acting in the direction indicated by the arrow.

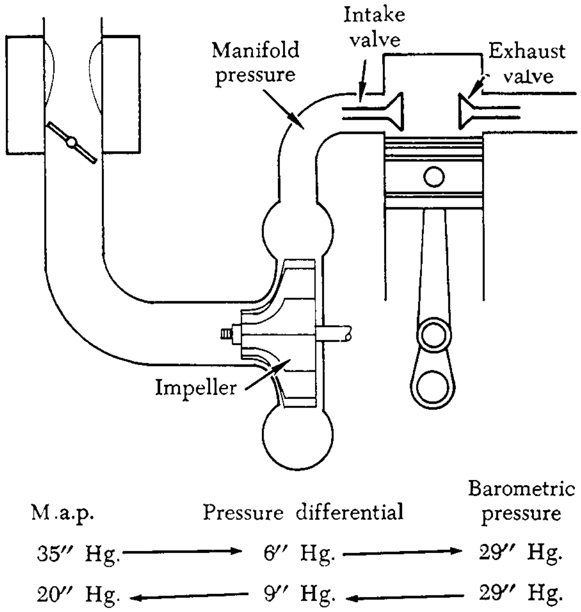


FIGURE 10–40. Effect of valve overlap.

During the valve overlap period, this pressure differential forces the fuel/air mixture across the combustion chamber toward the open exhaust. This flow of fuel/air mixture forces ahead of it the exhaust gases remaining in the cylinder, resulting in complete scavenging of the combustion chamber. This, in turn, permits complete filling of the cylinder with a fresh charge on the following intake event. This is the situation in which valve overlap gives increased power.

In a situation where the manifold pressure is below atmospheric pressure, 20 in. Hg, for example, there is a pressure differential of 9 in. Hg (4.5 p.s.i.) in the opposite direction. This causes air or exhaust gas to be drawn into the cylinder through the exhaust port during valve overlap.

In engines with collector rings, this inflow through the exhaust port at low power settings consists of burned exhaust gases. These gases are pulled back into the cylinder and mix with the incoming fuel/air mixture. However, these exhaust gases are inert; they do not contain oxygen. Therefore, the fuel/air mixture ratio is not affected much. With open exhaust stacks, the situation is entirely different. Here, fresh air containing oxygen is pulled into the cylinders through the exhaust. This leans out the mixture. Therefore, the carburetor must be set to deliver an excessively rich idle mixture so that, when this mixture is combined with the fresh air drawn in through the exhaust port, the effective mixture in the cylinder will be at the desired ratio.

At first thought, it does not appear possible that the effect of valve overlap on fuel/air mixture is sufficient to cause concern. However, the effect of valve overlap becomes apparent when considering idle fuel/air mixtures. These mixtures must be enriched 20 to 30% when open stacks instead of collector rings are used on the same engine. This is shown graphically in figure 10–41. Note the spread at idle between an open stack and an exhaust collector ring installation for engines that are otherwise identical. The mixture variation decreases as the engine speed or airflow is increased from idle into the cruise range.

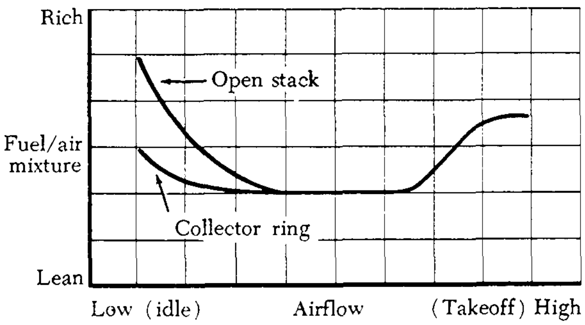


FIGURE 10–41. Comparison of fuel/air mixture curves for open stack and collector ring installations.

Engine, airplane, and equipment manufacturers provide a powerplant installation that will give satisfactory performance. Cams are designed to give best valve operation and correct overlap. But valve operation will be correct only if valve clearances are set and remain at the value recommended by the engine manufacturer. If valve clearances are set wrong, the valve overlap period will be longer or shorter than the manufacturer intended. The same is true if clearances get out of adjustment during operation.

Where there is too much valve clearance, the valves will not open as wide or remain open as long as they should. This reduces the overlap period. At idling speed, it will affect the fuel/air mixture, since a less-than-normal amount of air or exhaust gases will be drawn back into the cylinder during the shortened overlap period. As a result, the idle mixture will tend to be too rich.

When valve clearance is less than it should be, the valve overlap period will be lengthened. This permits a greater-than-normal amount of air or exhaust gases to be drawn back into the cylinder at idling speeds. As a result, the idle mixture will be leaned out at the cylinder. The carburetor is adjusted with the expectation that a certain amount of air or exhaust gases will be drawn back into the cylinder at idling. If more or less air or exhaust gases are drawn into the cylinder during the valve overlap period, the mixture will be too lean or too rich.

When valve clearances are wrong, it is unlikely that they will all be wrong in the same direction. Instead, there will be too much clearance on some cylinders and too little on others. Naturally, this gives a variation in valve overlap between cylinders. This, in turn, results in a variation in fuel/air ratio at idling and lower-power settings, since the carburetor delivers the same mixture to all cylinders. The carburetor cannot tailor the mixture to each cylinder to compensate for variation in valve overlap.

The effect of variation in valve clearance and valve overlap on the fuel/air mixture between cylinders is illustrated in figure 10–42. Note how the cylinders with too little clearance run rich and those with too much clearance run lean. Note also the extreme mixture variation between cylinders. On such an engine, it would be impossible to set the idle adjustment to give correct mixtures on all cylinders, nor can all cylinders of such an engine be expected to produce the same power. Variations in valve clearance of as little as 0.005 in. have a definite effect on mixture distribution between cylinders.

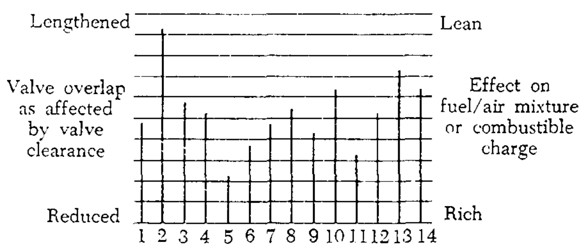


FIGURE 10–42. Effect of variation in valve overlap on fuel/air mixture between cylinders.

Another aspect of valve clearance is its effect on volumetric efficiency. Considering the intake valve first, suppose valve clearance is greater than that specified. As the cam lobe starts to pass under the cam roller, the cam step or ramp takes up part of this clearance. However, it doesn't take up all the clearance as it should. Therefore, the cam roller is well up on the lobe proper before the valve starts to open. As a result, the valve opens later than it should. In a similar way, the valve closes before the roller has passed from the main lobe to the ramp at its end. With excessive clearance, then, the intake valve opens late and closes early. This produces a throttling effect on the cylinder. The valve is not open long enough to admit a full charge of fuel and air. This will cut down the power output, particularly at high-power settings.

Insufficient intake valve clearance has the opposite effect. The clearance is taken up and the valve starts to open while the cam roller is still on the cam step. The valve doesn't close until the riser at the end of the lobe has almost completely passed under the roller. Therefore, the intake valve opens early, closes late, and stays open longer than it should. At low power, early opening of the intake valve can cause backfiring because of the hot exhaust gases backing out into the intake manifold and igniting the mixture there.

Excessive exhaust valve clearance causes the exhaust valve to open late and close early. This shortens the exhaust event and causes poor scavenging. The late opening may also lead to cylinder overheating. The hot exhaust gases are held in the cylinder beyond the time specified for their release.

When exhaust valve clearance is insufficient, the valve opens early and closes late. It remains open longer than it should. The early opening causes a power loss by shortening the power event. The pressure in the cylinder is released before all the useful expansion has worked on the piston. The late closing causes the exhaust valve to remain open during a larger portion of the intake stroke than it should. This may result in good mixture being lost through the exhaust port.

As mentioned before, there will probably be too little clearance on some cylinders and too much on others whenever valve clearances are incorrect. This means that the effect of incorrect clearances on volumetric efficiency will usually vary from cylinder to cylinder. One cylinder will take in a full charge while another receives only a partial charge. As a result, cylinders will not deliver equal power. One cylinder will backfire or run hot while another performs satisfactorily.

On some direct fuel-injection engines, variations in valve clearance will affect only the amount of air taken into the cylinders. This is true when the induction manifold handles only air. In this case there will be no appreciable effect on the distribution of fuel to the individual cylinders. This means that, when clearances vary between cylinders, air charges will also vary but fuel distribution will be uniform. This faulty air distribution, coupled with proper fuel distribution, will cause variations in mixture ratio.

In all cases, variations in valve clearance from the value specified have the effect of changing the valve timing from that obtained with correct clearance. This is certain to give something less than perfect performance.

Ignition System

The next item to be considered regarding engine operation is the ignition system. Although basically simple, it is sometimes not understood clearly.

An ignition system consists of four main parts:

(1) The basic magneto.

(2) The distributor.

(3) The ignition harness.

(4) The spark plug.

The basic magneto is a high-voltage generating device. It must be adjusted to give maximum voltage at the time the points break and ignition occurs. It must also be synchronized accurately to the firing position of the engine. The magneto generates a series of peak voltages which are released by the opening of the breaker points. A distributor is necessary to distribute these peak voltages from the magneto to the cylinders in the proper order. The ignition harness constitutes the insulated and shielded high-tension lines which carry the high voltages from the distributor to the spark plugs.

The magnetos used on aircraft engines are capable of developing voltages as high as 15,000 volts. The voltage required to jump the specified gap in a spark plug will usually be about 4,000 to 5,000 volts maximum. The spark plugs serve as safety valves to limit the maximum voltage in the entire ignition system. As spark plug gaps open up as a result of erosion, the voltage at the plug terminals increases. A higher voltage is required to jump the larger gap. This higher voltage is transmitted through the secondary circuit. The increased voltage in the circuit becomes a hazard. It is a possible source of breakdown in the ignition harness and can cause flashover in the distributor.

The distributor directs the firing impulses to the various cylinders. It must be timed properly to both the engine and the magneto. The distributor finger must align with the correct electrode on the distributor block at the time the magneto points break. Any misalignment may cause the high voltage to jump to a cylinder other than the one intended. This will cause severe backfiring and general malfunctioning of the engine.

The manufacturer has selected the best compromise and specified an alignment with the No. 1 electrode for timing. However, even with perfect distributor timing, the finger is behind on some electrodes and ahead on others. For a few electrodes (cylinders), the alignment is as far from perfect as it can safely be. A slight error in timing, added to this already imperfect alignment, may put the finger so far from the electrode that the high voltage will not jump from finger to electrode, or the high voltage may be routed to the wrong cylinder. Therefore, the distributor must be timed perfectly. The finger must be aligned with the No. 1 electrode exactly as prescribed in the maintenance manual for the particular engine and airplane.

Although the ignition harness is simple, it is a critical part of the ignition system. A number of things can cause failure in the ignition harness. Insulation may break down on a wire inside the harness and allow the high voltage to leak through to the shielding (and to ground), instead of going to the spark plug. Open circuits may result from broken wires or poor connections. A bare wire may be in contact with the shielding, or two wires may be shorted together.

Any serious defect in an individual lead prevents the high voltage impulse from reaching the spark plug to which the lead is connected. As a result, only one spark plug in the cylinder will fire. This causes the cylinder to operate on single ignition. This is certain to result in detonation, since dual ignition is required to prevent detonation at takeoff and during other high-power operation. Two bad leads to the same cylinder will cause the cylinder to go completely dead. On engines with separate distributors, a faulty magneto-to-distributor lead can cut out half the ignition system.

Among the most common ignition harness defects, and the most difficult to detect, are high-voltage leaks. However, a complete harness check will reveal these and other defects.

Although the spark plug is simple both in construction and in operation, it is, nevertheless, the direct or indirect cause of a great many malfunctions encountered in aircraft engines. Proper precaution begins with plug selection. Be sure to select and install the plug specified for the particular engine. One of the reasons a particular plug is specified is its heat range. The heat range of the spark plug determines the temperature at which the nose end of the plug operates. It also affects the ability of the spark plug to ignite mixtures which are borderline from the standpoint of high oil content or excessive richness or leanness.

A great many troubles attributed to spark plugs are the direct result of malfunctions somewhere else in the engine. Some of these are excessively rich idle mixtures, improperly adjusted valves, and impeller oil seal leaks.

Propeller Governor

The final item to be considered regarding engine operation is the effect of the propeller governor on engine operation. In the curve shown in figure 10–43, note that the manifold pressure change with r.p.m. is gradual until the propeller governor cut-in speed is reached. Beyond this point, the manifold pressure increases, but no change occurs in the engine r.p.m. as the carburetor throttle is opened wider.

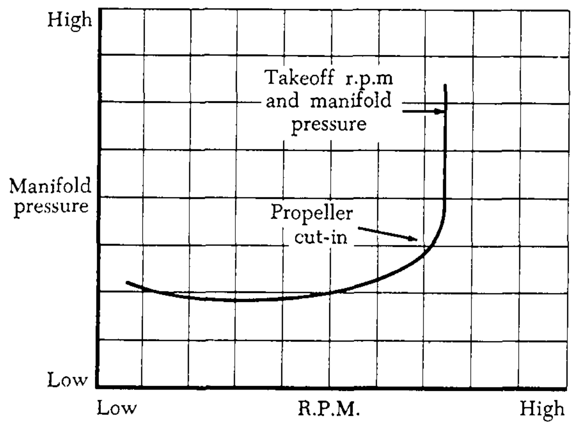


FIGURE 10–43. Effect of propeller governor on manifold pressure.

A true picture of the power output of the engine can be determined only at speeds below the propeller governor cut-in speed. The propeller governor is set to maintain a given engine r.p.m. Therefore, the relationship between engine speed and manifold pressure as an indication of power output is lost, unless it is known that all cylinders of the engine are functioning properly.

In fact, on a multi-engine aircraft, an engine can fail and still produce every indication that it is developing power. The propeller governor will flatten out the propeller blade angle and windmill the propeller to maintain the same engine r.p.m. Heat of compression within the cylinder will prevent the cylinder head temperature from falling rapidly. The fuel pressure will remain constant and the fuel flow will not change unless the manifold pressure is changed. On an engine not equipped with a turbocharger, the manifold pressure will remain where it was. On a turbocharged engine, the manifold pressure will not drop below the value which the mechanical supercharger can maintain. This may be well above atmospheric pressure, depending upon the blower ratio of the engine and the specific conditions existing. Thus, the pilot has difficulty in recognizing that he has encountered a sudden failure unless the engines are equipped with torquemeters, or he notices the fluctuation in r.p.m. at the time the engine cuts out.

Overlapping Phases of Engine Operation

Up to this point, the individual phases of engine operation have been discussed. The relationship of the phases and their combined effect on engine operation will now be considered. Combustion within the cylinder is the result of fuel metering, compression, and ignition. Since valve overlap affects fuel metering, proper combustion in all the cylinders involves correct valve adjustment in addition to the other phases. When all conditions are correct, there is a burnable mixture. When ignited, this mixture will give power impulses of the same intensity from all cylinders.

The system which ignites the combustible mixture requires that the following five conditions occur simultaneously if the necessary spark impulse is to be delivered to the cylinder at the proper time:

(1) The breaker points must be timed accurately to the magneto (E-gap).

(2) The magneto must be timed accurately to the engine.

(3) The distributor finger must be timed accurately to the engine and the magneto.

(4) The ignition harness must be in good condition with no tendency to flashover.

(5) The spark plug must be clean, have no tendency to short out, and have the proper electrode gap.

If any one of these requirements is lacking or if any one phase of the ignition system is maladjusted or is not functioning correctly, the entire ignition system can be disrupted to the point that improper engine operation results.

As an example of how one phase of engine operation can be affected by other phases, consider spark plug fouling. Spark plug fouling causes malfunctioning of the ignition system, but the fouling seldom results from a fault in the plug itself. Usually some other phase of operation is not functioning correctly, causing the plug to foul out. If excessively rich fuel/air mixtures are being burned because of either basically rich carburetion or improperly adjusted idle mixture, spark plug fouling will be inevitable. Generally, these causes will result in fouled spark plugs appearing over the entire engine, and not necessarily confined to one or a few cylinders.

If the fuel/air mixture is too lean or too rich on any one cylinder because of a loose intake pipe or improperly adjusted valves, improper operation of that cylinder will result. The cylinder will probably backfire. Spark plug fouling will occur continually on that cylinder until the defect is remedied.

Impeller oil seal leaks, which can be detected only by removal of intake pipes, will cause spark plug fouling. Here, the fouling is caused by excess oil being delivered to one or more cylinders. Stuck or broken rings will cause oil pumping in the affected cylinders with consequent plug fouling and high oil consumption. Improperly adjusted cylinder valves cause spark plug fouling, hard starting, and general engine malfunctioning. They may also cause valve failure as a result of high-seating velocities or of the valve holding open, with subsequent valve burning.

Whenever the true cause of engine malfunctioning is not determined and whenever the real disorder is not corrected, the corrective measure taken will provide only temporary relief. For example, the standard "fix" for engine backfiring is to change the carburetor. However, as a result of many tests, it is now known that the usual cause of engine backfiring is an improperly adjusted or defective ignition system or improperly adjusted engine valves.

Backfiring is usually caused by one cylinder, not all the cylinders. To remedy backfiring, first locate which cylinder is causing it, and then find out why that cylinder is backfiring.

ENGINE TROUBLESHOOTING

The need for troubleshooting normally is dictated by poor operation of the complete powerplant. Power settings for the type of operation at which any difficulty is encountered in many cases will indicate which part of the powerplant is the basic cause of difficulty.

The cylinders of an engine, along with the supercharger impeller, form an air pump. Furthermore, the power developed in the cylinders varies directly with the rate of air consumption. Therefore, a measure of air consumption or airflow into the engine is a measure of power input. Ignoring for the moment such factors as humidity and exhaust back pressure, the manifold pressure gage and the engine tachometer provide a measure of engine air consumption. Thus, for a given r.p.m. any change in power input will be reflected by a corresponding change in manifold pressure.

The power output of an engine is the power absorbed by the propeller. Therefore, propeller load is a measure of power output. Propeller load, in turn, depends on the propeller r.p.m., blade angle, and air density. For a given angle and air density, propeller load (power output) is directly proportional to engine speed.

The basic power of an engine is related to manifold pressure, fuel flow, and r.p.m. Because the r.p.m. of the engine and the throttle opening directly control manifold pressure, the primary engine power controls are the throttle and the r.p.m. control. An engine equipped with a fixed-pitch propeller has only a throttle control. In this case, the throttle setting controls both manifold pressure and engine r.p.m.

With proper precautions, manifold pressure can be taken as a measure of power input, and r.p.m. can be taken as a measure of power output. However, the following factors must be considered:

(1) Atmospheric pressure and air temperature must be considered, since they affect air density.

(2) These measures of power input and power output should be used only for comparing the performance of an engine with its previous performance or for comparing identical powerplants.

(3) With a controllable propeller, the blades must be against their low-pitch stops, since this is the only blade position in which the blade angle is known and does not vary. Once the blades are off their low-pitch stops, the propeller governor takes over and maintains a constant r.p.m. regardless of power input or engine condition. This precaution means that the propeller control must be set to maximum or takeoff r.p.m., and the checks made at engine speeds below this setting.

If the engine is equipped with a torquemeter, the torquemeter reading rather than the engine speed should be used as a measure of power output.

Having relative measures of power input and power output, the condition of an engine can be determined by comparing input and output. This is done by comparing the manifold pressure required to produce a given r.p.m. with the manifold pressure required to produce the same r.p.m. at a time when the engine (or an identical powerplant) was known to be in top operating condition.

An example will best show the practical application of this method of determining engine condition. With the propeller control set for takeoff r.p.m. (full low blade angle), an engine may require 32 in. of manifold pressure to turn 2,200 r.p.m. for the ignition check. On previous checks, this engine required only 30 in. of manifold pressure to turn 2,200 r.p.m. at the same station (altitude) and under similar atmospheric conditions. Obviously, something is wrong; a higher power input (manifold pressure) is now required for the same power output (r.p.m.). There is a good chance that one cylinder has cut out.

There are several standards against which engine performance can be compared. The performance of a particular engine can be compared with its past performance provided adequate records are kept. Engine performance can be compared with that of other engines on the same aircraft or aircraft having identical installations.

If a fault does exist, it may be assumed that the trouble lies in one of the following systems:

(1) Ignition system.
(2) Fuel metering system.
(3) Induction system.
(4) Power section (valves, cylinders, etc.).
(5) Instrumentation.

If a logical approach to the problem is taken and the instrument readings properly utilized, the malfunctioning system can be pinpointed and the specific problem in the defective system can be singled out.

The more information available about any particular problem, the better will be the opportunity for a rapid repair. Information that is of value in locating a malfunction includes:

(1) Was any roughness noted? Under what conditions of operation?
(2) What is the time on the engine and spark plugs? How long since last inspection?
(3) Was the ignition system operational check and power check normal?
(4) When did the trouble first appear?
(5) Was backfiring or afterfiring present?

(6) Was the full throttle performance normal?

From a different point of view, the powerplant is in reality a number of small engines turning a common crankshaft and being operated by two common phases: (1) Fuel metering, and (2) ignition. When backfiring, low power output, or other powerplant difficulty is encountered, first find out which system (fuel metering or ignition) is involved and then determine whether the entire engine or only one cylinder is at fault.

For example, backfiring normally will be caused by:

(1) Valves holding open or sticking open in one or more of the cylinders.
(2) Lean mixture.
(3) Intake pipe leakage.
(4) An error in valve adjustment which causes individual cylinders to receive too small a charge or one too large, even though the mixture to the cylinders has the same fuel/air ratio.

Ignition system reasons for backfiring might be a cracked distributor block or a high-tension leak between two ignition leads. Either of these conditions could cause the charge in the cylinder to be ignited during the intake stroke. Ignition system troubles involving backfiring normally will not be centered in the basic magneto, since a failure of the basic magneto would result in the engine not running, or it would run well at low speeds but cut out at high speeds. On the other hand, replacement of the magneto would correct a difficulty caused by a cracked distributor where the distributor is a part of the magneto.

If the fuel system, ignition system, and induction system are functioning properly, the engine should produce the correct b.hp. unless some fault exists in the basic power section.

Trouble—Cause—Remedy

Troubleshooting is a systematic analysis of the symptoms which indicate engine malfunction. Since it would be impractical to list all the malfunctions that could occur in a reciprocating engine, only the most common malfunctions are discussed. A thorough knowledge of the engine systems, applied with logical reasoning, will solve any problems which may occur.

Table 10 lists general conditions or troubles which may be encountered on reciprocating engines, such as "engine fails to start." They are further divided into the probable causes contributing to such conditions. Corrective actions are indicated in the "remedy" column. The items are presented with consideration given to frequency of occurrence, ease of accessibility, and complexity of the corrective action indicated.

TABLE 10. Troubleshooting opposed engines.

Trouble	Probable Causes	Remedy
Engine fails to start.	Lack of fuel.	Check fuel system for leaks. Fill fuel tank. Clean dirty lines, strainers, or fuel valves.
	Underpriming.	Use correct priming procedure.
	Overpriming.	Open throttle and "unload" engine by rotating the propeller.
	Incorrect throttle setting.	Open throttle to one-tenth of its range.
	Defective spark plugs.	Clean and re-gap or replace spark plugs.
	Defective ignition wire.	Test and replace any defective wires.
	Defective or weak battery.	Replace with charged battery.
	Improper operation of magneto or breaker points.	Check internal timing of magnetos.
	Water in carburetor.	Drain carburetor and fuel lines.
	Internal failure.	Check oil sump strainer for metal particles.

TABLE 10. Troubleshooting opposed engines—con.

Trouble	Probable Causes	Remedy
	Magnetized impulse coupling, if installed.	Demagnetize impulse coupling.
	Frozen spark plug electrodes.	Replace spark plugs or dry out plugs.
	Mixture control in idle cutoff.	Open mixture control.
	Shorted ignition switch or loose ground.	Check and replace or repair.
Engine fails to idle properly.	Incorrect carburetor idle speed adjustment.	Adjust throttle stop to obtain correct idle.
	Incorrect idle mixture.	Adjust mixture. (Refer to engine manufacturer's handbook for proper procedure.)
	Leak in the induction system.	Tighten all connections in the induction system. Replace any defective parts.
	Low cylinder compression.	Check cylinder compression.
	Faulty ignition system.	Check entire ignition system.
	Open or leaking primer.	Lock or repair primer.
	Improper spark plug setting for altitude.	Check spark plug gap.
	Dirty air filter.	Clean or replace.
Low power and engine running uneven.	Mixture too rich; indicated by sluggish engine operation, red exhaust flame, and black smoke.	Check primer. Re-adjust carburetor mixture.
	Mixture too lean; indicated by overheating or backfiring.	Check fuel lines for dirt or other restrictions. Check fuel supply.
	Leaks in induction system.	Tighten all connections. Replace defective parts.
	Defective spark plugs.	Clean or replace spark plugs.
	Improper grade of fuel.	Fill tank with recommended grade.
	Magneto breaker points not working properly.	Clean points. Check internal timing of magneto.
	Defective ignition wire.	Test and replace any defective wires.
	Defective spark plug terminal connectors.	Replace connectors on spark plug wire.
	Incorrect valve clearance.	Adjust valve clearance.
	Restriction in exhaust system.	Remove restriction.
	Improper ignition timing.	Check magnetos for timing and synchronization.
Engine fails to develop full power.	Throttle lever out of adjustment.	Adjust throttle lever.
	Leak in induction system.	Tighten all connections and replace defective parts.
	Restriction in carburetor airscoop.	Examine airscoop and remove restriction.
	Improper fuel.	Fill tank with recommended fuel.
	Propeller governor out of adjustment.	Adjust governor.
	Faulty ignition.	Tighten all connections. Check system. Check ignition timing.
Rough running engine.	Cracked engine mount(s).	Repair or replace engine mount(s).
	Unbalanced propeller.	Remove propeller and have it checked for balance.
	Defective mounting bushings.	Install new mounting bushings.
	Lead deposit on spark plugs.	Clean or replace plugs.
	Primer unlocked.	Lock primer.

TABLE 10. Troubleshooting opposed engines—con.

Trouble	Probable Causes	Remedy
Low oil pressure.	Insufficient oil.	Check oil supply.
	Dirty oil strainers.	Remove and clean oil strainers.
	Defective pressure gage.	Replace gage.
	Air lock or dirt in relief valve.	Remove and clean oil pressure relief valve.
	Leak in suction line or pressure line.	Check gasket between accessory housing crankcase.
	High oil temperature.	See "high oil temperature" in trouble column.
	Stoppage in oil pump intake passage.	Check line for obstruction. Clean suction strainer.
	Worn or scored bearings.	Overhaul engine.
High oil temperature.	Insufficient air cooling.	Check air inlet and outlet for deformation or obstruction.
	Insufficient oil supply.	Fill oil tank to proper level.
	Clogged oil lines or strainers.	Remove and clean oil lines or strainers.
	Failing or failed bearings.	Examine sump for metal particles and, if found, overhaul engine.
	Defective thermostats.	Replace thermostats.
	Defective temperature gage.	Replace gage.
	Excessive blow-by.	Usually caused by weak or stuck rings. Overhaul engine.
Excessive oil consumption.	Failing or failed bearing.	Check sump for metal particles and, if found, an overhaul of engine is indicated.
	Worn or broken piston rings.	Install new rings.
	Incorrect installation of piston rings.	Install new rings.
	External oil leakage.	Check engine carefully for leaking gaskets or O-rings.
	Leakage through engine fuel pump vent.	Replace fuel pump seal.
	Engine breather or vacuum pump breather.	Check engine, and overhaul or replace vacuum pump.

CYLINDER MAINTENANCE

Each cylinder of the engine is, in reality, an engine in itself. In most cases the cylinder receives its fuel and air from a common source such as the carburetor. Every phase of cylinder operation, such as compression, fuel mixture, and ignition must function properly, since even one type of malfunctioning will cause engine difficulty. Engine backfiring, for example, may be caused by a lean fuel/air mixture in one of the cylinders. The lean mixture may be caused by such difficulties as an improper valve adjustment, a sticking intake or exhaust valve, or a leaking intake pipe. Most engine difficulties can be traced to one cylinder, or a small number of cylinders. Therefore, engine difficulty can be corrected only after malfunctioning cylinders have been located and defective phases of cylinder operation brought up to normal.

Hydraulic Lock

Whenever a radial engine remains shut down for any length of time beyond a few minutes, oil or fuel may drain into the combustion chambers of the lower cylinders or accumulate in the lower intake pipes ready to be drawn into the cylinders when the engine starts (figure 10–44). As the piston approaches top center of the compression stroke (both valves closed), this liquid, being incompressible, stops piston movement. If the crankshaft continues to rotate, something must give. Therefore, starting or attempting to start an engine with a hydraulic lock of this nature may cause the affected cylinder to blow out or, more likely, may result in a bent or broken connecting rod.

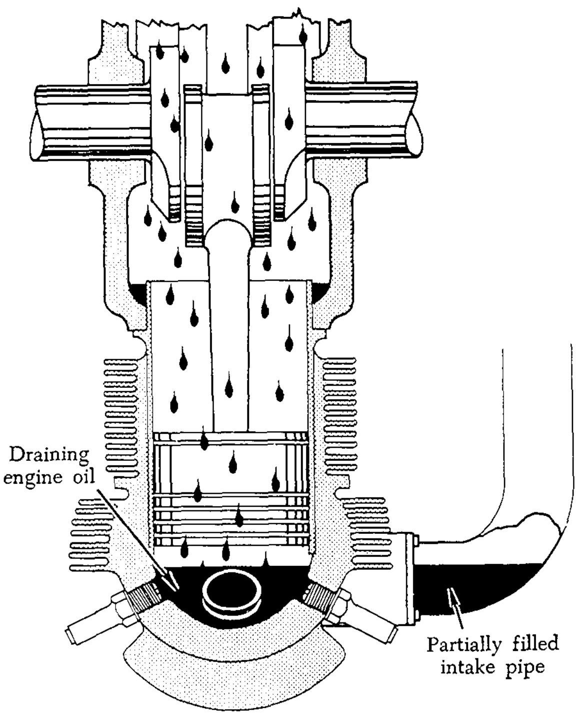


FIGURE 10–44. Initial step in developing a hydraulic lock.

A complete hydraulic lock—one that stops crankshaft rotation—can result in serious damage to the engine. Still more serious, however, is the slight damage resulting from a partial hydraulic lock which goes undetected at the time it occurs. The piston meets extremely high resistance but is not completely stopped. The engine falters but starts and continues to run as the other cylinders fire. The slightly bent connecting rod resulting from the partial lock also goes unnoticed at the time it is damaged but is sure to fail later. The eventual failure is almost certain to occur at a time when it can be least tolerated, since it is during such critical operations as takeoff and go-around that maximum power is demanded of the engine and maximum stresses are imposed on its parts. A hydraulic lock and some possible results are shown in figure 10–45.

Before starting any radial engine that has been shut down for more than 30 min., check the ignition switches for "off" and then pull the propeller through in the direction of rotation a minimum of two complete turns to make sure that there is no hydraulic lock or to detect the hydraulic lock if one is present. Any liquid present in a cylinder will be indicated by the abnormal effort required to rotate the propeller. However, never use force when a hydraulic lock is detected. When engines which employ direct drive

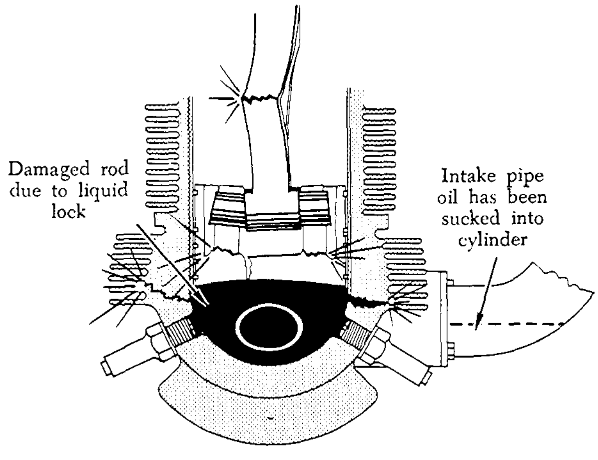


FIGURE 10–45. Results of a hydraulic lock.

or combination inertia and direct drive starters are being started, and an external power source is being used, a check for hydraulic lock may be made by intermittently energizing the starter and watching for a tendency of the engine to stall. Use of the starter in this way will not exert sufficient force on the crankshaft to bend or break a connecting rod if a lock is present.

To eliminate a lock, remove either the front or rear spark plug of the lower cylinders and pull the propeller through in the direction of rotation. The piston will expel any liquid that may be present.

If the hydraulic lock occurs as a result of overpriming prior to initial engine start, eliminate the lock in the same manner, *i.e.*, remove one of the spark plugs from the cylinder and rotate the crankshaft through two turns.

Never attempt to clear the hydraulic lock by pulling the propeller through in the direction opposite to normal rotation, since this tends to inject the liquid from the cylinder into the intake pipe with the possibility of a complete or partial lock occurring on the subsequent start.

Valve Blow-by

Valve blow-by is indicated by a hissing or whistle when pulling the propeller through prior to starting the engine, when turning the engine with the starter, or when running the engine at slow speeds. It is caused by a valve sticking open or warped to the extent that compression is not built up in the cylinder as the piston moves toward top dead center on the compression stroke. Blow-by past the exhaust valve can be heard at the exhaust stack, and blow-by past the intake valve is audible through the carburetor.

Correct valve blow-by immediately to prevent valve failure and possible engine failure by taking the following steps:

(1) Perform a cylinder compression test to locate the faulty cylinder.

(2) Check the valve clearance on the affected cylinder. If the valve clearance is incorrect, the valve may be sticking in the valve guide. To release the sticking valve, place a fiber drift on the rocker arm immediately over the valve stem and strike the drift several times with a mallet. Sufficient hand pressure should be exerted on the fiber drift to remove any space between the rocker arm and the valve stem prior to hitting the drift.

(3) If the valve is not sticking and the valve clearance is incorrect, adjust it as necessary.

(4) Determine whether blow-by has been eliminated by again pulling the engine through by hand or turning it with the starter. If blow-by is still present, it may be necessary to replace the cylinder.

CYLINDER COMPRESSION TESTS

The cylinder compression test determines if the valves, piston rings, and pistons are adequately sealing the combustion chamber. If pressure leakage is excessive, the cylinder cannot develop its full power. The purpose of testing cylinder compression is to determine whether cylinder replacement is necessary. The detection and replacement of defective cylinders will prevent a complete engine change because of cylinder failure. It is essential that cylinder compression tests be made periodically.

Although it is possible for the engine to lose compression for other reasons, low compression for the most part can be traced to leaky valves. Conditions which affect engine compression are:

(1) Incorrect valve clearances.

(2) Worn, scuffed, or damaged piston.

(3) Excessive wear of piston rings and cylinder walls.

(4) Burned or warped valves.

(5) Carbon particles between the face and the seat of the valve or valves.

(6) Early or late valve timing.

Perform a compression test as soon as possible after the engine is shut down so that piston rings, cylinder walls, and other parts are still freshly lubricated. However, it is not necessary to operate the engine prior to accomplishing compression checks during engine buildup or on individually replaced cylinders. In such cases, before making the test, spray a small quantity of lubricating oil into the cylinder or cylinders and turn the engine over several times to seal the piston and rings in the cylinder barrel.

Be sure that the ignition switch is in the "off" position so that there will be no accidental firing of the engine. Remove necessary cowling and the most accessible spark plug from each cylinder. When removing the spark plugs, identify them to coincide with the cylinder. Close examination of the plugs will aid in diagnosing problems within the cylinder. Review the maintenance records of the engine being tested. Records of previous compression checks help in determining progressive wear conditions and in establishing the necessary maintenance actions.

The two basic types of compression testers currently in use for checking cylinder compression in aircraft engines are the direct compression tester and the differential pressure tester. The procedures and precautions to observe when using either of these types of testers are outlined in this section. When performing a compression test, follow the manufacturer's instructions for the particular tester being used.

Direct Compression Tester

This type of compression test indicates the actual pressures within the cylinder. Although the particular defective component within the cylinder is difficult to determine with this method, the consistency of the readings for all cylinders is an indication of the condition of the engine as a whole. The following are suggested guidelines for performing a direct compression test:

(1) Warm up the engine to operating temperatures and perform the test as soon as possible after shutdown.

(2) Remove the most accessible spark plug from each cylinder.

(3) Rotate the engine with the starter to expel any excess oil or loose carbon in the cylinders.

(4) If a complete set of compression testers is available, install one tester in each cylinder. However, if only one tester is being used, check each cylinder in turn.

(5) Using the engine starter, rotate the engine at least three complete revolutions and record the compression reading. Use an external power source, if possible, as a low battery will result in a slow engine-turning rate and lower readings.

(6) Re-check any cylinder which shows an abnor-

mal reading when compared with the others. Any cylinder having a reading approximately 15 p.s.i. lower than the others should be suspected of being defective.

(7) If a compression tester is suspected of being defective, replace it with one known to be accurate, and re-check the compression of the affected cylinders.

Differential Pressure Tester

The differential pressure tester checks the compression of aircraft engines by measuring the leakage through the cylinders. The design of this compression tester is such that minute valve leakages can be detected, making possible the replacement of cylinders where valve burning is starting.

The operation of the compression tester is based on the principle that, for any given airflow through a fixed orifice, a constant pressure drop across the orifice will result. As the airflow varies, the pressure changes accordingly and in the same direction. If air is supplied under pressure to the cylinder with both intake and exhaust valves closed, the amount of air that leaks by the valves or piston rings indicates their condition; the perfect cylinder, of course, would have no leakage.

The differential pressure tester (figure 10–46) requires the application of air pressure to the cylinder being tested with the piston at top-center compression stroke.

Guidelines for performing a differential compression test are:

(1) Perform the compression test as soon as possible after engine shutdown to provide uniform lubrication of cylinder walls and rings.

(2) Remove the most accessible spark plug from the cylinder or cylinders and install a spark plug adapter in the spark plug insert.

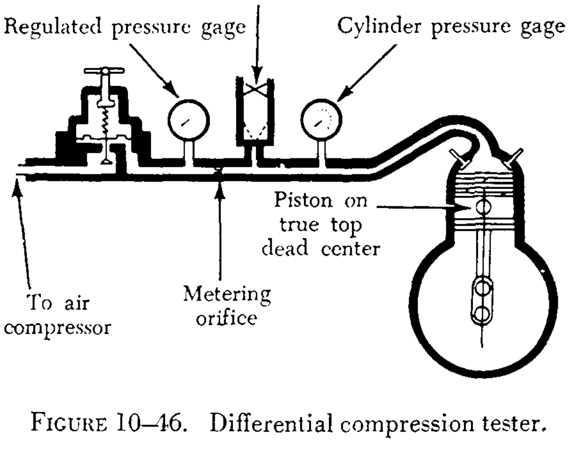


FIGURE 10–46. Differential compression tester.

(3) Connect the compression tester assembly to a 100- to 150-p.s.i. compressed air supply. With the shutoff valve on the compression tester closed, adjust the regulator of the compression tester to obtain 80 p.s.i. on the regulated pressure gage.

(4) Open the shutoff valve and attach the air hose quick-connect fitting to the spark plug adapter. The shutoff valve, when open, will automatically maintain a pressure of 15 to 20 p.s.i. in the cylinder when both the intake and exhaust valves are closed.

(5) By hand, turn the engine over in the direction of rotation until the piston in the cylinder being tested comes up on the compression stroke against the 15 p.s.i. Continue turning the propeller slowly in the direction of rotation until the piston reaches top dead center. Top dead center can be detected by a decrease in force required to move the propeller. If the engine is rotated past top dead center, the 15 to 20 p.s.i. will tend to move the propeller in the direction of rotation. If this occurs, back the propeller up at least one blade prior to turning the propeller again in the direction of rotation. This backing up is necessary to eliminate the effect of backlash in the valve-operating mechanism and to keep the piston rings seated on the lower ring lands.

(6) Close the shutoff valve in the compression tester and re-check the regulated pressure to see that it is 80 p.s.i. with air flowing into the cylinder. If the regulated pressure is more or less than 80 p.s.i., re-adjust the regulator in the test unit to obtain 80 p.s.i. When closing the shutoff valve, make sure that the propeller path is clear of all objects. There will be sufficient air pressure in the combustion chamber to rotate the propeller if the piston is not on top dead center.

(7) With regulated pressure adjusted to 80 p.s.i., if the cylinder pressure reading indicated on the cylinder pressure gage is below the minimum specified for the engine being tested, move the propeller in the direction of rotation to seat the piston rings in the grooves. Check all the cylinders and record the readings.

If low compression is obtained on any cylinder, turn the engine through with the starter or re-start and run the engine to takeoff power and re-check the cylinder or cylinders having low compression.

If the low compression is not corrected, remove the rocker-box cover and check the valve clearance to determine if the difficulty is caused by inadequate valve clearance. If the low compression is not caused by inadequate valve clearance, place a fiber drift on the rocker arm immediately over the valve stem and tap the drift several times with a 1- to 2-pound hammer to dislodge any foreign material that may be lodged between the valve and valve seat. After staking the valve in this manner, rotate the engine with the starter and re-check the compression. Do not make a compression check after staking a valve until the crankshaft has been rotated either with the starter or by hand to re-seat the valve in normal manner. The higher seating velocity obtained when staking the valve will indicate valve seating even though valve seats are slightly egged or eccentric.

Cylinders having compression below the minimum specified after staking should be further checked to determine whether leakage is past the exhaust valve, intake valve, or piston. Excessive leakage can be detected: (1) at the exhaust valve by listening for air leakage at the exhaust outlet; (2) at the intake valve by escaping air at the air intake; and (3) past the piston rings by escaping air at the engine breather outlets.

The wheeze test is another method of detecting leaking intake and exhaust valves. In this test, as the piston is moved to top dead center on the compression stroke, the faulty valve may be detected by listening for a wheezing sound in the exhaust outlet or intake duct.

Another method is to admit compressed air into the cylinder through the spark plug hole. The piston should be restrained at top dead center of the compression stroke during this operation. A leaking valve or piston rings can be detected by listening at the exhaust outlet, intake duct, or engine breather outlets.

Next to valve blow-by, the most frequent cause of compression leakage is excessive leakage past the piston. This leakage may occur because of lack of oil. To check this possibility, squirt engine oil into the cylinder and around the piston. Then re-check the compression. If this procedure raises compression to or above the minimum required, continue the cylinder in service. If the cylinder pressure readings still do not meet the minimum requirement, replace the cylinder. When it is necessary to replace a cylinder as a result of low compression, record the cylinder number and the compression value of the newly installed cylinder on the compression checksheet.

Cylinder Replacement

Reciprocating engine cylinders are designed to operate a specified time before normal wear will require their overhaul. If the engine is operated as recommended and proficient maintenance is performed, the cylinders normally will last until the engine is removed for "high-time" reasons. It is known from experience that materials fail and engines are abused through incorrect operation; this has a serious effect on cylinder life. Another reason for premature cylinder change is poor maintenance. Therefore, exert special care to ensure that all the correct maintenance procedures are adhered to when working on the engine.

Some of the reasons for cylinder replacement are:

(1) Low compression.
(2) High oil consumption in one or more cylinders.
(3) Excessive valve guide clearance.
(4) Loose intake pipe flanges.
(5) Loose or defective spark plug inserts.
(6) External damage, such as cracks.

When conditions like these are limited to one or a few cylinders, replacing the defective cylinders should return the engine to a serviceable condition.

The number of cylinders that can be replaced on air-cooled, in-service engines more economically than changing engines is controversial. Experience has indicated that, in general, one-fourth to one-third of the cylinders on an engine can be replaced economically. Consider these factors when making a decision:

(1) Time on the engine.
(2) Priority established for returning the aircraft to service.
(3) Availability of spare cylinders and spare engines.
(4) Whether QECA (quick engine change assemblies) are being used.
(5) The number of persons available to make the change.

When spare serviceable cylinders are available, replace cylinders when the man-hour requirement for changing them does not exceed the time required to make a complete engine change.

The cylinder is always replaced as a complete assembly, which includes piston, rings, valves, and valve springs. Obtain the cylinder by ordering the cylinder assembly under the part number specified in the engine parts catalog.

Except under certain conditions, do not attempt to replace individual parts, such as pistons, rings, or valves. This precaution guarantees that clearances and tolerances are correct. Other parts, such as valve springs, rocker arms, and rocker box covers, may be replaced individually.

Normally, all the cylinders in an engine are similar; that is, all are standard size or all a certain oversize, and all are steel bore or all are chrome-plated. In some instances, because of shortages at the time of overhaul, it may be necessary that engines have two different sizes of cylinder assemblies.

Replace a cylinder with an identical one, if possible. If an identical cylinder is not available, it is permissible to install either a standard or oversize cylinder and piston assembly, since this will not adversely affect engine operation. The size of the cylinder is indicated by a color code around the barrel (figure 10–47) between the attaching flange and the lower barrel cooling fin.

In some instances, air-cooled engines will be equipped with chrome-plated cylinders. Chrome-plated cylinders are usually identified by a paint band around the barrel between the attaching flange and the lower barrel cooling fin. This color band is usually international orange. When installing a chrome-plated cylinder, do not use chrome-plated piston rings. The matched assembly will, of course, include the correct piston rings. However, if a piston ring is broken during cylinder installation,

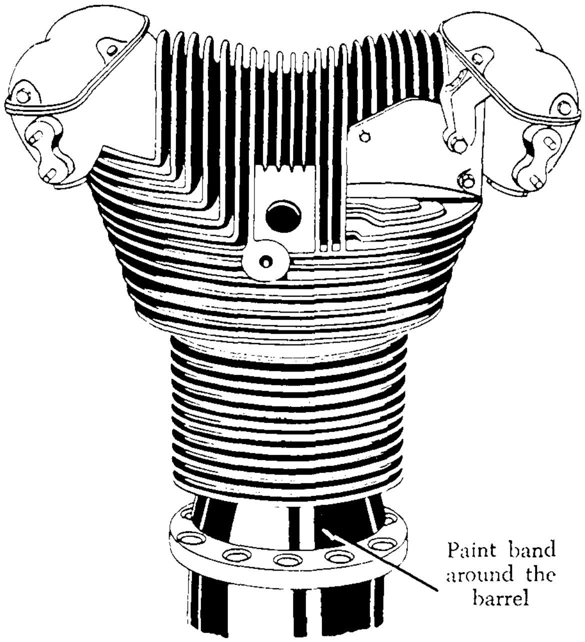


FIGURE 10–47. Identification of cylinder size.

check the cylinder marking to determine what ring, chrome plated or otherwise, is correct for replacement. Similar precautions must be taken to be sure that the correct size rings are installed.

Correct procedures and care are important when replacing cylinders. Careless work or the use of incorrect tools can damage the replacement cylinder or its parts. Incorrect procedures in installing rocker-box covers may result in troublesome oil leaks. Improper torquing of cylinder holddown nuts or capscrews can easily result in a cylinder malfunction and subsequent engine failure.

The discussion of cylinder replacement in this handbook is limited to the removal and installation of air-cooled engine cylinders. The discussion is centered around radial and opposed engines, since these are the aircraft engines on which cylinder replacements are most often performed.

Since these instructions are meant to cover all air-cooled engines, they are necessarily of a general nature. The applicable manufacturer's maintenance manual should be consulted for torque values and special precautions applying to a particular aircraft and engine. However, always practice neatness and cleanliness and always protect openings so that nuts, washers, tools and miscellaneous items do not enter the engine's internal sections.

CYLINDER REMOVAL

Assuming that all obstructing cowling and brackets have been removed, first remove the intake pipe and exhaust pipes. Plug or cover openings in the diffuser section. Then remove cylinder deflectors and any attaching brackets which would obstruct cylinder removal. Loosen the spark plugs and remove the spark-plug lead clamps. Do not remove the spark plugs until ready to pull the cylinder off.

Remove the rocker box covers. First remove the nuts and then tap the cover lightly with a rawhide mallet or plastic hammer. Never pry the cover off with a screwdriver or similar tool.

Loosen the pushrod packing gland nuts or hose clamps, top and bottom. Pushrods are removed by depressing the rocker arms with a special tool or by removing the rocker arm. Before removing the pushrods, turn the crankshaft until the piston is at top dead center on the compression stroke. This relieves the pressure on both intake and exhaust rocker arms. It is also wise to back off the adjusting nut as far as possible, because this allows maximum clearance for pushrod removal when the rocker arms are depressed.

On some model engines, tappets and springs of lower cylinders can fall out. Provision must be made to catch them as the pushrod and housing are removed.

After removing the pushrods, examine them for markings or mark them so that they may be replaced in the same location as they were before removal. The ball ends are usually worn to fit the sockets in which they have been operating. Furthermore, on some engines pushrods are not all of the same length. A good procedure is to mark the pushrods near the valve tappet ends "No. 1 IN," "No. 1 EX," "No. 2 IN," "No. 2 EX," etc.

On fuel injection engines, disconnect the fuel injection line and remove the fuel injection nozzle and any line clamps which will interfere with cylinder removal.

If the cylinder to be removed is a master rod cylinder, special precautions, in addition to regular cylinder removal precautions, must be observed. Information designating which cylinder has the master rod is included on the engine data plate. Arrangements must be made to hold the master rod in the mid-position of the crankcase cylinder hole (after the cylinder has been removed). Templates or guides are usually provided by the manufacturer for this purpose, or they are manufactured locally.

Under no circumstances should the master rod be moved from side to side. It must be kept centered until the guide is in place. Do not turn the crankshaft while the master rod cylinder is removed and other cylinders in the row remain on the engine. These precautions are necessary to prevent bottom rings on some of the other pistons from coming out of the cylinders, expanding, and damaging rings and piston skirts. If several cylinders are to be removed, one of which is the master rod cylinder, it should always be removed last and should be the first installed.

The next step in removing the cylinder is to cut the lockwire or remove the cotter pin, and pry off the locking device from the cylinder-attaching capscrews or nuts. Remove all the screws or nuts except two located 180° apart. Use the wrench specified for this purpose in the special tools section of the applicable manual.

Finally, while supporting the cylinder, remove the two remaining screws or nuts and gently pull the cylinder away from the crankcase. Two men must work together during this step as well as during the remaining procedure for cylinder replacement. After the cylinder skirt has cleared the crankcase and before the piston protrudes from the skirt, provide some means (usually a shop cloth) for preventing pieces of broken rings from falling into the crankcase. After the piston has been removed, remove the cloths and carefully check for piston ring pieces. To make certain that no ring pieces have entered the crankcase, collect and arrange all the pieces to see that they form a complete ring.

Place a support on the cylinder mounting pad and secure it with two capscrews or nuts. Then remove the piston and ring assembly from the connecting rod. When varnish makes it hard to remove the pin, a pin pusher or puller tool must be used. If the special tool is not available and a drift is used to remove the piston pin, the connecting rod should be supported so that it will not have to take the shock of the blows. If this is not done, the rod may be damaged.

After the removal of a cylinder and piston, the connecting rod must be supported to prevent damage to the rod and crankcase. This can be done by supporting each connecting rod with the removed cylinder base oil seal ring looped around the rod and cylinder base studs.

Using a wire brush, clean the studs or capscrews and examine them for cracks, damaged threads, or any other visible defects. If one capscrew is found loose or broken at the time of cylinder removal, all the capscrews for the cylinder should be discarded, since the remaining capscrews may have been seriously weakened. A cylinder holddown stud failure will place the adjacent studs under a greater operating pressure, and they are likely to be stretched beyond their elastic limit. The engine manufacturer's instruction must be followed for the number of studs that will have to be replaced after a stud failure.

When removing a broken stud, take proper precautions to prevent metal chips from entering the engine power section.

In all cases, both faces of the washers and the seating faces of stud nuts or capscrews must be cleaned and any roughness or burrs removed.

CYLINDER INSTALLATION

See that all preservative oil accumulation on the cylinder and piston assembly is washed off with solvent and thoroughly dried with compressed air. Install the piston and ring assembly on the connecting rod. Be sure that the piston faces in the right direction. The piston number stamped on the bottom of the piston head should face toward the front of the engine. Lubricate the piston pin before inserting it. It should fit with a push fit. If a drift must be used, follow the same precaution that was taken during pin removal.

Oil the exterior of the piston assembly generously, forcing oil around the piston rings and in the space between the rings and grooves. Stagger the ring gaps around the piston and check to see that rings are in the correct grooves and whether they are positioned correctly, because some are used as oil scrapers, others as pumper rings. The number, type and arrangement of the compression and oil-control rings will vary with the make and model of engine.

If it is necessary to replace the rings on one or more of the pistons, check the side clearance against the manufacturer's specification, using a thickness gage. The ring end gap must also be checked. The method for checking side and end clearance is shown in figure 10–48. If the ring gage shown is not available, a piston (without rings) may be inserted in the cylinder and the ring inserted in the cylinder bore. Insert the ring in the cylinder skirt below the mounting flange, since this is usually the smallest bore diameter. Pull the piston against the ring to align it properly in the bore.

If it is necessary to remove material to obtain the correct side clearance, it can be done either by turning the piston grooves a slight amount on each side or by lapping the ring on a surface plate.

If the end gap is too close, the excess metal can be removed by clamping a mill file in a vise, holding the ring in proper alignment, and dressing off the ends. In all cases the engine manufacturer's procedures must be followed.

Before installing the cylinder, check the flange to see that the mating surface is smooth and clean. Coat the inside of the cylinder barrel generously with oil. Be sure that the cylinder oil-seal ring is in place and that only one seal ring is used.

Using a ring compressor, compress the rings to a diameter equal to that of the piston. Start the cylinder assembly down over the piston, making certain that the cylinder and piston plane remain the same. Ease the cylinder over the piston with a straight, even movement which will move the ring compressor as the cylinder slips on. Do not rock the cylinder while slipping it on the piston, since any rocking is apt to release a piston ring or a part of a ring from the ring compressor prior to the ring's entrance into the cylinder bore. A ring released in this manner will expand and prevent the piston from entering the cylinder. Any attempt to force the cylinder onto the piston is apt to cause cracking or chipping of the ring or damage to the ring lands.

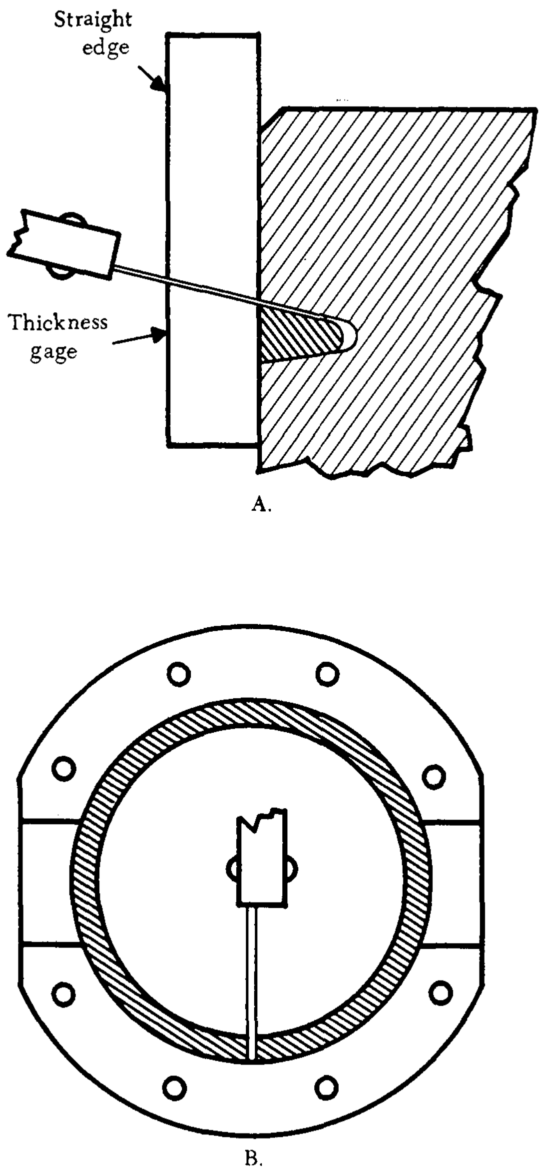


FIGURE 10–48. (A) Measuring piston ring side clearance and (B) end gap.

After the cylinder has slipped on the piston so that all piston rings are in the cylinder bore, remove the ring compressor and the connecting rod guide. Then slide the cylinder into place on the mounting pad. If capscrews are used, rotate the cylinder to align the holes. While still supporting the cylinder, install two capscrews or stud nuts 180° apart.

If the cylinder is secured to the crankcase by conical washers and nuts or capscrews, position the cylinder on the crankcase section by two special locating nuts or capscrews. These locating nuts or capscrews do not remain on the engine, but are removed and replaced with regular nuts or capscrews and conical washers after they have served their purpose and the other nuts or capscrews have been installed and tightened to the prescribed torque.

Install the remaining nuts or capscrews with their conical washers, and tighten the nuts or capscrews until they are snug. Make sure that the conical side of each washer is toward the cylinder mounting flange. Before inserting capscrews, coat them with a good sealer to prevent oil leakage. Generally, studs fit into holes and the fit is tight enough to prevent leakage.

The holddown nuts or capscrews must now be torqued to the value specified in the table of torque values in the engine manufacturer's service or overhaul manual. A definite and specific sequence of tightening all cylinder fastenings must be followed. Always refer to the appropriate engine service manual. A general rule is to tighten the first two nuts or capscrews 180° from each other; then tighten two alternate nuts or capscrews 90° from the first two.

If locating nuts or capscrews are being used, they should be torqued first. The tightening of the remaining screws or nuts should be alternated 180° as the torquing continues around the cylinder. Apply the torque with a slow, steady motion until the prescribed value is reached. Hold the tension on the wrench for a sufficient length of time to ensure that the nut or capscrew will tighten no more at the prescribed torque value. In many cases, additional turning of the capscrew or nut as much as one-quarter turn can be done by maintaining the prescribed torque on the nut for a short period of time. After tightening the regular nuts or capscrews, remove the two locating nuts or capscrews, install regular nuts or capscrews, and tighten them to the prescribed torque.

After the stud nuts or capscrews have been torqued to the prescribed value, safety them in the manner recommended in the engine manufacturer's service manual.

Re-install the push rods, push rod housings, rocker arms, barrel deflectors, intake pipes, ignition harness lead clamps and brackets, fuel injection line clamps and fuel injection nozzles, exhaust stack, cylinder head deflectors, and spark plugs. Remember that the push rods must be installed in their original locations and must not be turned end to end. Make sure, too, that the push rod ball end seats properly in the tappet. If it rests on the edge or shoulder of the tappet during valve clearance adjustment and later drops into place, valve clearance will be off. Furthermore, rotating the crankshaft with the push rod resting on the edge of the tappet may bend the push rod.

After installing the push rods and rocker arms, set the valve clearance.

Before installing the rocker box covers, lubricate the rocker arm bearings and valve stems. Check the rocker box covers for flatness, and re-surface them if necessary. After installing the gaskets and covers, tighten the rocker box cover nuts to the specified torque.

Safety those nuts, screws, and other fasteners which require safetying. Follow the recommended safetying procedures.

VALVE AND VALVE MECHANISM

Valves open and close the ports in the cylinder head to control the entrance of the combustible mixture and the exit of the exhaust gases. It is important that they open and close properly and seal tight against the port seats to secure maximum power from the burning fuel/air mixture for the crankshaft, and to prevent valve burning and warping. The motion of the valves is controlled by the valve-operating mechanism.

The valve mechanism includes cam plates or shafts, cam followers, pushrods, rocker arms, valve springs, and retainers. All parts of a valve mechanism must be in good condition and valve clearances must be correct if the valves are to operate properly.

Checking and adjusting the valve clearance is perhaps the most important part of valve inspection, and certainly it is the most difficult part. However, the visual inspection should not be slighted. It should include a check for the following major items:

(1) Metal particles in the rocker box are indications of excessive wear or partial failure of the valve mechanism. Locate and replace the defective parts.

(2) Excessive side clearance or galling of the rocker arm side. Replace defective rocker arms. Add shims when permitted, to correct excessive side clearance.

(3) Insufficient clearance between the rocker arm and the valve spring retainer. Follow the procedure outlined in the engine service manual for checking this clearance, and increase it to the minimum specified.

(4) Replace any damaged parts, such as cracked, broken, or chipped rocker arms, valve springs, or spring retainers. If the damaged part is one which cannot be replaced in the field, replace the cylinder.

(5) Excessive valve stem clearance. A certain amount of valve stem wobble in the valve guide is normal. Replace the cylinder only in severe cases.

(6) Evidence of incorrect lubrication. Excessive dryness indicates insufficient lubrication. However, the lubrication varies between engines and between cylinders in the same model engine. For example, the upper boxes of radial engines will normally run drier than the lower rocker boxes. These factors must be taken into account in determining whether or not ample lubrication is being obtained. Wherever improper lubrication is indicated, determine the cause and correct it. For example, a dry rocker may be caused by a plugged oil passage in the pushrod. Excessive oil may be caused by plugged drains between the rocker box and the crankcase. If the push rod drains become clogged, the oil forced to the rocker arm and other parts of the valve mechanism cannot drain back to the crankcase. This may result in oil leakage at the rocker box cover or in oil seepage along valve stems into the cylinder or exhaust system, causing excessive oil consumption on the affected cylinder and smoking in the exhaust.

(7) Excessive sludge in the rocker box. This indicates an excessive rocker box temperature, which, in turn, may be caused by improper positioning of cowling or exhaust heat shields or baffles. After correcting the cause of the difficulty, spray the interior of the rocker box with dry cleaning solvent, blow it dry with compressed air, and then coat the entire valve mechanism and interior of the rocker box with clean engine oil.

(8) Variation in valve clearance not explained by normal wear. If there is excessive valve clearance, check for bent push rods. Replace any that are defective. Check also for valve sticking. If the push rod is straight and the valve opens and closes when the propeller is pulled through by hand, check the tightness of the adjusting screw to determine whether the clearance was set incorrectly or the adjusting screw has loosened.

After adjusting the clearance on each valve, tighten the lock screw or nut to the torque specified in the maintenance manual. After completing all clearance adjustments and before installing the rocker box covers, make a final check of all lock screws or nuts for tightness with a torque wrench.

Warped rocker box covers are a common cause of oil leakage. Therefore, the box covers should be checked for flatness at each valve inspection. Re-surface any warped covers by lapping them on emery cloth laid on a surface plate. Rocker box cover warpage is often caused by improper tightening of the rocker box cover nuts. Eliminate further warpage by torquing the nuts to the values specified in the manufacturer's service manual.

Valve Clearance

The amount of power that can be produced by a cylinder depends primarily on the amount of heat that can be produced in that cylinder without destructive effects on the cylinder components. Any condition that limits the amount of heat in the cylinder also limits the amount of power which that cylinder can produce.

The manufacturer, in determining valve timing and establishing the maximum power setting at which the engine will be permitted to run, considers the amount of heat at which cylinder components such as spark plugs and valves can operate efficiently. The heat level of the exhaust valve must be below that at which pitting and warping of the valve occurs.

The head of the exhaust valve is exposed to the heat of combustion at all times during the combustion period. In addition, the head of this valve and a portion of the stem are exposed to hot exhaust gases during the exhaust event. Under normal operation, the exhaust valve remains below the critical heat level because of its contact with the valve seat when closed and because of the heat dissipated through the stem. Any condition which prevents the valve from seating properly for the required proportion of time will cause the valve to exceed the critical heat limits during periods of high power output. In cases of extremely poor valve seat contact, the exhaust valve can warp during periods of low power output.

Normally, the exhaust valve is closed and in contact with its seat about 65% of the time during the four-stroke cycle. If the valve adjustment is correct, and if the valve seats firmly when closed, much of the heat is transferred from the valve, through the seat, into the cylinder head.

In order for a valve to seat, the valve must be in good condition, with no significant pressure being exerted against the end of the valve by the rocker arm. If the expansion of all parts of the engine including the valve train were the same, the problem of ensuring valve seating would be very easy to solve. Practically no free space would be necessary in the valve system. However, since there is a great difference in the amount of expansion of various parts of the engine, there is no way of providing a constant operating clearance in the valve train. The clearance in the valve-actuating system is very small when the engine is cold but is much greater when the engine is operating at normal temperature. The difference is caused by differences in the expansion characteristics of the various metals and by the differences in temperature of various engine parts.

There are many reasons why proper valve clearances are of vital importance to satisfactory and stable engine operation. For example, when the engine is operating, valve clearances establish valve timing. Since all cylinders receive their fuel/air mixture (or air) from a common supply, valve clearance affects both the amount and the richness or leanness of the fuel/air mixture. Therefore, it is essential that valve clearances be correct and uniform between each cylinder.

On radial engines, valve clearance decreases with a drop in temperature; therefore, insufficient clearance may cause the valve to hold open when extremely cold temperatures are encountered. This may make cold-weather starting of the engine difficult, if not impossible, because of the inability of the cylinders to pull a combustible charge into the combustion chamber.

Accurate valve adjustment establishes the intended valve seating velocity. If valve clearances are excessive, the valve seating velocity is too high. The result is valve pounding and stem stretching, either of which is conducive to valve failure. Insufficient clearance may make starting difficult and cause valves to stick in the "open" position, causing blow-by and subsequent valve failure as a result of the extreme temperatures to which the valve is subjected.

The engine manufacturer specifies the valve inspection period for each engine. In addition to the regular periods, inspect and adjust the valve mechanism any time there is rough engine operation, backfiring, loss of compression, or hard starting.

Because of variations in engine designs, various methods are required for setting valves to obtain correct and consistent clearances. In all cases, follow the exact procedure prescribed by the engine manufacturer, since obscure factors may be involved. For example, there is considerable cam float on many radial engines, and the valve-adjusting procedure for these engines is developed to permit accurate and consistent positioning of the cam. Since the ratio of valve movement to pushrod movement may be as much as two to one, each 0.001 in. shift of the cam can result in a 0.002 in. variation in valve clearances.

Wright engines incorporate pressure-lubricated valves. Oil under pressure passes through the pushrod and into the center of the valve-clearance adjusting screw. From this point, oil passages radiate in three directions. To permit proper lubrication, one of the three passages in the adjusting screw must be at least partially open to the passage leading to the rocker arm bearing. At the same time, neither of the other two passages must be uncovered by being in the slot in the rocker arm. Determine the location of the oil passages in the adjusting screw by locating the "0" stamped in three places on its top (figure 10–49). If there are only two stamped circles, the third oil passage is midway between the two marked ones. After final tailoring of the valve adjustment, if any one of the three oil passages aligns with or is closer than 3/32 in. to the nearest edge of the slot in the rocker arm, turn the adjusting screw in a direction to increase or decrease the clearance until the reference "0" mark is 3/32 in. from the nearest edge of the slot in the rocker arm, or until the maximum or minimum valve clearance is reached.

Pratt and Whitney engines also incorporate pressure-lubricated valves. On these engines, there is no slot in the rocker arm, but the valve-clearance adjusting screw can be turned in or backed out so far that the oil passage from the screw into the rocker arm is blocked. The specific instructions

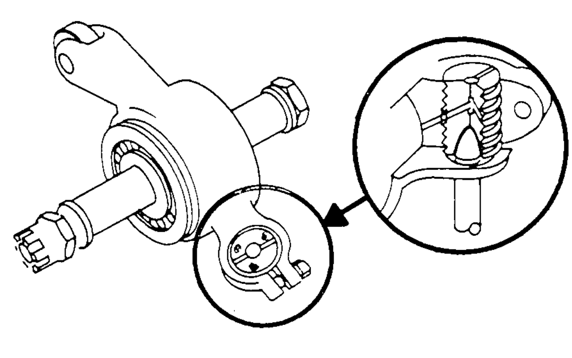


FIGURE 10–49. Aligning valve adjusting screw.

for setting clearance on the Pratt and Whitney engines state that a certain number of threads must show above the rocker arm. For example, on one model engine at least two threads and not more than five must show, and will, providing the pushrod is the correct length. Correct the pushrod length by pulling off one of the ball ends and changing the washer beneath for a thicker or thinner one. If there is no washer and the rod is too long, correct it by grinding away the end of the rod. Check the engine manufacturer's service or overhaul manual for the maximum or minimum number of threads which may show on the engine in question.

When adjusting valve clearances, always use the valve clearance gage or the dial gage specified in the "tools" section of the engine manufacturer's service manual. The specified gage is of the proper thickness and is so shaped that the end being used for checking can be slipped in a straight line between the valve and the rocker arm roller of the rocker arm. When a standard gage is used without being bent to the proper angle, a false clearance will be established since the gage will be cocked between the valve stem and rocker arm or rocker arm roller.

In making the check with the feeler gage, do not use excessive force to insert the gage between the valve stem and the adjustment screw or rocker arm roller. The gage can be inserted by heavy force, even though the clearance may be several thousandths of an inch less than the thickness of the gage. This precaution is particularly important on engines where the cam is centered during valve clearance adjustment, since forcing the gage on these engines may cause the cam to shift, with subsequent false readings.

When a dial gage and brackets for mounting the gage on the rocker box are specified, be sure to use them. A dial gage with a bracket may be used for checking valve clearances on any engine, provided the rocker arm arrangement is such that the pickup arm of the gage is located over the center line of the valve stem.

With a dial gage, the clearance is the amount of travel obtained when the rocker arm is rotated from the valve stem until the other end of the rocker arm contacts the pushrod.

Since valve clearance adjustment procedures vary between engines, a single treatment will not be sufficient. Thus, the procedures for various engines or groups of engines are treated separately in the following paragraphs. However, the procedures are described only to provide an understanding of the operations involved. Consult the engine manufacturer's instructions for the clearance to be set, the torque to be applied to lockscrews and rocker box cover nuts, and other pertinent details.

The first step in checking and adjusting valve clearances is to set the piston in the No. 1 cylinder at top-center compression stroke. Turn the propeller by hand until the valve action or cylinder pressure against a thumb held over the spark plug hole indicates that the piston is coming up on the compression stroke. Insert a piece of aluminum tubing into the spark plug hole and turn the propeller in the direction of rotation until the piston reaches its highest position. Proper precaution must be taken to make sure that the piston is on compression stroke.

After positioning the piston and crankshaft, adjust intake and exhaust valve clearances on the No. 1 cylinder to the prescribed values. Then adjust each succeeding cylinder in firing order, properly positioning the crankshaft for each cylinder.

Re-check the valve clearances and re-adjust any that are outside the limits. On this second check, align the oil passages in the adjusting screws of engines incorporating pressure-lubricated valves.

Adjusting Valves on R-2800 Engine

Establish top-center position of the No. 11 cylinder on the exhaust stroke. To do this, first ascertain that the piston is coming up on the compression stroke. Then insert an aluminum tube into the spark plug hole and turn the propeller in the direction of rotation until the piston has gone through the power stroke and returned to the top of the cylinder again. After the approximate top piston position has been ascertained, establish true top piston position by turning the propeller first in one direction and then in the other, until the position of the aluminum tube indicates the piston is at its highest point in the cylinder. A top-center indicator can also be used to establish top piston position.

Depress the intake valve on the No. 7 cylinder and the exhaust valve on the No. 15 cylinder, using a valve depressor tool. The valves must be depressed and released simultaneously and smoothly. These valves must be unloaded to remove the spring tension from the side positions on the cam and thus permit the cam to slide away from the valves to be adjusted until it contacts the cam bearing. This locates the cam in a definite position and prevents cam shift from introducing errors in clearance.

Adjust the intake valve on the No. 1 cylinder and the exhaust valve on the No. 3 cylinder. Follow the chart in figure 10–50 in adjusting the remaining valves.

Set Piston on Top Center Exhaust	Unload Valves on Cylinders		Check and Adjust Valves on Cylinders	
Cylinder Number	Intake	Exhaust	Intake	Exhaust
11	7	15	1	3
4	18	8	12	14
15	11	1	5	7
8	4	12	16	18
1	15	5	9	11
12	8	16	2	4
5	1	9	13	15
16	12	2	6	8
9	5	13	17	1
2	16	6	10	12
13	9	17	3	5
6	2	10	14	16
17	13	3	7	9
10	6	14	18	2
3	17	7	11	13
14	10	18	4	6
7	3	11	15	17
18	14	4	8	10

FIGURE 10–50. Valve clearance adjustment chart for R–2800 engine.

After completing the first check and adjustment of valve clearances, make a second check and re-adjust any clearances which vary from those specified in the engine manufacturer's service manual. On this second check, follow the precautions outlined in this chapter under adjustment of pressure-lubricated valves for Pratt and Whitney engines.

Adjusting Valves on R-1830 Engine

Establish compression stroke of the No. 1 cylinder by holding a thumb over the spark plug hole to feel cylinder compresion as the propeller is turned in the direction of rotation. When the pressure indicates that the piston is coming up on compression stroke, insert an aluminum tube into the spark plug hole and continue turning the propeller until the piston is at the top of its stroke.

With the crankshaft properly set, depress the intake valve on the No. 9 cylinder and the exhaust valve on the No. 7 cylinder with a valve depressor tool, and release them simultaneously. This operation relieves pressure on the sides of the cam and permits it to shift away from the valves in the No. 1 cylinder. The valves to be depressed are open at this time; thus. the ball end of the push rod will not fall out of position when the valves are depressed.

Adjust both intake and exhaust valves on the No. 1 cylinder. Check and adjust the valves on the remaining cylinders in firing order, following the chart in figure 10–51.

After completing this initial check, make a second check and re-adjust any clearances which are outside the limits specified in the engine manufacturer's maintenance manual. On this second check, follow the special precautions for adjustment of pressure-lubricated valves on Pratt and Whitney engines.

Adjusting Valves on 0-300, 0-335, 0-405, 0-425, V0-435 and 0-470 Engines

In checking and adjusting valve clearances on any of these engines, first set the piston in the No. 1 cylinder at top-center compression stroke. To find the right stroke, hold a thumb over the spark plug hole and turn the propeller in the direction of rotation until the pressure buildup indicates that the piston is coming up on compression stroke. Then insert an aluminum tube into the spark plug hole and continue turning the propeller until the piston is at the top of its stroke. Rock the propeller back and forth to aid in accurately positioning the piston.

After positioning the piston and crankshaft, displace the oil in the hydraulic tappet assembly by depressing the rocker arm with the tool specified in the engine manufacturer's service manual. Apply pressure smoothly and evenly since excessive force may damage the rocker arm or the push rod. Four or 5 seconds will be required to displace the oil

Set Piston on Top Center Compression	Unload Valves on Cylinders		Check and Adjust Valves on Cylinders
Cylinder Number	Intake	Exhaust	Intake and Exhaust
1	9	7	1
10	4	2	10
5	13	11	5
14	8	6	14
9	3	1	9
4	12	10	4
13	7	5	13
8	2	14	8
3	11	9	3
12	6	4	12
7	1	13	7
2	10	8	2
11	5	3	11
6	14	12	6

FIGURE 10–51. Valve clearance adjustment chart for R–1830 engine.

from the hydraulic tappet. If no clearance is obtained, remove and wash the tappet plunger and then re-check the clearance. Where valve adjustments are provided, re-adjust as necessary. On engines on which no adjustment is provided, replace the push rod with a longer or shorter rod, as outlined in the specific instructions for the engine.

Adjust the valves on succeeding cylinders in the engine firing order. After completing this initial check, make a second check and re-adjust any clearances which are outside the specified limits.

Valve Spring Replacement

A broken valve spring seldom affects engine operation and can, therefore, be detected only during careful inspection. Because multiple springs are used, one broken spring is hard to detect. But when a broken valve spring is discovered, it can be replaced without removing the cylinder. During valve spring replacement, the important precaution to remember is not to damage the spark plug hole threads. The complete procedure for valve spring replacement is as follows:

(1) Remove one spark plug from the cylinder.
(2) Turn the propeller in the direction of rotation until the piston is at the top of the compression stroke.
(3) Remove rocker arm.
(4) Using a valve spring compressor, compress the spring and remove the valve keepers. During this operation, it may be necessary to insert a piece of brass rod through the spark plug hole to decrease the space between the valve and the top of the piston head to break the spring retaining washer loose from the keepers. The piston, being at the top position on the compression stroke, prevents the valve from dropping down into the cylinder once the spring retaining washers are broken loose from the keepers on the stem.
(5) Remove the defective spring and any broken pieces from the rocker box.
(6) Install a new spring and correct washers. Then, using the valve spring compressor, compress the spring and, if necessary, move the valve up from the piston by means of a brass rod inserted through the spark plug hole.
(7) Re-install the keepers and rocker arms. Then check and adjust the valve clearance.
(8) Re-install the rocker box cover and the spark plug.

COLD CYLINDER CHECK

The cold cylinder check determines the operating characteristics of each cylinder of an air-cooled engine. The tendency for any cylinder or cylinders to be cold or to be only slightly warm indicates lack of combustion or incomplete combustion within the cylinder. This must be corrected if best operation and power conditions are to be obtained. The cold cylinder check is made with a cold cylinder indicator (Magic Wand). Engine difficulties which can be analyzed by use of the cold cylinder indicator (figure 10–52) are:

(1) Rough engine operation.
(2) Excessive r.p.m. drop during the ignition system check.
(3) High manifold pressure for a given engine r.p.m. during the ground check when the propeller is in the full low-pitch position.
(4) Faulty mixture ratios caused by improper valve clearance.

In preparation for the cold cylinder check, head

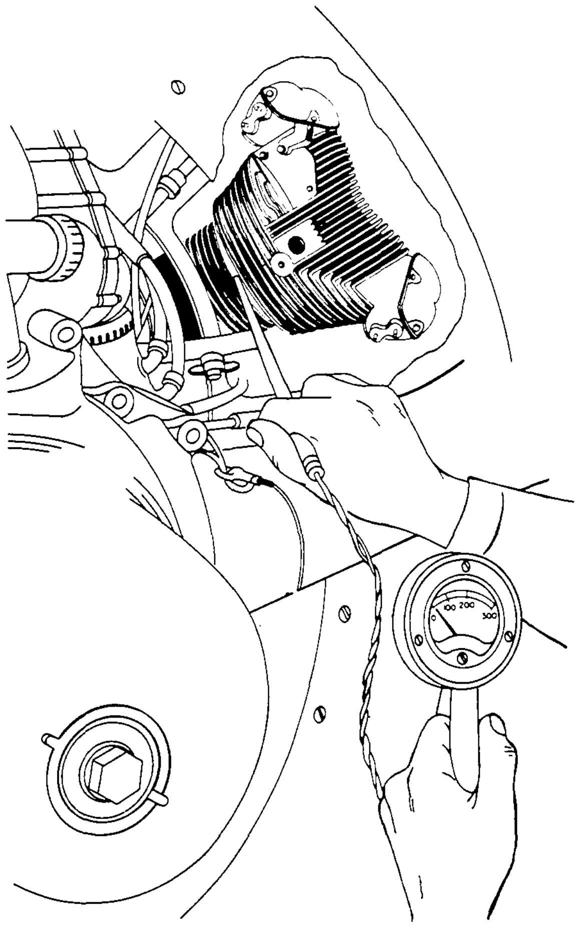


FIGURE 10–52. Using a cold cylinder indicator.

the aircraft into the wind to minimize irregular cooling of the individual cylinders and to ensure even propeller loading during engine operation.

Open the cowl flaps. Do not close the cowl flaps under any circumstances, as the resulting excessive heat radiation will affect the readings obtained and can damage the ignition leads.

Start the engine with the ignition switch in the "BOTH" position. After the engine is running, place the ignition switch in the position in which any excessive r.p.m. drop is obtained. When excessive r.p.m. drop is encountered on both right and left switch positions, or when excessive manifold pressure is obtained at a given engine r.p.m., perform the check twice, once on the left and once on the right switch position.

Operate the engine at its roughest speed between 1,200 and 1,600 r.p.m. until a cylinder head temperature reading of 150° to 170° C. (302° to 338° F.) is obtained, or until temperatures stabilize at a lower reading. If engine roughness is encountered at more than one speed, or if there is an indication that a cylinder ceases operating at idle or higher speeds, run the engine at each of these speeds and perform a cold cylinder check to pick out all the dead or intermittently operating cylinders. When low-power output or engine vibration is encountered at speeds above 1,600 r.p.m. when operating with the ignition switch on "BOTH," run the engine at the speed where the difficulty is encountered until the cylinder head temperatures are up to 150° to 170° C. or until the temperatures have stabilized at a lower value.

When cylinder head temperatures have reached the values prescribed in the foregoing paragraph, stop the engine by moving the mixture control to the idle cutoff or full lean position. When the engine ceases firing, turn off both ignition and master switches. Record the cylinder head temperature reading registered on the cockpit gage.

As soon as the propeller has ceased rotating, move a maintenance stand to the front of the engine. Connect the clip attached to the cold cylinder indicator lead to the engine or propeller to provide a ground for the instrument. Press the tip of the indicator pickup rod against each cylinder, and record the relative temperature of each cylinder. Start with number one and proceed in numerical order around the engine, as rapidly as possible. To obtain comparative temperature values, a firm contact must be made at the same relative location on each cylinder. Re-check any outstandingly low values. Also re-check the two cylinders having the highest readings to determine the amount of cylinder cooling during the test. Compare the temperature readings to determine which cylinders are dead or are operating intermittently.

Difficulties which may cause a cylinder to be inoperative (dead) on both right and left magneto positions are:

(1) Defective spark plugs.
(2) Incorrect valve clearances.
(3) Leaking impeller oil seal.
(4) Leaking intake pipes.
(5) Lack of compression.
(6) Plugged push rod housing drains.
(7) Faulty operation of the fuel-injection nozzle (on fuel-injection engines).

Before changing spark plugs or making an ignition harness test on cylinders that are not operating or are operating intermittently, check the magneto ground leads to determine that the wiring is connected correctly.

Repeat the cold cylinder test for the other magneto positions on the ignition switch, if necessary. Cooling the engine between tests is unnecessary. The airflow created by the propeller and the cooling effect of the incoming fuel/air mixture will be sufficient to cool any cylinders that are functioning on one test and not functioning on the next.

In interpreting the results of a cold cylinder check, remember that the temperatures are relative. A cylinder temperature taken alone means little, but when compared with the temperatures of other cylinders on the same engine, it provides valuable diagnostic information. The readings shown in figure 10–53 illustrate this point. On this check, the cylinder head temperature gage reading at the time the engine was shut down was 160° C. on both tests.

A review of these temperature readings reveals that, on the right magneto, cylinder number 6 runs cool and cylinders 8 and 9 run cold. This indicates that cylinder 6 is firing intermittently and cylinders 8 and 9 are dead during engine operation on the front plugs (fired by the right magneto). Cylinders 9 and 10 are dead during operation on the rear plugs (fired by the left magneto). Cylinder 9 is completely dead.

An ignition system operational check would not disclose this dead cylinder since the cylinder is inoperative on both right and left switch positions.

A dead cylinder can be detected during run-up, since an engine with a dead cylinder will require a

Cylinder No.	Right Magneto	Left Magneto
1	180	170
2	170	175
3	170	170
4	145	150
5	150	155
6	100	150
7	155	160
8	70	155
9	60	45
10	150	65
11	150	145
12	145	150
13	150	145
14	145	145

FIGURE 10–53. Readings taken during a cold-cylinder check.

higher-than-normal manifold pressure to produce any given r.p.m. below the cut-in speed of the propeller governor. A dead cylinder could also be detected by comparing power input and power output with the aid of a torquemeter.

Defects within the ignition system that can cause a cylinder to go completely dead are:

(1) Both spark plugs inoperative.

(2) Both ignition leads grounded, leaking, or open.

(3) A combination of inoperative spark plugs and defective ignition leads.

Faulty fuel-injection nozzles, incorrect valve clearances, and other defects outside the ignition system can also cause dead cylinders.

In interpreting the readings obtained on a cold-cylinder check, the amount the engine cools during the check must be considered. To determine the extent to which this factor should be considered in evaluating the readings, re-check some of the first cylinders tested and compare the final readings with those made at the start of the check. Another factor to be considered is the normal variation in temperature between cylinders and between rows. This variation results from those design features which affect the airflow past the cylinders.

TURBINE ENGINE MAINTENANCE

Turbine powerplant maintenance procedures vary widely according to the design and construction of the particular engine being serviced. The detailed procedures recommended by the engine manufacturer should be followed when performing inspections or maintenance.

Maintenance information presented in this section is not intended to specify the exact manner in which maintenance operations are to be performed, but is included to convey a general idea of the procedures involved. For the most part, the Pratt and Whitney JT3 turbojet engine is used in describing procedures for axial-flow compressor and turbine blade maintenance.

For inspection purpose, the turbine engine is divided into two main sections, the cold section and the hot section.

Compressor Section

Maintenance of the compressor, or cold section, is one of the concerns of the aviation mechanic. Damage to blades can cause engine failure and possible loss of costly aircraft. Much of the damage to the blades arises from foreign matter being drawn into the turbine engine air intakes.

The atmosphere near the ground is filled with tiny particles of dirt, oil, soot, and other foreign matter. A large volume of air is introduced into the compressor, and centrifugal force throws the dirt particles outward so that they build up to form a coating on the casing, the vanes, and the compressor blades.

Accumulation of dirt on the compressor blades reduces the aerodynamic efficiency of the blades with resultant deterioration in engine performance. The efficiency of the blades is impaired by dirt deposits in a manner similar to that of an aircraft wing under icing conditions. Unsatisfactory acceleration and high exhaust gas temperature can result from foreign deposits on compressor components.

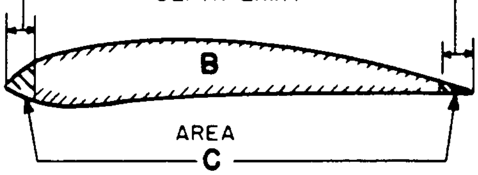
An end result of foreign particles, if allowed to accumulate in sufficient quantity, would be complete engine failure. The condition can be remedied by periodic inspection, cleaning, and repair of compressor components. This subject is treated in a general manner in this text because of the many different models of turbojet engines now in use in aviation.

Inspection and Cleaning

Minor damage to axial-flow engine compressor blades may be repaired if the damage can be removed without exceeding the allowable limits established by the manufacturer. Typical compressor blade repair limits are shown in figure 10–54. Well-rounded damage to leading and trailing edges that is evident on the opposite side of the blade is usually acceptable without re-work, provided the damage is in the outer half of the blade only and the indentation does not exceed values specified in

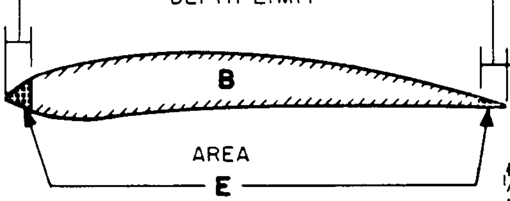
MAXIMUM ALLOWABLE REPAIR LIMITS—INCHES				
	STEEL BLADES		TITANIUM BLADES	
BLADE AREA	STAGES		STAGES	
	1 through 4	5 through 9	1 through 4	5 through 9
A	5/16 R	1/4 R	5/16 R	1/4 R
B	1/32 D	1/32 D	1/32 D	1/32 D
C	5/32 D	1/8 D	5/32 D	1/8 D
D	.008 D	.005 D	NONE	NONE
E	1/32 D	1/32 D	1/32 D	1/32 D

R—RADIUS D—DEPTH



CAUTION

THE LIMITS REFERRED TO IN THIS FIGURE IN AREAS "C" AND "E" PERTAIN TO LOCAL, ISOLATED, DAMAGED AREAS ONLY AND MUST NOT BE INTERPRETED AS AUTHORITY FOR REMOVAL OF MATERIAL ALL ACROSS THE TIP AND LEADING OR TRAILING EDGES AS MIGHT BE DONE IN A SINGLE MACHINING CUT.



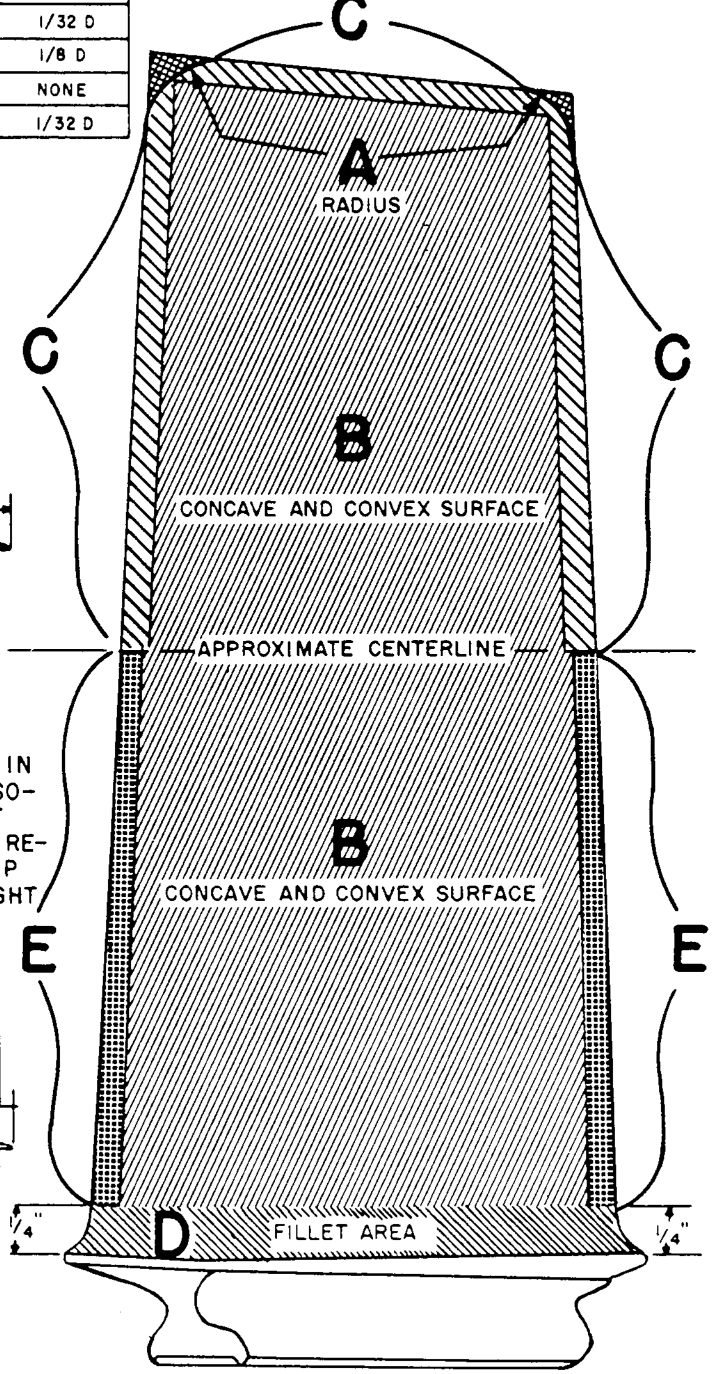


FIGURE 10–54. Typical compressor blade repair limits.

the engine manufacturer's service and overhaul instruction manuals.

When working on the inner half of the blade, damage must be treated with extreme caution. Repaired compressor blades are inspected by either magnetic particle or fluorescent penetrant inspection methods, or they are dye checked to ensure that all traces of the damage have been removed. All repairs must be well blended so that surfaces are smooth (figure 10–55). No cracks of any extent are tolerated in any area.

Whenever possible, stoning and local rework of the blade are performed parallel to the length of the blade. Rework must be accomplished by hand, using stones, files, or emery cloth. Do not use a power tool to buff the entire area of the blade. The surface finish in the repaired area must be comparable to that of a new blade.

On centrifugal flow engines, it is difficult to inspect the compressor inducers without first removing the air-inlet screen. After removing the screen, clean the compressor inducer and inspect it with a strong light. Check each vane for cracks by slowly turning the compressor.

Look for cracks in the leading edges. A crack is usually cause for engine replacement. The compressor inducers are normally the parts that are damaged by the impingement of foreign material during engine operation.

Compressor inducers are repaired by stoning out and blending the nicks and dents in the "critical band" (1-1/2 to 2-1/2 inches from the outside edge), if the depth of such nicks or dents does not exceed that specified in the engine manufacturer's service or overhaul instruction manuals. For nicks requiring repair, stone out material beyond the depth of damage to remove the resulting cold-worked metal. A generous radius must be applied at the edges of the blend. After blending the nick, it should be smoothed over with a crocus cloth. Pitting, nicks, or corrosion found on the sides of the inducer vanes are similarly removed by blending.

Causes of Blade Damage

Loose objects often enter an engine either accidentally or through carelessness. Items, such as pencils, handkerchiefs, and cigarette lighters, are often drawn into the engine. Do not carry any objects in shirt pockets when working around turbojet engines.

A compressor rotor can be damaged beyond repair by tools that are left in the air intake, where they are drawn into the engine on subsequent starts. A simple solution to the problem of tools being

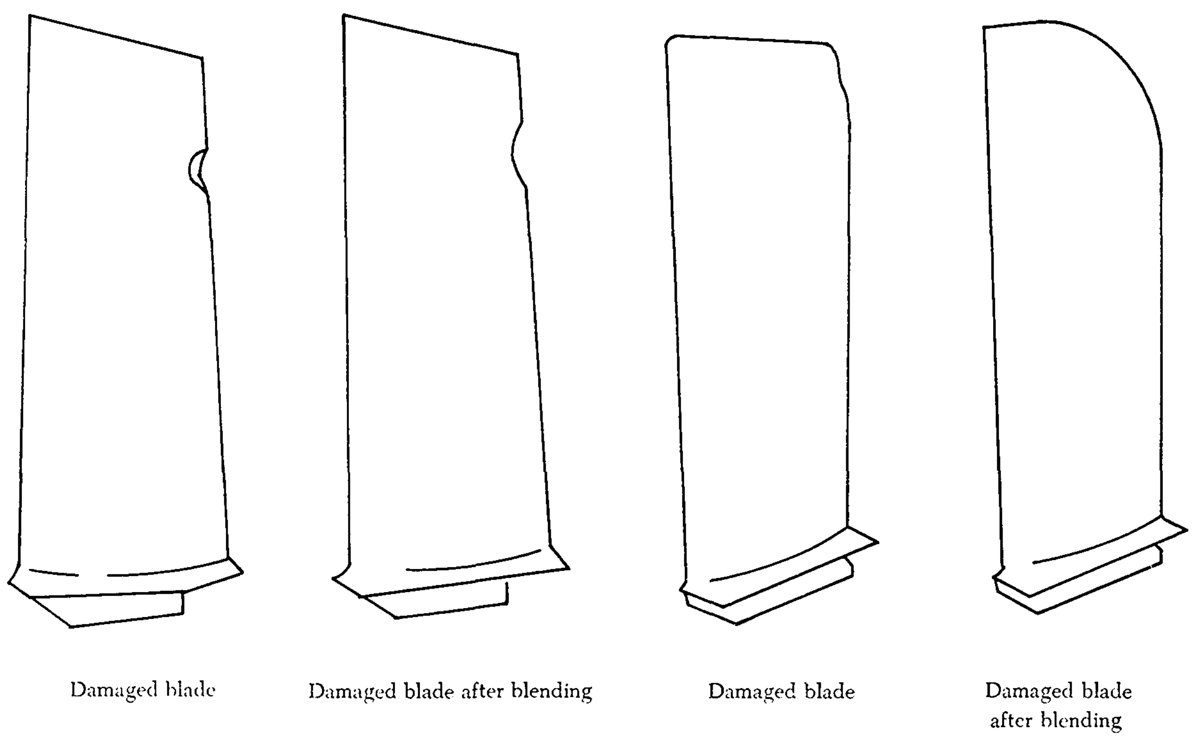


FIGURE 10–55. Compressor blade repair.

drawn into an engine is to check the tools against a tool checklist. Prior to starting a turbine engine, make a minute inspection of engine inlet ducts to assure that items such as nuts, bolts, lockwire, or tools were not left there after work had been performed.

Figure 10–56 shows some examples of blade damage to an axial-flow engine. The descriptions and possible causes of blade damage are given in table 11.

Corrosion pitting is not considered serious on the compressor stator vanes of axial-flow engines if the pitting is within the allowed tolerance.

Do not attempt to repair any vane by straightening, brazing, welding, or soldering. Crocus cloth, fine files, and stones are used to blend out damage by removing a minimum of material and leaving a surface finish comparable to that of a new part. The purpose of this blending is to minimize stresses that concentrate at dents, scratches, or cracks.

The inspection and repair of air intake guide vanes, swirl vanes, and screens on centrifugal-flow engines necessitates the use of a strong light. Inspect screen assemblies for breaks, rips, or holes. Screens may be tin-dipped to tighten the wire mesh, provided the wires are not worn too thin. If the frame strip or lugs have separated from the screen frames, re-brazing may be necessary.

Inspect the guide and swirl vanes for looseness. Inspect the outer edges of the guide vanes, paying particular attention to the point of contact between the guide and swirl vanes for cracks and dents due to the impingement of foreign particles; also inspect the edges of the swirl vanes. Inspect the downstream edge of the guide vanes very closely, because cracks are generally more prevalent in this area. Cracks which branch or fork out so that a piece of metal could break free and fall into the compressor are cause for vane rejection.

Blending and Replacement

Because of the thin-sheet construction of hollow vanes, blending on the concave and convex surfaces, including the leading edge, is limited. Small, shallow dents are acceptable if the damage is of a rounded or gradual contour type and not a sharp or V-type, and if no cracking or tearing of vane material is evident in the damaged area.

Trailing edge damage (figure 10–57) may be blended, if one-third of the weld seam remains after repair. Concave surfaces of rubber-filled vanes may have allowable cracks extending inward from the outer airfoil, provided there is no suggestion of pieces breaking away. Using a light and mirror, inspect each guide vane trailing edge and vane body for cracks or damage caused by foreign objects.

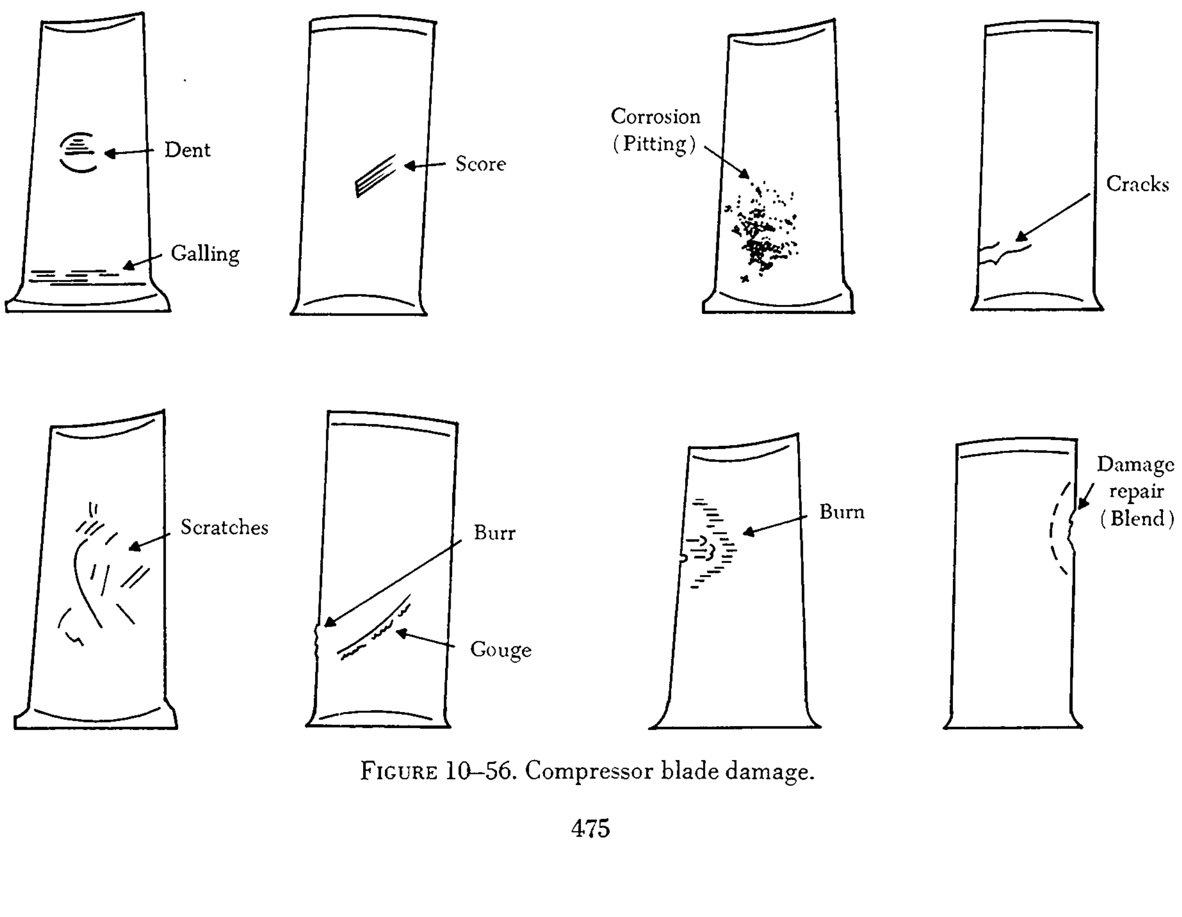


FIGURE 10–56. Compressor blade damage.

TABLE 11. Blade maintenance terms

Term	Appearance	Usual causes
Blend	Smooth repair of ragged edge or surface into the contour of surrounding area.	
Bow	Bent blade.	Foreign objects.
Burning	Damage to surfaces evidenced by discoloration or, in severe cases, by flow of material.	Excessive heat.
Burr	A ragged or turned out edge.	Grinding or cutting operation.
Corrosion (pits)	Breakdown of the surface; pitted appearance.	Corrosive agents—moisture, etc.
Cracks	A partial fracture (separation).	Excessive stress due to shock, overloading, or faulty processing; defective materials; overheating.
Dent	Small, smoothly rounded hollow.	Striking of a part with a dull object.
Gall	A transfer of metal from one surface to another.	Severe rubbing.
Gouging	Displacement of material from a surface; a cutting or tearing effect.	Presence of a comparatively large foreign body between moving parts.
Growth	Elongation of blade.	Continued and/or excessive heat and centrifugal force.
Pit	(See Corrosion.)	
Profile	Contour of a blade or surface.	
Score	Deep scratches.	Presence of chips between surfaces.
Scratch	Narrow shallow marks.	Sand or fine foreign particles; careless handling.

COMBUSTION SECTION

One of the controlling factors in the service life of the turbine engine is the inspection and cleaning of the hot section. Too much emphasis cannot be placed on the importance of careful inspection and repair of this section. One of the most frequent discrepancies that will be detected while inspecting the hot section of a turbine engine is cracking. These cracks may occur in many forms, and the only way to determine that they are within acceptable limits is to refer to the applicable engine manufacturer's service and overhaul manuals.

Cleaning the hot section is not usually necessary for a repair in the field. However, if it becomes necessary to disassemble the engine, a correct and thorough cleaning is of the greatest importance to a successful inspection and repair.

Engine parts can be degreased by using the emulsion-type cleaners or chlorinated solvents. The emulsion-type cleaners are safe for all metals, since they are neutral and noncorrosive. Cleaning parts by the chlorinated solvent method leaves the parts absolutely dry; if they are not to be subjected to further cleaning operations, they should be sprayed with a corrosion-preventive solution to protect them against rust or corrosion.

The extent of disassembly is to open the combustion case for the inspection of the hot section. However, in performing this disassembly, numerous associated parts will be readily accessible for inspection.

The importance of properly supporting the engine and the parts being removed cannot be overstressed. The alignment of parts being removed and installed is also of the utmost importance.

After all repairs are made, the manufacturer's detailed assembly instructions should be followed. These instructions are important in efficient engine maintenance, and the ultimate life and performance of the engine can be seriously affected if they are slighted through carelessness or neglect.

Extreme care must be taken to prevent dirt, dust, cotter pins, lockwire, nuts, washers, or other foreign material from entering the engine. If, at any time, such pieces are dropped, the assembly of the engine must stop until the dropped article is located, even though this may require a considerable amount of disassembly.

Marking Materials for Combustion Section Parts

Certain materials may be used for temporary marking during assembly and disassembly. Layout dye (lightly applied) or chalk may be used to mark parts that are directly exposed to the engine's gas path, such as turbine blades and disks, turbine vanes, and combustion chamber liners. A wax marking pencil may be used for parts that are not

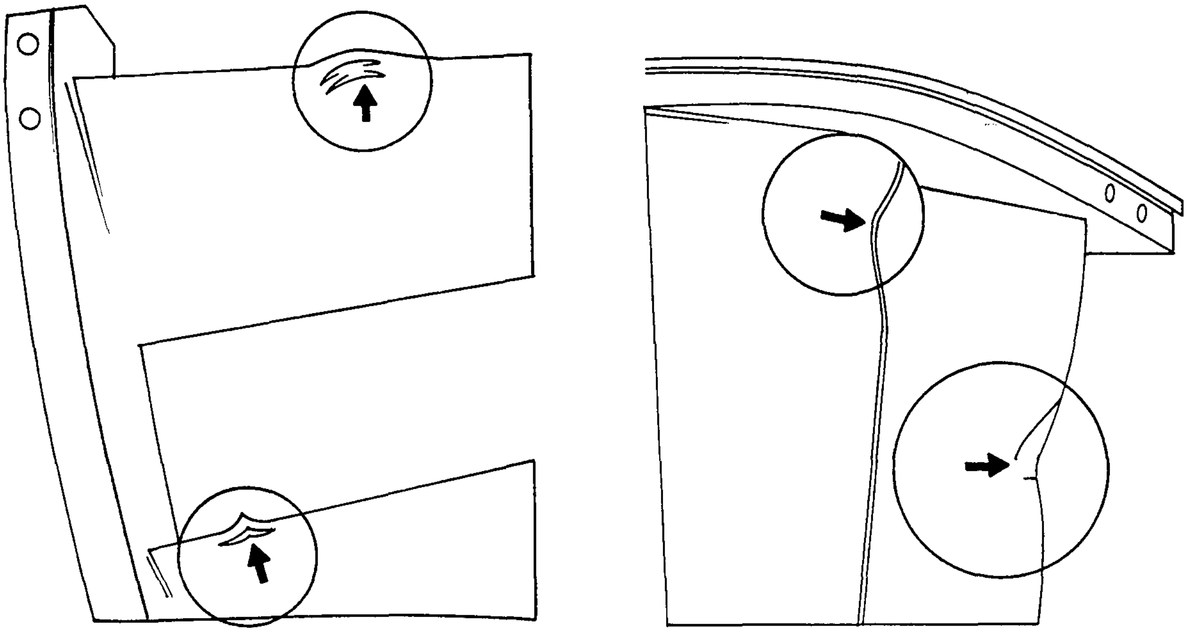


FIGURE 10–57. Guide vane trailing edge damage.

directly exposed to the gas path. Do not use a wax marking pencil on a liner surface or a turbine rotor.

The use of carbon alloy or metallic pencils is not recommended because of the possibility of causing intergranular attack, which could result in a reduction in material strength.

Combustion Section Inspection

The following are general procedures for performing a hot section (turbine and combustion section) inspection. It is not intended to imply that these procedures are to be followed when performing repairs or inspections on turbine engines. However, the various practices are typical of those used on many turbine engines. Where a clearance or tolerance is shown it is for illustrative purposes only. Always follow the instructions contained in the applicable manufacturer's maintenance and overhaul manuals.

The entire external combustion case should be inspected for evidence of hotspots, exhaust leaks, and distortions before the case is opened. After the combustion case has been opened, the combustion chambers can be inspected for localized overheating, cracks, or excessive wear. Inspect the first-stage turbine blades and nozzle guide vanes for cracks, warping, or foreign object damage. Also inspect the combustion chamber outlet ducts and turbine nozzle for cracks and for evidence of foreign object damage.

Inspection and Repair of Combustion Chambers and Covers

Inspect the combustion chambers and covers for cracks by using dye penetrant or the fluorescent penetrant inspection method. Any cracks, nicks, or dents in the cover are usually cause for rejection. Inspect the covers, noting particularly the area around the fuel drain bosses for any pits or corrosion.

Inspect the interior of the combustion liners for excess weld material expelled from the circumferentially welded seams. To prevent future damage to the turbine blades, remove weld material or slag that is not thoroughly fused to the base material of the combustion liner.

When repairing the combustion chamber liner, the procedures given in the appropriate engine manufacturer's overhaul instruction manual should be followed. If there is doubt that the liner is serviceable, it should be replaced.

Acceptance Standards for Combustion Chamber Liners

The combustion chamber liner is inspected to determine the serviceability of liner weldments that have deteriorated from engine operation. Limitations on such deterioration are based on the requirement that the combustion chambers must give satisfactory service during the period of operation between successive inspections of the parts.

Certain types of cracking and burning deterioration resulting from thermal stresses may be found after periods of operation. However, the progress of such discrepancies with further operation is usually negligible, since the deterioration produced by thermal stresses, in effect, relieves the original stress condition.

Usually, a given type of deterioration will recur from chamber to chamber in a given engine.

Current manufacturer's service and overhaul manuals should be consulted for allowable limits of cracks and damage. The following paragraphs describe some typical discrepancies found on combustion chambers. Figure 10–58 shows a combustion chamber liner with the components listed to help locate discrepancies.

When considering the acceptability of a suspected liner, the aim must be to prevent the breakaway of an unsupported area of metal such as that lying in the fork of a crack or between two cracks radiating from the same airhole. Single cracks are acceptable in most cases, provided they do not cause mechanical weakness that could lead to further failure.

Combustion Chamber Cracks

Combustion chambers should be replaced or repaired if two cracks are progressing from a free edge so that their meeting is imminent and could allow a piece of metal (that could cause turbine damage) to break loose.

Separate cracks in the baffle are acceptable. Baffle cracks connecting more than two holes should be repaired.

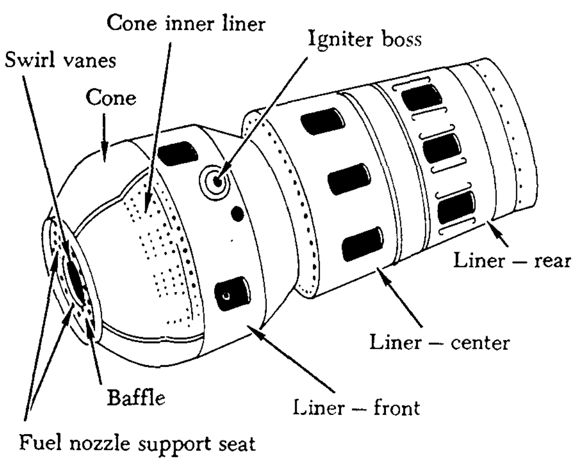


FIGURE 10–58. Combustion chamber liner nomenclature.

Cracks in the cone are rare but, at any location on this component, are cause for rejection of the liner.

Cracks in the swirl vanes are cause for rejection of the liner. Loose swirl vanes may be repaired by silver brazing.

Cracks in the front liner emanating from the airholes are acceptable, provided they do not exceed allowable limits. If such cracks fork or link with others, the liner must be repaired. If two cracks originating from the same airhole are diametrically opposite, the liner is acceptable.

Radial cracks extending from the interconnector and spark-igniter boss are acceptable if they do not exceed allowable limits and if such cracks do not fork or link with others. Circumferential cracks around the boss pads should be repaired prior to re-use of the liner.

After long periods of engine operation, the external surfaces of the combustion chamber liner location pads will often show signs of fretting. This is acceptable, provided no resultant cracks or perforation of the metal is apparent.

Any cover or chamber inadvertently dropped on a hard surface or mishandled should be thoroughly inspected for minute cracks which may elongate over a period of time and then open, creating a hazard.

Burned or Buckled Areas

Parts may be found wherein localized areas have been heated to an extent to buckle small portions of the chamber. Such parts are considered acceptable if the burning of the part has not progressed into an adjacent welded area or to such an extent as to weaken the structure of the liner weldment. Buckling of the combustion chamber liner can be corrected by straightening the liner.

Moderate buckling and associated cracks are acceptable in the row of cooling holes. More severe buckling that produces a pronounced shortening or tilting of the liner is cause for rejection.

Upon completion of the repairs by welding, the liner should be restored as closely as possible to its original shape. This usually can be accomplished by using ordinary sheetmetal-forming hand dollies and hammers available at most metal working and welding shops.

Fuel Nozzle and Support Assemblies

Clean all carbon deposits from the nozzles by washing with a cleaning fluid approved by the engine manufacturer and remove the softened deposits with a soft bristle brush or small piece of wood. It is desirable to have filtered air passing through the nozzle during the cleaning operation to carry away deposits as they are loosened. Make sure all parts are clean. Dry the assemblies with clean, filtered air.

Because the spray characteristics of the nozzle may become impaired, no attempt should be made to clean the nozzles by scraping with a hard implement or by rubbing with a wire brush.

Inspect each component part of the fuel nozzle assembly for nicks and burrs.

INSPECTION AND REPAIR OF TURBINE DISK

Turbine Disk Inspection

The inspection for cracks is of the utmost importance. Crack detection, when dealing with the turbine disk and blades, is practically all visual. The material of which the disk and blades are made does not lend itself freely to crack detection fluids; therefore, they should be scrutinized most carefully under at least a 9- to 12-power magnifying glass. Any questionable areas call for more minute inspection. Cracks, on the disk, however minute, necessitate the rejection of the disk and replacement of the turbine rotor. Slight pitting caused by the impingement of foreign matter may be blended by stoning and polishing.

Turbine Blade Inspection

Turbine blades are usually inspected and cleaned in the same manner as compressor blades. However, because of the extreme heat under which the turbine blades operate, they are more susceptible to damage. Using a strong light and a magnifying glass, inspect the turbine blades for stress rupture cracks (figure 10–59) and deformation of the leading edge (figure 10–60).

Stress rupture cracks usually appear as minute hairline cracks on or across the leading or trailing edge at a right angle to the edge length. Visible cracks may range in length from one-sixteenth inch upward. Deformation, caused by over-temperature, may appear as waviness and/or areas of varying airfoil thickness along the leading edge. The leading edge must be straight and of uniform thickness along its entire length, except for areas repaired by blending.

Do not confuse stress rupture cracks or deformation of the leading edge with foreign material impingement damage or with blending repairs to the blade. When any stress rupture cracks or deformation of the leading edges of the first-stage turbine

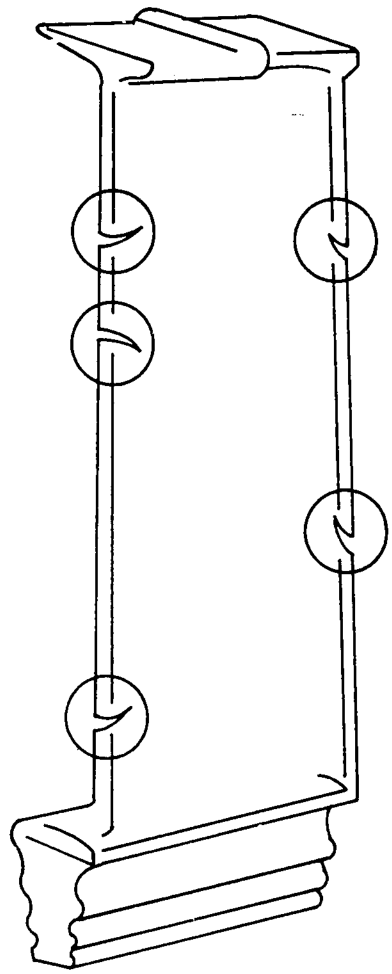


FIGURE 10–59. Stress rupture cracks.

blades are found, an over-temperature condition must be suspected. Check the individual blades for stretch and the turbine disk for hardness and stretch.

Blades removed for a detailed inspection or for a check of turbine disk stretch must be re-installed in the same slots from which they were removed. Number the blades prior to removal.

The turbine blade outer shroud should be inspected for air seal wear. If shroud wear is found, measure the thickness of the shroud at the worn area. Use a micrometer or another suitable and accurate measuring device that will ensure a good reading in the bottom of the comparatively narrow wear groove. If the remaining radial thickness of the shroud is less than that specified, the stretched blade must be replaced.

Typical blade inspection requirements are indicated in figure 10–61. Blade tip curling within a one-half-inch square area on the leading edge of the blade tip is usually acceptable if the curling is not

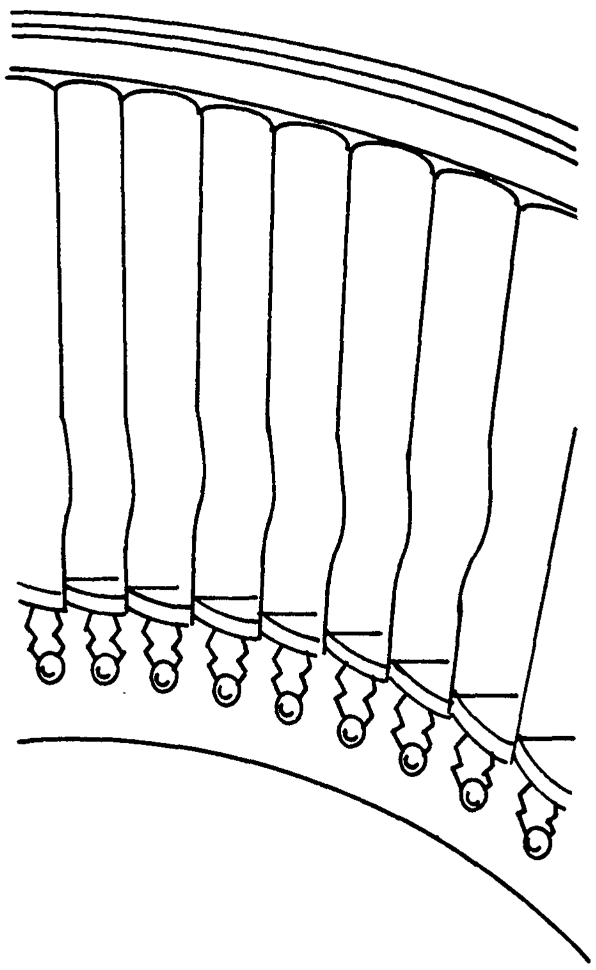


FIGURE 10–60. Turbine blade waviness.

sharp. Curling is acceptable on the trailing edge if it does not extend beyond the allowable area. Any sharp bends that may result in cracking or a piece breaking out of the turbine blade is cause for rejection, even though the curl may be within the allowable limits. Each turbine blade should be inspected for cracks.

Turbine Blade Replacement Procedure

Turbine blades are generally replaceable, subject to moment-weight limitations. These limitations are contained in the engine manufacturer's applicable technical instructions.

If visual inspection of the turbine assembly discloses several broken, cracked, or eroded blades, replacing the entire turbine assembly may be more economical than replacing the damaged blades.

A typical disk and blade assembly is illustrated in figure 10–62. In the initial buildup of the turbine, a complete set of 54 blades made in coded pairs (two blades having the same code letters), is laid out on a bench in the order of diminishing moment-weight. The code letters indicating the moment-weight balance in ounces are marked on the rear face of the fir-tree section of the blade (viewing the blade as installed at final assembly of the engine). The pair of blades having the heaviest moment-weight is numbered 1 and 28; the next heaviest pair of blades is numbered 2 and 29; the third heaviest pair is numbered 3 and 30. This is continued until all the blades have been numbered.

Mark a number 1 on the face of the hub on the turbine disk. The No. 1 blade is then installed adjacent to the number 1 on the disk (figure 10–63). The remaining blades are then installed consecutively in a clockwise direction, viewed from the rear face of the turbine disk. If there are several pairs of blades having the same code letters, they are installed consecutively before going to the next code letters.

If a blade requires replacement, the diametrically opposite blade must also be replaced. The blades used as replacements must be of the same code, but do not have to be of the same code as the blades removed. The maximum number of blades that may be replaced in the field varies between make and model of engines and is established by the engine manufacturer.

To replace a blade, or any number of blades, of a turbine disk and blade assembly, the procedures in the following paragraphs are given as an example.

Bend up the tab of each tab lock; then drive out the blade, knocking it toward the front of the turbine disk, using a brass drift and a hammer. Withdraw and discard the turbine blade locks from the blades.

Insert a new blade with the tab blade toward the front of the disk; then, while holding the tab against the disk, check the clearance between the blade shoulder and the turbine disk. It may be necessary to grind material from the shoulder of the blade to bring the clearance within limits (figure 10–64). Refer to the Table of Limits in the engine manufacturer's overhaul manual for the clearances concerning the turbine blades.

While holding the blade in the direction of rotation (counterclockwise), check the clearance between the blade shoulder tips and those of the adjacent blades (figure 10–64). If the clearance is insufficient, remove the blade and grind material from the tips to bring the clearance within limits. Using a

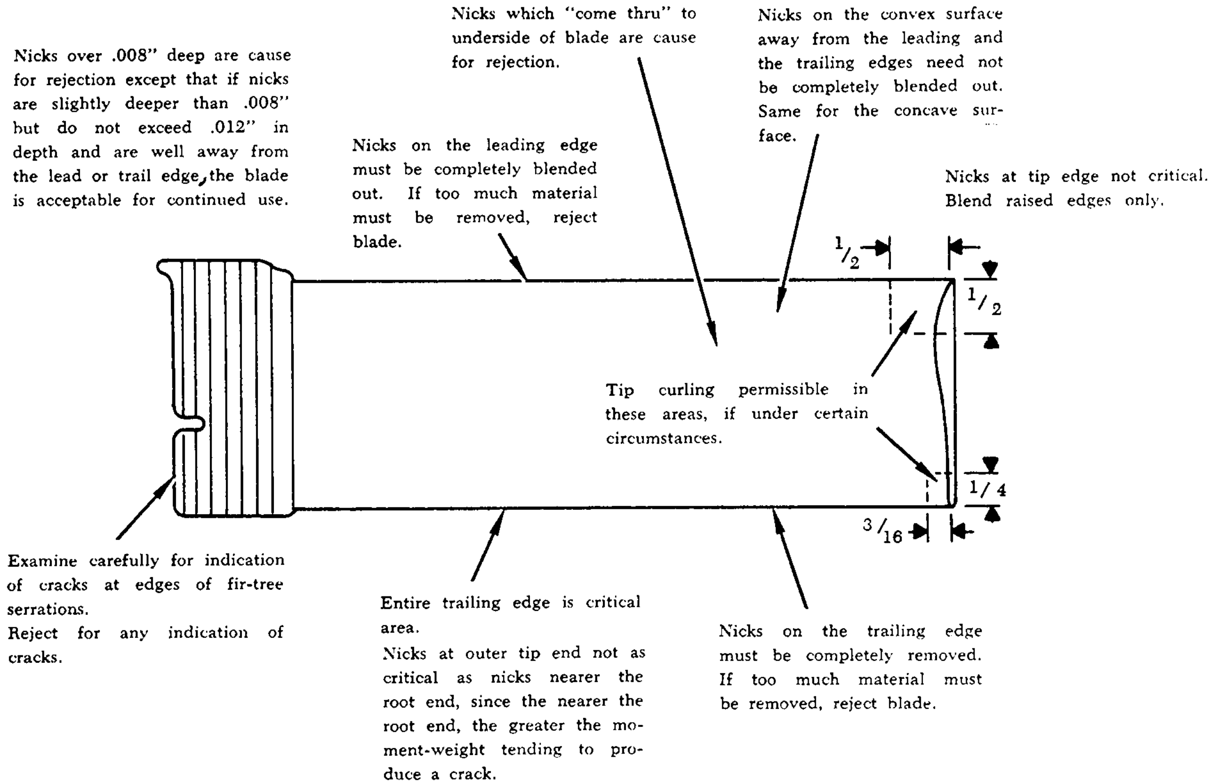


FIGURE 10–61. Typical turbine blade inspection.

dial indicator, check the blade tip radial movement while holding the blade tab against the disk.

Place a new lock in the turbine blade; then install the blade in its correct position in the turbine disk. Position the turbine so that the blade is over a peening plate, an anvil, or other suitable support. Using a starting punch, peen the tab of the lock in an inward direction. Finish peening the lock, using a finishing punch to obtain the allowable maximum axial end play. Examine the peened lock for evidence of cracking, using a 3- to 5-power glass. If it is cracked, remove the blade and install a new lock until a satisfactory installation is accomplished.

Turbine Nozzle Vane Inspection

After opening the combustion chambers and removing the combustion liners, the first-stage turbine blades and turbine nozzle vanes are accessible for inspection. The blade limits specified in the engine manufacturer's overhaul and service instruction manual should be adhered to. Figure 10–65 shows where cracks usually occur on a turbine nozzle assembly. Slight nicks and dents are permissible if the depth of damage is within limits.

Inspect the turbine nozzle vanes for bowing, measuring the amount of bowing on the trailing edge of each vane. Bowed nozzle vanes may be an indication of a malfunctioning fuel nozzle. Reject vanes which are bowed more than the allowable amount. Bowing is always greater on the trailing edge; thus if this edge is within limits, the leading edge is also acceptable.

Inspect the nozzle vanes for nicks or cracks. Small nicks are not cause for vane rejection, provided such nicks blend out smoothly.

Inspect the nozzle vane supports for defects caused by the impingement of foreign particles. Use a stone to blend any doubtful nicks to a smooth radius.

Like turbine blades, it is possible to replace a maximum number of turbine nozzle vanes in some engines. If more than this number of vanes are damaged, a new turbine nozzle vane assembly must be installed.

With the tailpipe removed, the rear turbine stage can be inspected for any cracks or evidence of blade stretch. The rear-stage nozzle can also be inspected with a strong light by looking through the rear-stage turbine.

Clearances

Checking the clearances is one of the procedures in the maintenance of the turbine section of a

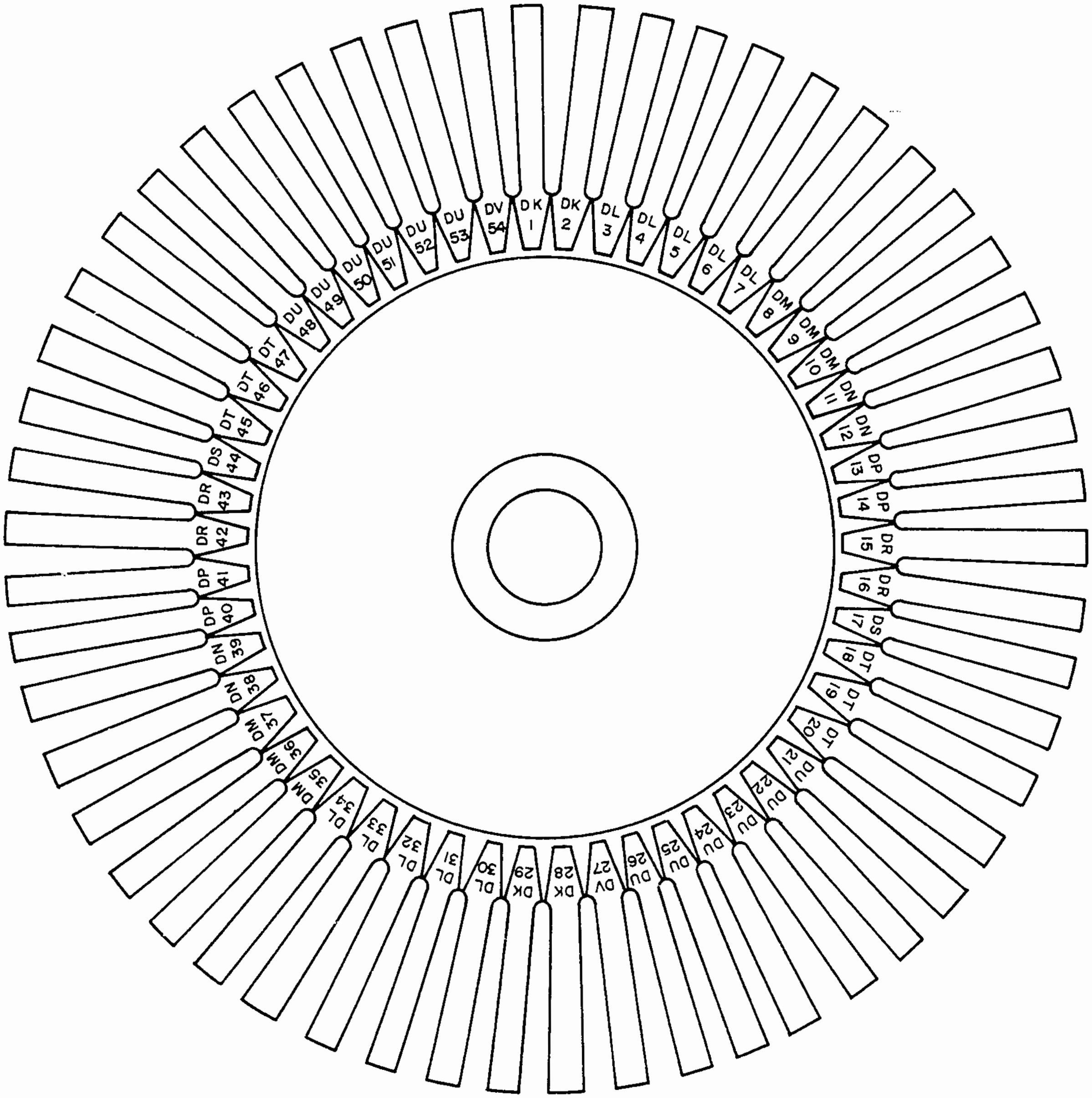


FIGURE 10–62. Typical turbine rotor blade moment-weight distribution.

turbine engine. The manufacturer's service and overhaul manual gives the procedures and tolerances for checking the turbine. Figures 10–66 and 10–67 show clearances being measured at various locations. To obtain accurate readings, special tools provided by each manufacturer must be used as described in the service instructions for specific engines.

Exhaust Section

The exhaust section of the turbojet engine is susceptible to heat cracking. This section must be thoroughly inspected along with the inspection of the combustion section and turbine section of the engine. Inspect the exhaust cone and tailpipe for cracks, warping, buckling, or hotspots. Hotspots on the tail cone are a good indication of a malfunctioning fuel nozzle or combustion chamber.

The inspection and repair procedures for the hot section of any one gas turbine engine are similar to those of other gas turbine engines. One usual difference is the nomenclature applied to the various parts of the hot section by the different manufacturers. Other differences include the manner of disassembly, the tooling necessary, and the repair methods and limits.

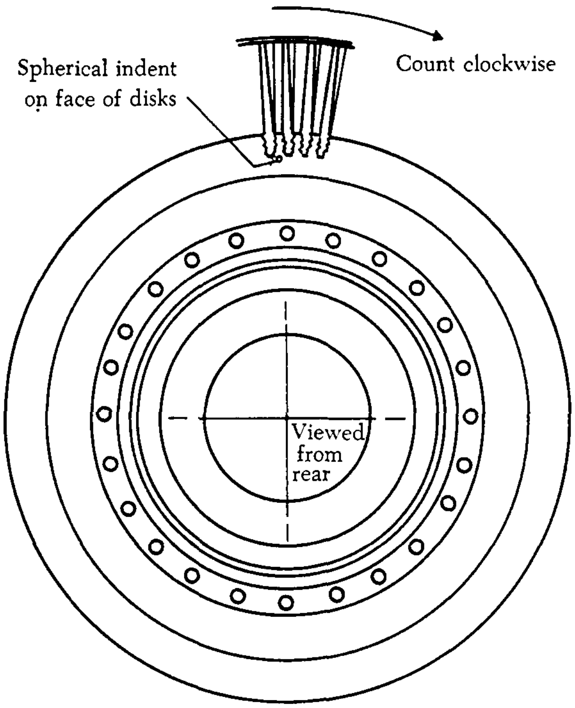


FIGURE 10–63. Turbine blades.

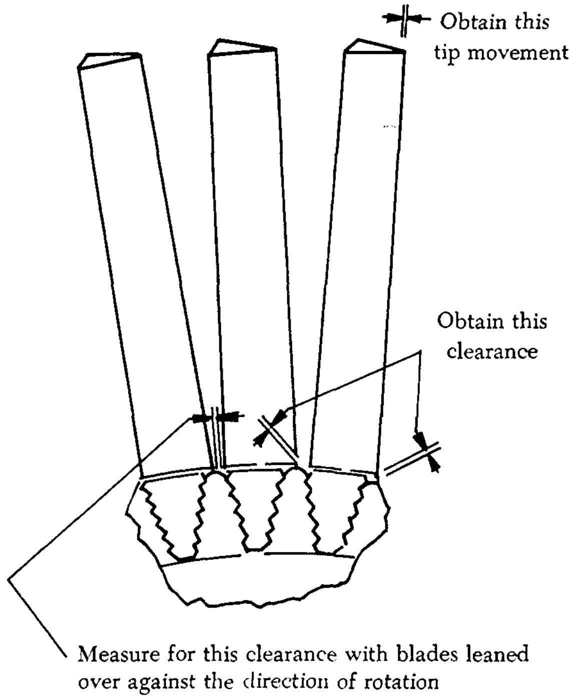


FIGURE 10–64. Turbine blade replacement clearances.

COMMERCIAL RATINGS

An understanding of gas turbine engine ratings is necessary to use intelligently the engine operating curves contained in the aircraft and engine maintenance manuals. The ratings for commercial engines are defined by the SAE (Society of Automotive Engineers).

Takeoff (wet). This is the maximum allowable thrust for takeoff. The rating is obtained by actuating the water-injection system and setting the computed "wet" thrust with the throttle, in terms of a predetermined turbine discharge pressure or engine pressure ratio for the prevailing ambient conditions. The rating is restricted to takeoff, is time-limited, and will have an altitude limitation. Engines without water injection do not have this rating.

Takeoff (dry). This is the maximum allowable thrust without the use of water injection. The rating is obtained by adjusting the throttle to the takeoff (dry) thrust for the existing ambient conditions, in terms of a predetermined turbine discharge pressure or engine pressure ratio. The rating is time-limited and is to be used for takeoff only.

Maximum continuous. This rating is the maximum thrust which may be used continuously and is intended only for emergency use at the discretion of the pilot. The rating is obtained by adjusting the throttle to a predetermined turbine discharge pressure or engine pressure ratio.

Normal rated. Normal rated thrust is the maximum thrust approved for normal climb. The rating is obtained in the same manner as maximum continuous. Maximum continuous thrust and normal rated thrust are the same on some engines.

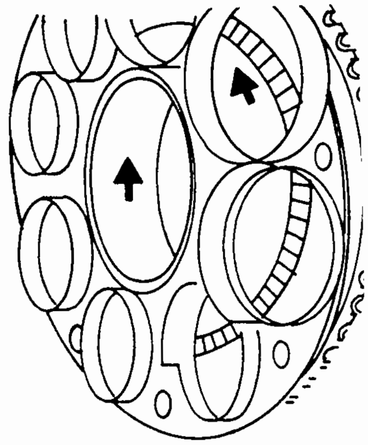
Maximum cruise. This is the maximum thrust approved for cruising. It is obtained in the same manner as maximum continuous.

Idle. This is not an engine rating, but rather a throttle position suitable for minimum thrust operation on the ground or in flight. It is obtained by placing the throttle in the idle detent on the throttle quadrant.

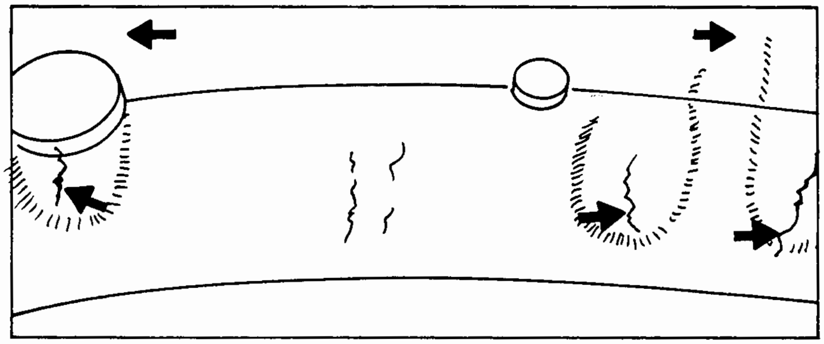
ENGINE INSTRUMENTATION

Although engine installations may differ, depending upon the type of both the aircraft and the engine, gas turbine engine operation is usually controlled by observing the instruments discussed in the following paragraphs.

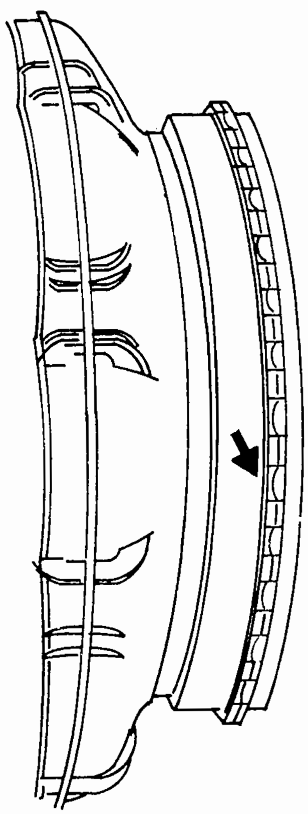
Engine thrust is indicated by either a turbine pressure indicator or an engine pressure ratio indicator, depending upon the installation. Both types of pressure instruments are discussed here because

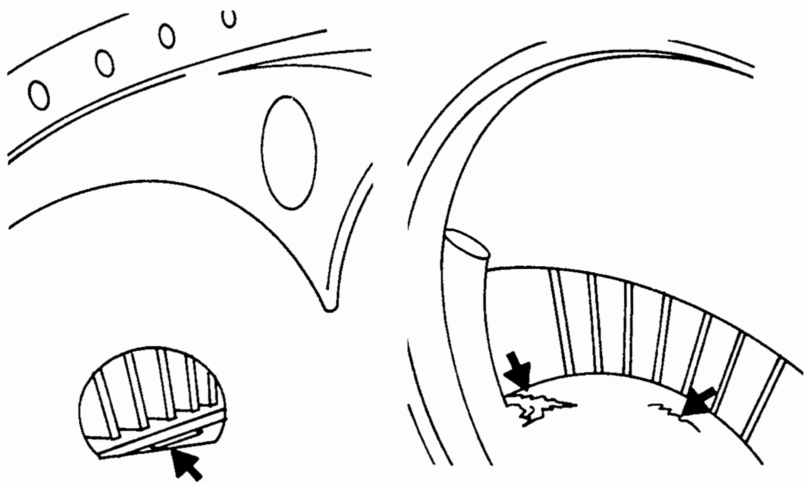


Turbine nozzle assembly.

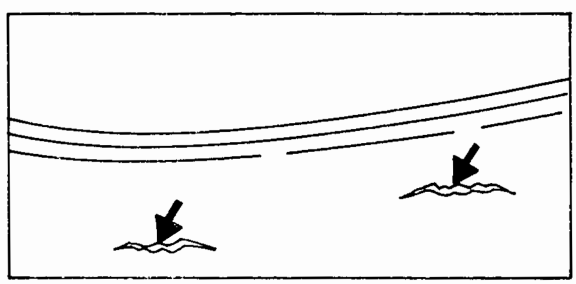


Turbine nozzle assembly at junction of combustion chamber outlet duct and turbine nozzle outer case.





Cracked area along spot weld line on inner duct.



Spot weld cracks on inner duct.

FIGURE 10–65. Typical turbine nozzle assembly defects.

either indicator may be used. Of the two, the turbine discharge pressure indicator is usually more accurate, primarily because of its simplicity of construction. It may be installed on the aircraft permanently or, in some instances temporarily, such as during an engine trim. An engine pressure ratio indicator, on the other hand, is less complex to use because it compensates automatically for the effects of airspeed and altitude factors by considering compressor inlet pressure.

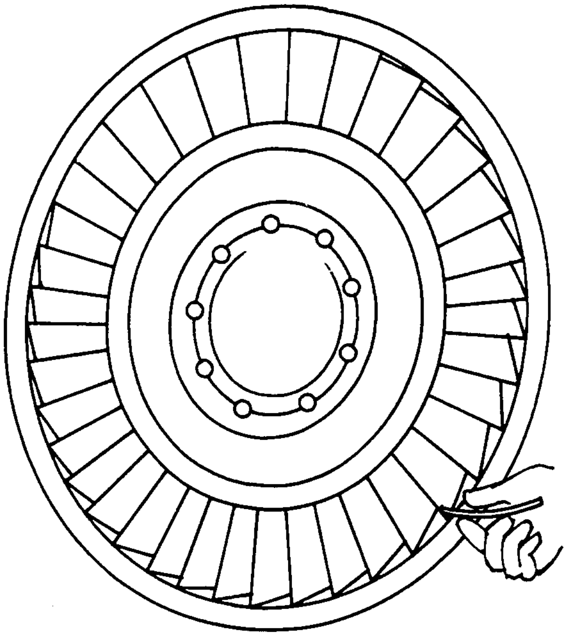


FIGURE 10–66. Measuring the turbine blades to shroud (tip) clearances.

Turbine Discharge Pressure Indicator

This instrument not only indicates the total engine internal pressure immediately aft of the last turbine stage, but also indicates the pressure available to generate thrust, when used with compressor inlet pressure.

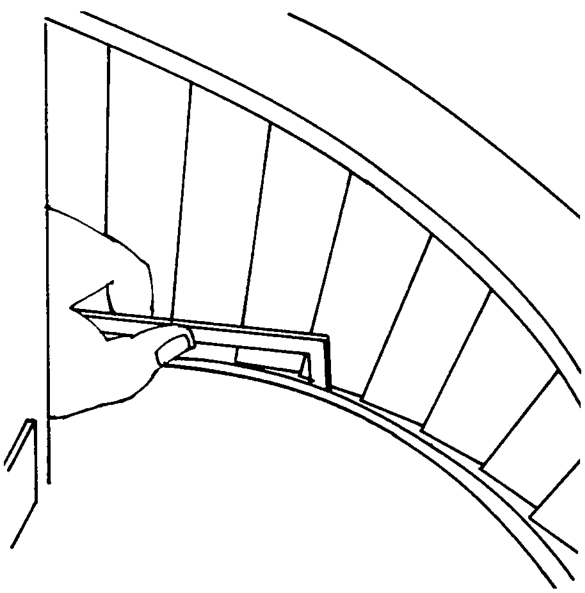


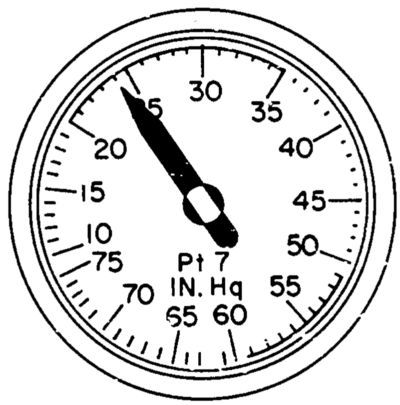
FIGURE 10–67. Measuring turbine wheel to exhaust cone clearance.

Engine Pressure Ratio Indicator

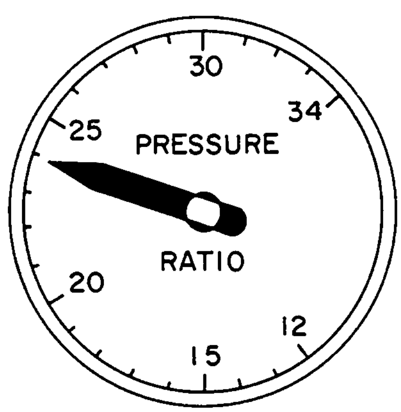
EPR (engine pressure ratio) is an indication of the thrust being developed by the engine. It is instrumented by total pressure pickups in the engine inlet and in the turbine exhaust. The reading is displayed in the cockpit by the EPR gage, which is used in making engine power settings. Figure 10–68 illustrates a turbine discharge pressure indicator (A) and an EPR gage (B).

Torquemeter (Turboprop Engines)

Because only a small part of the propulsive force is derived from the jet thrust, neither turbine discharge pressure nor engine pressure ratio is used as an indicator of the power produced by a turboprop engine. Turboprops are usually fitted with a torquemeter. The torquemeter (figure 10–69) can be operated by a torquemeter ring gear in the engine nose section similar to that provided on large



(A)



(B)

FIGURE 10–68. (A) Turbine discharge pressure, and (B) engine pressure ratio indicators.

reciprocating engines or by pick-ups on a torque shaft. The torque being developed by the engine is proportional to the horsepower, and is used to indicate shaft horsepower.

Tachometer

Gas turbine engine speed is measured by the compressor r.p.m., which will also be the turbine r.p.m. Tachometers (figure 10–69) are usually calibrated in percent r.p.m. so that various types of engines can be operated on the same basis of comparison. As previously noted, compressor r.p.m. on centrifugal-compressor turbojet engines is a direct indication of the engine thrust being produced. For axial-compressor engines, the principal purpose of the tachometer is to monitor r.p.m. during an engine start and to indicate an overspeed condition, if one occurs.

Exhaust Gas Temperature Indicator

EGT (exhaust gas temperature), TIT (turbine inlet temperature), tailpipe temperature, and turbine discharge temperature are one and the same. Temperature is an engine operating limit and is used to monitor the mechanical integrity of the turbines, as well as to check engine operating conditions. Actually, the turbine inlet temperature is the important consideration, since it is the most critical of all the engine variables. However, it is impractical to measure turbine inlet temperature in most engines, especially large models. Consequently, temperature thermocouples are inserted at the turbine discharge, where the temperature provides a relative indication of that at the inlet. Although the temperature at this point is much lower than at the inlet, it provides surveillance over the engine's internal operating conditions. Several thermocouples are usually used, which are spaced at intervals around the perimeter of the engine exhaust duct near the turbine exit. The EGT indicator (figure 10–69) in the cockpit shows the average temperature measured by the individual thermocouples.

Fuel-Flow Indicator

Fuel-flow instruments indicate the fuel flow in lbs./hr. from the engine fuel control. Fuel flow is of interest in monitoring fuel consumption and checking engine performance. A typical fuel-flow indicator is illustrated in figure 10–69.

Engine Oil Pressure Indicator

To guard against engine failure resulting from inadequate lubrication and cooling of the various engine parts, the oil supply to critical areas must be monitored. The oil pressure indicator usually shows the engine-oil-pump discharge pressure.

Engine Oil Temperature Indicator

The ability of the engine oil to lubricate and cool depends on the temperature of the oil, as well as the amount of oil supplied to the critical areas. An oil-inlet temperature indicator frequently is provided to show the temperature of the oil as it enters the oil pressure pump. Oil-inlet temperature is also an indication of proper operation of the engine oil cooler.

TURBOJET ENGINE OPERATION

The engine operating procedures presented here apply generally to all turbojet engines. The procedures, pressures, temperatures, and r.p.m.'s which follow are intended primarily to serve as a guide. It should be understood that they do not have general application. The manufacturer's operating instructions should be consulted before attempting to start and operate a turbojet engine.

In contrast to the many controls for a reciprocating engine, a turbojet engine has only one power control lever. Adjusting the power lever or throttle sets up a thrust condition for which the fuel control meters fuel to the engine. Engines equipped with thrust reversers go into reverse thrust at throttle positions below "idle." A separate fuel shutoff lever is usually provided on engines equipped with thrust reversers.

Prior to start, particular attention should be paid to the engine air inlet, the visual condition and free movement of the compressor and turbine assembly, and the parking ramp area fore and aft of the aircraft. The engine is started by using an external power source or a self-contained, combustion-starter unit. Starter types and the engine starting cycle have been discussed previously. On multi-engine aircraft, one engine usually is started by a ground cart that supplies the air pressure for a pneumatic starter on the engine. Air bled from the first engine started then is used as a source of power for starting the other engines.

During the start, it is necessary to monitor the tachometer, the oil pressure, and the exhaust gas temperature. The normal starting sequence is: (1) Rotate the compressor with the starter, (2) turn the ignition on, and (3) open the engine fuel valve, either by moving the throttle to "idle" or by moving a fuel shutoff lever or turning a switch. Adherence to the procedure prescribed for a particular engine

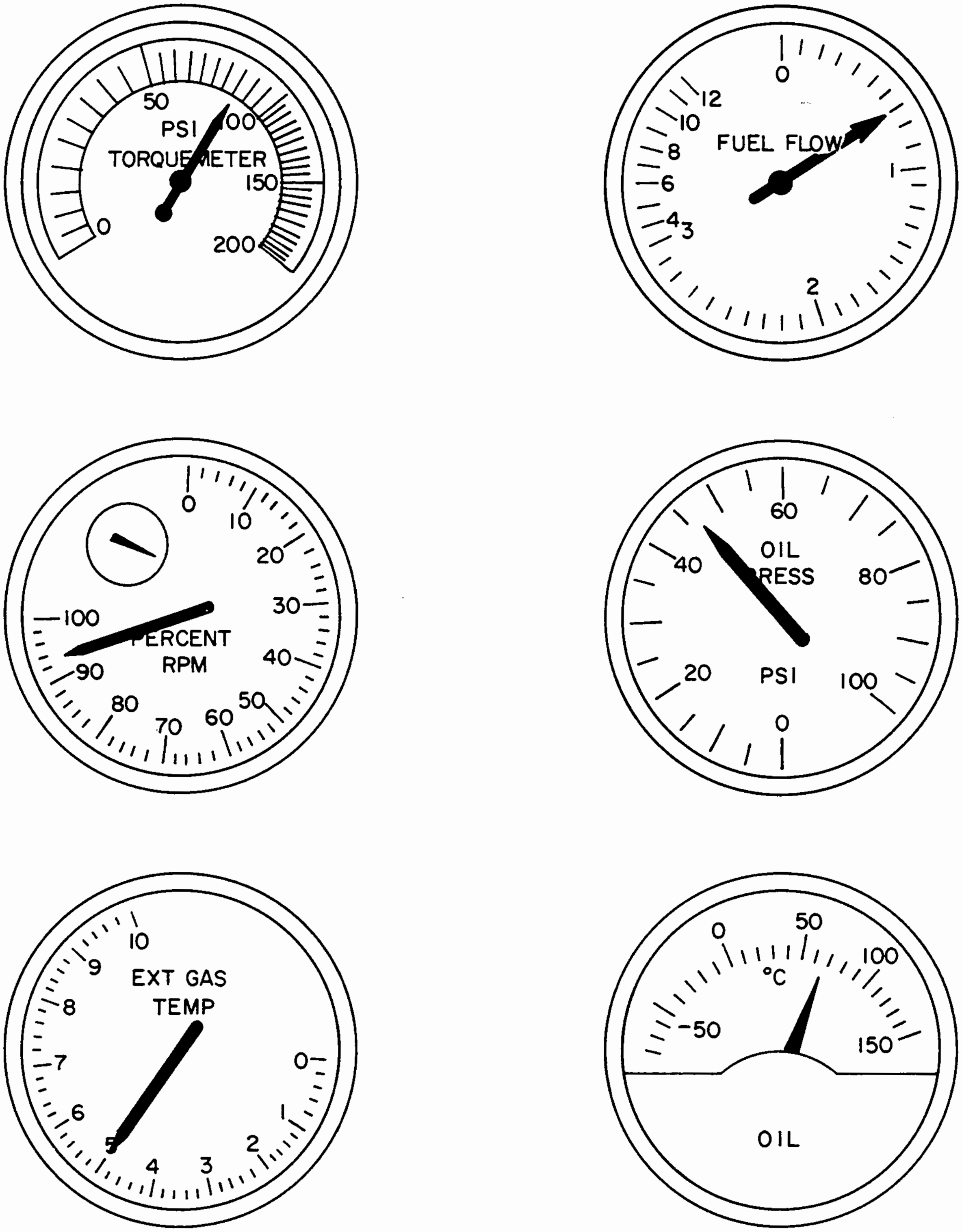


FIGURE 10–69. Typical turbine engine instruments.

is necessary as a safety measure and to avoid a "hot" or "hung" start.

A successful start will be noted first by a rise in exhaust gas temperature. If the engine does not "light up" within a prescribed period of time, or if the exhaust-gas-starting-temperature limit is exceeded, the starting procedure should be aborted. Hot starts are not common, but when they do occur, they can usually be stopped in time to avoid excessive temperature by observing the exhaust gas temperature constantly during the start. When necessary, the engine is cleared of trapped fuel or gases by continuing to rotate the compressor with the starter, but with the ignition and fuel turned off.

GROUND OPERATION

Engine Fire

If an engine fire occurs or if the fire warning light is illuminated during the starting cycle, move the fuel shutoff lever to the "off" position. Continue cranking or "motoring" the engine until the fire has been expelled from the engine. If the fire persists, CO_2 can be discharged into the inlet duct while it is being cranked. Do not discharge CO_2 directly into the engine exhaust because it may damage the engine. If the fire cannot be extinguished, secure all switches and leave the aircraft.

If the fire is on the ground under the engine overboard drain, discharge the CO_2 on the ground rather than on the engine. This also is true if the fire is at the tailpipe and the fuel is dripping to the ground and burning.

Engine Checks

Checking turbojet and turbofan engines for proper operation consists primarily of simply reading the engine instruments and then comparing the observed values with those known to be correct for any given engine operating condition.

Idle Checks

After the engine has started, idle r.p.m. has been attained, and the instrument readings have stabilized, the engine should be checked for satisfactory operation at idling speed. The oil pressure indicator, the tachometer, and the exhaust gas temperature readings should be compared with the allowable ranges. Fuel flow is not considered a completely reliable indication of engine condition at idling r.p.m. because of the inaccuracies frequently encountered in fuel flowmeters and indicators in the low range on the meters.

Checking Takeoff Thrust

Takeoff thrust is checked by adjusting the throttle to obtain a single, predicted reading on the engine pressure ratio indicator in the aircraft. The value for engine pressure ratio which represents takeoff thrust for the prevailing ambient atmospheric conditions is calculated from a takeoff thrust setting curve similar to that shown in figure 10–70.

This curve has been computed for static conditions. Therefore, for all precise thrust checking, the aircraft should be stationary, and stable engine operation should be established. If it is needed for calculating thrust during an engine trim check, turbine discharge pressure (P_{t7}) is also shown on these curves. Appropriate manuals should be consulted for the charts for a specific make and model engine.

The engine pressure ratio computed from the thrust setting curve represents either wet or dry takeoff thrust. The aircraft throttle is advanced to obtain this predicted reading on the engine pressure ratio indicator in the aircraft. If an engine develops the predicted thrust and if all the other engine instruments are reading within their proper ranges, engine operation is considered satisfactory.

Ambient Conditions

The sensitivity of gas turbine engines to compressor-inlet air temperature and pressure necessitates that considerable care be taken to obtain correct values for the prevailing ambient air conditions when computing takeoff thrust. Some things to remember are:

(1) The engine senses the air temperature and pressure at the compressor inlet. This will be the actual air temperature just above the runway surface. When the aircraft is stationary, the pressure at the compressor inlet will be the static field or true barometric pressure and not the barometric pressure corrected to sea level that is normally reported by airport control towers as the altimeter setting.

(2) Some airports provide the runway temperature, which should be used when available. The aircraft free air temperature indicator may or may not suffice for obtaining the temperature to be used, depending upon the manner in which the free air temperature is instrumented. If the thermometer bulb or thermocouple is exposed to the rays of the sun, the instrument reading will obviously not be accurate. When the control tower temperature must be used, a correction factor should be applied. For an accurate thrust computation, such as when trimming an engine, it is best to measure the actual temperature at the compressor inlet just before the engine is started, by means of a handheld thermometer of known accuracy. When

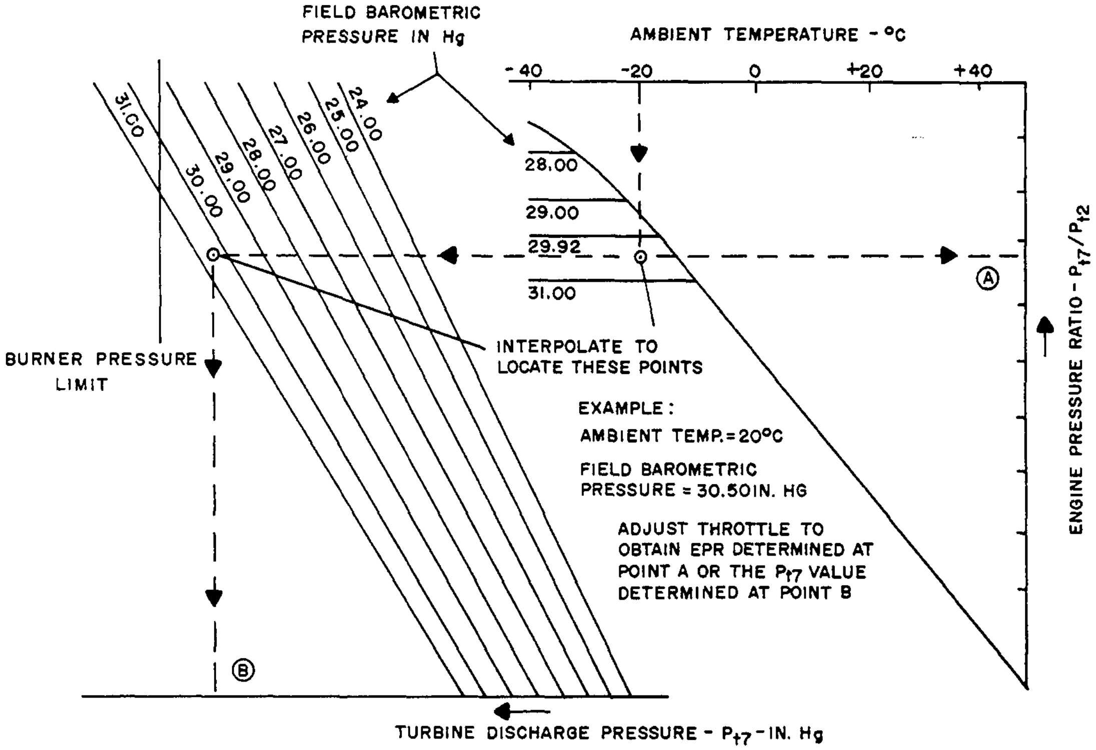


FIGURE 10–70. Typical takeoff thrust setting curve for static conditions.

it is realized that a 5° C. (9° F.) variation on compressor-inlet temperature will result in approximately 2 in. Hg variation in turbine discharge pressure, or 0.06 variation in engine pressure ratio indication, the importance of using the correct temperature for the thrust computation can be readily appreciated.

(3) If only the altimeter setting or the barometric pressure corrected to sea level is available when using the thrust setting curves to calculate turbine discharge pressure, this pressure must be re-corrected to field elevation. A method of obtaining the true pressure is to set the aircraft altimeter to zero altitude and read the field barometric pressure directly in the altimeter setting window on the face of the instrument. This method will work at all but the higher field elevations because of the limit of the altimeter setting scale.

(4) Relative humidity, which affects reciprocating engine power appreciably, has a negligible effect on turbojet engine thrust, fuel flow, and r.p.m. Therefore, relative humidity is not usually considered when computing thrust for takeoff or determining fuel flow and r.p.m. for routine operation.

ENGINE SHUTDOWN

On turbine engines, that do not have a thrust reverser, retarding the aircraft throttle or power lever to "off" cuts the fuel supply to the engine and shuts down the engine. On engines equipped with thrust reversers, this is accomplished by means of a separate fuel shutoff lever. An engine normally will be sufficiently cool to shut down immediately. However, as a rule of thumb, when an engine has been operated above approximately 85% r.p.m. for periods exceeding 1 min. during the last 5 min. prior to shutdown, it is recommended the engine be operated below 85% r.p.m. (preferably at idle) for a period of 5 min. to prevent possible seizure of the rotors. This applies, in particular, to prolonged operation at high r.p.m. on the ground, such as during engine trimming.

The turbine case and the turbine wheels operate at approximately the same temperature when the engine is running. However, the turbine wheels are relatively massive, compared with the case, and are not cooled so readily. The turbine case is exposed to cooling air from both inside and outside the engine. Consequently, the case and the wheels lose their residual heat at different rates after the engine has been shut down. The case, cooling faster, tends to shrink upon the wheels, which are still rotating. Under extreme conditions, the turbine blades may squeal or seize; thus a cooling period is required if the engine has been operating at prolonged high speed. Should the turbine wheels seize, no harm will normally result, provided no attempt is made to turn the engine over until it has cooled sufficiently to free the wheels. In spite of this, every effort should be made to avoid seizure.

The aircraft fuel boost pump must be turned off after, not before, the throttle or the fuel shutoff lever is placed in the off position, to ensure that fuel remains in the lines and that the engine-driven fuel pumps do not lose their prime. Under such conditions, the aircraft fuel boost pump usually is unable to re-prime the engine-driven fuel pump without air being bled from the fuel control.

Generally, an engine should not be shut down by the fuel shutoff lever until after the aircraft throttle has been retarded to "idle." Because the fuel shutoff valve is located on the fuel control discharge, a shutdown from high thrust settings will result in high fuel pressures within the control that can harm the fuel system parts.

When an accurate reading of the oil level in the oil tank is needed following an engine shutdown, the engine should be operated at approximately 75% r.p.m. for not less than 15 nor more than 30 sec. immediately before shutdown to properly scavenge oil from inside the engine.

TROUBLESHOOTING TURBOJET ENGINES

Included in this section are typical guidelines for locating engine malfunctions on most turbojet engines. Since it would be impractical to list all the malfunctions that could occur, only the most common malfunctions are covered. A thorough knowledge of the engine systems, applied with logical reasoning, will solve any problems which may occur.

Table 12 enumerates some malfunctions which may be encountered. Possible causes and suggested actions are given in the adjacent columns. The malfunctions presented herein are solely for the purpose of illustration and should not be construed to have general application. ***For exact information about a specific engine model, consult the applicable manufacturer's instructions.***

TURBOPROP OPERATION

Turboprop engine operation is quite similar to that of a turbojet engine, except for the added feature of a propeller. The starting procedure and the various operational features are very much alike. The turboprop chiefly requires attention to engine operating limits, the throttle or power lever setting, and the torquemeter pressure gage. Although torquemeters indicate only the power being supplied to the propeller and not the equivalent shaft horsepower, torquemeter pressure is approximately proportional to the total power output and, thus, is used as a measure of engine performance. The torquemeter pressure gage reading during the takeoff engine check is an important value. It is usually necessary to compute the takeoff power in the same manner as is done for a turbojet engine. This computation is to determine the maximum allowable exhaust gas temperature and the torquemeter pressure that a normally functioning engine should produce for the outside (ambient) air temperature and barometric pressure prevailing at the time.

TABLE 12. Troubleshooting turbojet engines.

Indicated malfunction	Possible cause	Suggested action
Engine has low r.p.m., exhaust gas temperature, and fuel flow when set to expected engine pressure ratio.	Engine pressure ratio indication has high reading error.	Check inlet pressure line from probe to transmitter for leaks.
		Check engine pressure ratio transmitter and indicator for accuracy.
Engine has high r.p.m., exhaust gas temperature, and fuel flow when set to expected engine pressure ratio.	Engine pressure ratio indication has low reading error due to:	
	Misaligned or cracked turbine discharge probe.	Check probe condition.
	Leak in turbine discharge pressure line from probe to transmitter.	Pressure-test turbine discharge pressure line for leaks.
	Inaccurate engine pressure ratio transmitter or indicator.	Check engine pressure ratio transmitter and indicator for accuracy.

TABLE 12. Troubleshooting turbojet engines—con.

Indicated malfunction	Possible cause	Suggested action
	Carbon particles collected in turbine discharge pressure line or restrictor orifices.	
Engine has high exhaust gas temperature, low r.p.m., and high fuel flow at all engine pressure ratio settings.	Possible turbine damage and/or loss of turbine efficiency.	Confirm indication of turbine damage by: Checking engine coast-down for abnormal noise and reduced time. Visually inspect turbine area with strong light.
NOTE: Engines with damage in turbine section may have tendency to hang up during starting.	If only exhaust gas temperature is high, other parameters normal, the problem may be thermocouple leads or instrument.	Re-calibrate exhaust gas temperature instrumentation.
Engine vibrates throughout r.p.m. range, but indicated amplitude reduces as r.p.m. is reduced.	Turbine damage.	Check turbine as outlined in preceding item.
Engine vibrates at high r.p.m. and fuel flow when compared to constant engine pressure ratio.	Damage in compressor section.	Check compressor section for damage.
Engine vibrates throughout r.p.m. range, but is more pronounced in cruise or idle r.p.m. range.	Engine-mounted accessory such as constant-speed drive, generator, hydraulic pump, etc.	Check each component in turn.
No change in power setting parameters, but oil temperature high.	Engine main bearings.	Check scavenge oil filters and magnetic plugs.
Engine has higher-than-normal exhaust gas temperature during takeoff, climb, and cruise. R.P.M. and fuel flow higher than normal.	Engine bleed-air valve malfunction.	Check operation of bleed valve.
	Turbine discharge pressure probe or line to transmitter leaking.	Check condition of probe and pressure line to transmitter.
Engine has high exhaust gas temperature at target engine pressure ratio for takeoff.	Engine out of trim.	Check engine with jetcal. Re-trim as desired.
Engine rumbles during starting and at low power cruise conditions.	Pressurizing and drain valve malfunction.	Replace pressurizing and drain valves.
	Cracked air duct.	Repair or replace duct.
	Fuel control malfunction.	Replace fuel control.
Engine r.p.m. hangs up during starting.	Subzero ambient temperatures.	If hang-up is due to low ambient temperature, engine usually can be started by turning on fuel booster pump or by positioning start lever to run earlier in the starting cycle.
	Compressor section damage.	Check compressor for damage.
	Turbine section damage.	Inspect turbine for damage.
High oil temperature.	Scavenge pump failure.	Check lubricating system and scavenge pumps.
	Fuel heater malfunction.	Replace fuel heater.
High oil consumption.	Scavenge pump failure.	Check scavenge pumps.
	High sump pressure.	Check sump pressure as outlined in manufacturer's maintenance manual.
	Gearbox seal leakage.	Check gearbox seal by pressurizing overboard vent.
Overboard oil loss.	Can be caused by high airflow through the tank, foaming oil, or unusual amounts of oil returned to the tank through the vent system.	Check oil for foaming; vacuum-check sumps; check scavenge pumps.

TROUBLESHOOTING PROCEDURES FOR TURBO-PROP ENGINES

All test run-ups, inspections, and troubleshooting should be performed in accordance with the applicable engine manufacturer's instructions. In table 13, the troubleshooting procedures for the turboprop reduction gear, torquemeter, and power sections are combined because of their inter-relationships. The table includes the principal troubles, together with their probable causes and remedies.

TABLE 13. Troubleshooting turboprop engines.

Trouble	Probable cause	Remedy
Power unit fails to turn over during attempted start.	No air to starter.	Check starter air valve solenoid and air supply.
	Propeller brake locked.	Unlock brake by turning propeller by hand in direction of normal rotation.
Power unit fails to start.	Starter speed low because of inadequate air supply to starter.	Check starter air valve solenoid and air supply.
	If fuel is not observed leaving the exhaust pipe during start, fuel selector valve may be inoperative because of low power supply or may be locked in "off."	Check power supply or electrically operated valves. Replace valves if defective.
	Fuel pump inoperative.	Check pump for sheared drives or internal damage; check for air leaks at outlet.
	Aircraft fuel filter dirty.	Clean filter and replace filtering elements if necessary.
	Fuel control cutoff valve closed.	Check electrical circuit to ensure that actuator is being energized. Replace actuator or control.
Engine fires, but will not accelerate to correct speed.	Insufficient fuel supply to control unit.	Check fuel system to ensure all valves are open and pumps are operative.
	Fuel control main metering valve sticking.	Flush system. Replace control.
	Fuel control bypass valve sticking open.	Flush system. Replace control.
	Drain valve stuck open. Starting fuel enrichment pressure switch setting too high.	Replace drain valve. Replace pressure switch.
Acceleration temperature too high during starting.	Fuel control bypass valve sticking closed.	Flush system. Replace control.
	Fuel control acceleration cam incorrectly adjusted.	Replace control.
	Defective fuel nozzle.	Replace nozzle with a known satisfactory unit.
	Fuel control thermostat failure.	Replace control.
Acceleration temperature during starting too low.	Acceleration cam of fuel control incorrectly adjusted.	Replace control.
Engine speed cycles after start.	Unstable fuel control governor operation.	Continue engine operation to allow control to condition itself.
Power unit oil pressure drops off severely.	Oil supply low.	Check oil supply and refill as necessary.
	Oil pressure transmitter or indicator giving false indication.	Check transmitter or indicator and repair or replace if necessary.

TABLE 13. Troubleshooting turboprop engines—con.

Trouble	Probable cause	Remedy
Oil leakage at accessory drive seals.	Seal failure	Replace seal or seals.
Engine unable to reach maximum controlled speed of 100%.	Faulty propeller governer.	Replace propeller control assembly.
	Faulty fuel control or air sensing tip.	Replace faulty control. If dirty, use air pressure in reverse direction of normal flow through internal engine passage and sensing tip.
Vibration indication high.	Vibration pickup or vibration meter malfunctioning.	Calibrate vibration meter. Start engine and increase power gradually. Observe vibration indicator. If indications prove pickup to be at fault, replace it. If high vibration remains as originally observed, remove power unit for overhaul.

JET CALIBRATION TEST UNIT

Two of the most important factors affecting turbine engine life are EGT (exhaust gas temperature) and engine speed. Excess EGT of a few degrees will reduce turbine blade life as much as 50%. Low exhaust gas temperature materially reduces turbine engine efficiency and thrust. Excessive engine speed can cause premature engine failure.

Indications of fuel system troubles, tailpipe temperature, and r.p.m. can be checked more accurately from the jet calibration test unit than from the gages in the cockpit of the aircraft. Errors up to 10° C. may be made in the interpretation of the temperature gages because of the height of the observer in the seat. Similarly, errors may be made in interpretation of tachometers. With proper utilization of the jet calibration test unit, such errors can be reduced greatly.

One type of calibration test unit used to analyze the turbine engine is the jetcal analyzer (figure 10–71). A jetcal analyzer is a portable instrument made of aluminum, stainless steel, and plastic. The major components of the analyzer are the thermocouple, r.p.m., EGT indicator, resistance, and insulation check circuits, as well as the potentiometer, temperature regulators, meters, switches, and all the necessary cables, probes, and adapters for performing all tests. A jetcal analyzer also includes fire warning overheat detection and wing anti-icing system test circuits.

Jetcal Analyzer Uses

The jetcal analyzer may be used to:

(1) Functionally check the aircraft EGT system for error without running the engine or disconnecting the wiring.

(2) Check individual thermocouples before placement in a parallel harness.

(3) Check each engine thermocouple in a parallel harness for continuity.

(4) Check the thermocouples and parallel harness for accuracy.

(5) Check the resistance of the EGT circuit.

(6) Check the insulation of the EGT circuit for shorts to ground, or for shorts between leads.

(7) Check EGT indicators (either in or out of the aircraft) for error.

(8) Determine engine r.p.m. with an accuracy of ±0.1% during engine run-up. Added to this is the checking and troubleshooting of the aircraft tachometer system.

(9) Establish the proper relationship between the EGT and engine r.p.m. on engine run-up during tabbing (micing) procedures by the r.p.m. check (takcal) and potentiometer in the jetcal analyzer. (Tabbing procedures are those procedures followed when adjusting fixed exhaust nozzle exit areas.)

(10) Check aircraft fire detector, overheat detector, and wing anti-icing systems by using tempcal probes.

Operating Instructions for the Jetcal Tester

The complete step-by-step procedure on the instruction plate of the jetcal analyzer can be followed during actual operation of the analyzer. The operation plate is visible at all times when operating the analyzer.

It would be useless to list the step-by-step procedure in this section. The procedure consists of turning on or off many separate switches and dials.

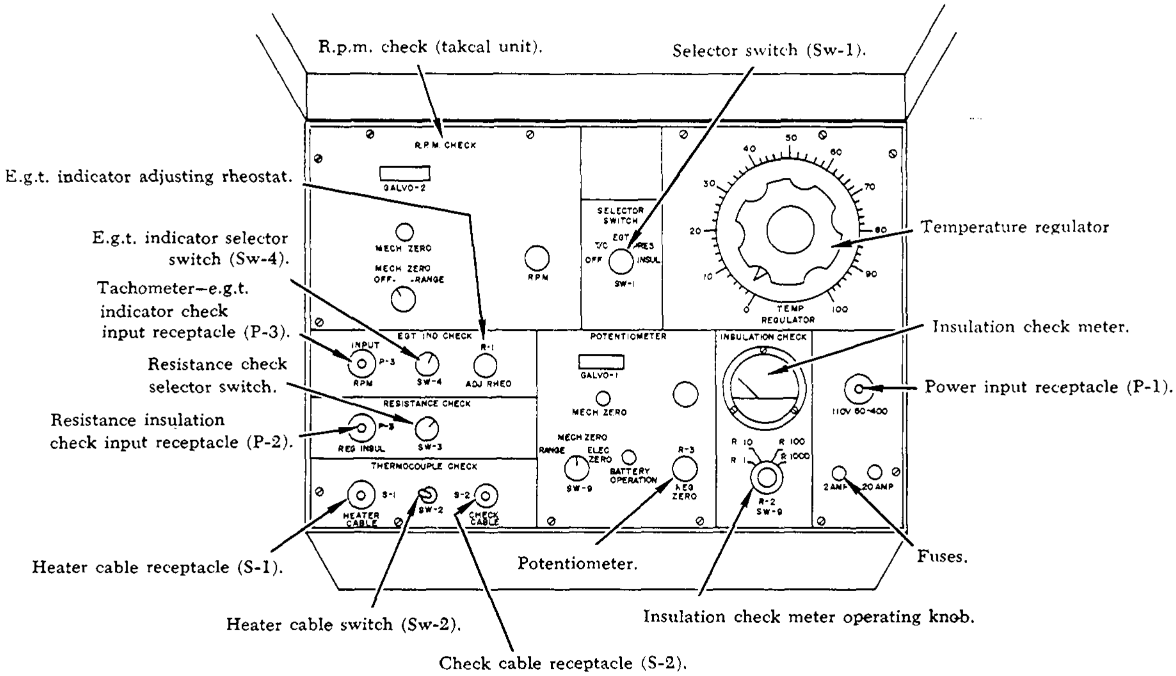


FIGURE 10–71. Jetcal analyzer instrument compartment.

To avoid confusion, this section will be confined to the operation of the jetcal analyzer in a general sense.

Safety Precautions

Observe the following safety precautions while operating the jetcal analyzer:

(1) Never use a volt-ohmmeter to check the potentiometer for continuity. If a volt-ohmmeter is used, damage to the galvanometer and standard battery cell will result.

(2) Check the thermocouple harness before engine run-up. This must be done because the circuit must be correct before the thermocouples can be used for true EGT pickup.

(3) For safety, ground the jetcal analyzer when using an a.c. power supply. Any electrical equipment operated on a.c. power and utilizing wire-wound coils, such as the probes with the jetcal analyzer, has an induced voltage on the case that can be discharged if the equipment is not grounded. This condition is not apparent during dry weather, but on damp days the operator can be shocked slightly. Therefore, for the operator's protection, the jetcal analyzer should be grounded using the pigtail lead in the power inlet cable.

(4) Use heater probes designed for use on the engine thermocouples to be tested. Temperature gradients are very critical in the design of heater probes. Each type of aircraft thermocouple has its own specially designed probe. Never attempt to modify heater probes to test other types of thermocouples.

(5) Do not leave heater probes assemblies in the tailpipe during engine run-up.

(6) Never allow the heater probes to go over 900° C. (1,652° F.). Exceeding these temperatures will result in damage to the jetcal analyzer and heater probe assemblies.

Continuity Check of Aircraft EGT Circuit

To eliminate any error caused by one or more inoperative aircraft thermocouples, a continuity check is performed. The check is made by heating one heater probe to between 500° and 700° C. and placing the hot probe over each of the aircraft thermocouples, one at a time. The EGT indicator must show a temperature rise as each thermocouple is checked. When large numbers of thermocouples are used in the harness (eight or more), it is difficult to see a rise on the aircraft instrument because of the electrical characteristics of a parallel circuit. Therefore, the temperature indication of the aircraft thermocouples is read on the potentiometer of the jetcal analyzer by using the check cable and necessary adapter.

Functional Check of Aircraft EGT Circuit

The time required to test the EGT system of any one aircraft will depend on several factors: (1) The number of engines; (2) the number of thermocouples in the harness, and their position in the engine; (3) the errors, if any are found; and (4) the time required to correct the errors. The normal functional test of a single engine can be performed in 10 to 20 min.; special conditions may require more time.

During the EGT system functional test and the thermocouple harness checks, the jetcal analyzer has a guaranteed accuracy of ±4° C. at the test temperature, which is usually the maximum operating temperature of the jet engine. Each engine has its own maximum operating temperature, which can be found in applicable technical instructions.

The test is made by heating the engine thermocouples in the tail cone to the engine test temperature. The heat is supplied by heater probes through the necessary cables. With the engine thermocouples hot, their temperature is registered on the aircraft EGT indicator. At the same time, the thermocouples embedded in the heater probes, which are completely isolated from the aircraft system, are picking up and registering the same temperature on the jetcal analyzer.

The temperature registered on the aircraft EGT indicator (figure 10–72) should be within the specified tolerance of the aircraft system and the temperature reading on the jetcal potentiometer. The thermocouples embedded in the heater probes are of U.S. Bureau of Standards accuracy; therefore, jetcal readings are accepted as the standard and are used as the basis of comparison for checking the accuracy of the aircraft EGT system.

Since the junction box is wired in parallel, it is not necessary to have heater probes connected to all the outlets of the junction box when making a check. On engines that have a balancing type thermocouple system, the balancing thermocouple must be removed from the circuit. The remaining thermocouples can be checked individually or together. The balancing thermocouple is checked, using a single probe. The output of the balancing thermocouple is also read on the jetcal potentiometer and compared to the heater probe thermocouple reading.

When the temperature difference exceeds the allowable tolerance, troubleshoot the aircraft system

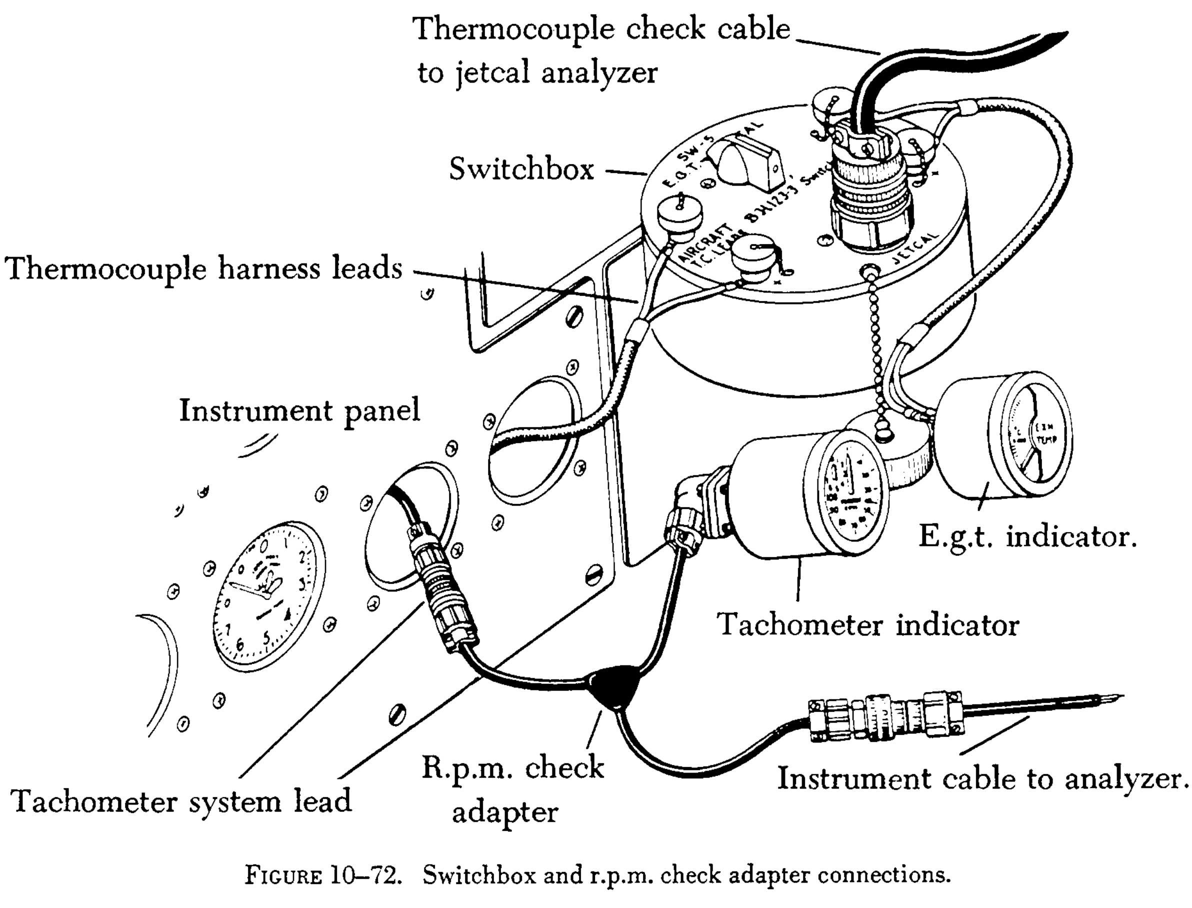


FIGURE 10–72. Switchbox and r.p.m. check adapter connections.

to determine which parts are in error. Troubleshooting is discussed at the end of this section.

Functional Test of Thermal Switches

The tempcal probe functionally tests the operation of the fire detection, overheat, and wing anti-icing systems that incorporate a thermal switch as the detection device. Test the thermal switch in position on the aircraft by placing the probe over the thermal switch. The tempcal probe incorporates the principles of the heater probe for its temperature pickup. The temperature is controlled by the temperature regulator and is read on the jetcal potentiometer.

With the tempcal probe over the thermal switch, the temperature of the probe is raised and lowered to take the switch through its operating temperatures. The indicator on the aircraft instrument panel, generally a red light, then is checked for indication to make sure that the switch is actuating at proper temperatures. If the system is not indicating properly, the circuit must be corrected.

If a hot tempcal probe is placed over a cold thermal switch, the contacts will close almost immediately due to an action called "thermal shock." As the thermal switch continues to absorb heat, the contacts will open and then close again when the operating temperature of the switch is reached.

EGT Indicator Check

The EGT indicator is tested after being removed from the aircraft instrument panel and disconnected from the aircraft EGT circuit leads. Attach the instrument cable and EGT indicator adapter leads to the indicator terminals and place the indicator in its normal operating position. Adjust jetcal analyzer switches to the proper settings. The indicator reading should correspond to the potentiometer readings of the jetcal analyzer within the allowable limits of the EGT indicator.

Correction for ambient temperature is not required for this test, as both the EGT indicator and jetcal analyzer are temperature compensated.

The temperature registered on the aircraft EGT indicator should be within the specified tolerance of the aircraft system and the temperature reading on the jetcal potentiometer. When the temperature difference exceeds the allowable tolerance, troubleshoot the aircraft system to determine which parts are in error.

Resistance and Insulation Check

The thermocouple harness continuity is checked while the EGT system is being checked functionally. The resistance of the thermocouple harness is held to very close tolerances, since a change in resistance changes the amount of current flow in the circuit. A change of resistance will give erroneous temperature readings.

The resistance and insulation check circuits make it possible to analyze and isolate any error in the aircraft system. How the resistance and insulation circuits are used will be discussed with troubleshooting procedures.

Tachometer Check

To read engine speed with an accuracy of $\pm 0.1\%$ during engine run, the frequency of the tachometer-generator is measured by the r.p.m. check (takcal) circuit in the jetcal analyzer. The scale of the r.p.m. check circuit is calibrated in percent r.p.m. to correspond to the aircraft tachometer indicator, which also reads in percent r.p.m. The calibration intervals are 0.2%. The aircraft tachometer and the r.p.m. check circuit are connected in parallel, and both are indicating during engine run-up.

The r.p.m. check circuit readings can be compared with the readings of the aircraft tachometer to determine the accuracy of the aircraft instrument.

Troubleshooting EGT System

The jetcal analyzer is used to test and troubleshoot the aircraft thermocouple system at the first indication of trouble or during periodic maintenance checks.

The test circuits of the jetcal analyzer make it possible to isolate all the troubles listed below. Following the list is a discussion of each trouble mentioned.

(1) One or more inoperative thermocouples in engine parallel harness.
(2) Engine thermocouples out of calibration.
(3) EGT indicator error.
(4) Resistance of circuit out of tolerance.
(5) Shorts to ground.
(6) Shorts between leads.

One or More Inoperative Thermocouples in Engine Parallel Harness

This error is found in the regular testing of aircraft thermocouples with a hot heater probe and will be a broken lead wire in the parallel harness or a short to ground in the harness. In the latter case the current from the grounded thermocouple can leak off and never be shown on the indicator.

However, this grounded condition can be found by using the insulation resistance check.

Engine Thermocouples Out of Calibration

When thermocouples are subjected for a period of time to oxidizing atmospheres, such as encountered in turbine engines, they will drift appreciably from their original calibration. On engine parallel harnesses, when individual thermocouples can be removed, these thermocouples can be bench-checked, using one heater probe. The temperature reading obtained from the thermocouples should be within manufacturer's tolerances.

EGT Circuit Error

This error is found by using the switchbox and comparing the reading of the aircraft EGT indicator with the jetcal temperature reading (figure 10–72). With switch (SW-5) in the jetcal position, the indication of the thermocouple harness is carried back to the jetcal analyzer. With the switch (SW-5) in the EGT position, the temperature reading of the thermocouple harness is indicated on the aircraft EGT indicator. The jetcal and aircraft temperature readings are then compared.

Resistance of Circuit Out of Tolerance

The engine thermocouple circuit resistance is a very important adjustment since a high-resistance condition will give a low indication on the aircraft EGT indicator. This condition is dangerous, because the engine will be operating with excess temperature, but the high resistance will make the indicator read low. Adjusting a resistor and/or a resistance coil in the EGT circuit generally corrects this condition.

Shorts to Ground and Shorts Between Leads

These errors are found by using the insulation check meter as an ohmmeter. Resistance values from zero to 550,000 ohms can be read on the insulation check meter by selecting the proper range.

TROUBLESHOOTING AIRCRAFT TACHOMETER SYSTEM

A related function of the r.p.m. check is troubleshooting the aircraft tachometer system. The r.p.m. check circuit in the jetcal analyzer is used to read engine speed during engine run-up with an accuracy of $\pm 0.1\%$. The connections for the r.p.m. check are the instrument cable, and aircraft tachometer system lead to the tachometer indicator (figure 10–72). After the connections have been made between the jetcal analyzer r.p.m. check circuit and the aircraft tachometer circuit, the two circuits (now classed as one) will be a parallel circuit. The engine is then run-up as prescribed in applicable technical instructions. Both systems can be read simultaneously.

If the difference between the readings of the aircraft tachometer indicator and the jetcal analyzer r.p.m. check circuit exceeds the tolerance prescribed in applicable technical instructions, the engine must be stopped, and the trouble located and corrected. The following steps will assist in locating and isolating the trouble:

(1) If the aircraft tachometer error exceeds the authorized tolerance when compared to the r.p.m. check readings, the instrument should be replaced.

(2) If it is impossible to read 100% r.p.m. on the aircraft tachometer, but the r.p.m. check circuit does read 100% r.p.m., the trouble will be a bad aircraft tachometer indicator or a bad tachometer-generator. Replace the defective parts.

(3) If there is no reading on the aircraft tachometer indicator, but there is a reading on the r.p.m. check circuit, the trouble will either be a bad aircraft tachometer or an open or a grounded phase from the aircraft tachometer-generator. Replace the defective aircraft tachometer or tachometer-generator, or repair the defective lead.

(4) If there is no r.p.m. indication on either the aircraft tachometer or the jetcal analyzer r.p.m. check circuit, there will be an open or shorted lead in the aircraft circuit or a defective tachometer-generator. The defect in the aircraft circuit should be located and corrected, or the tachometer-generator should be replaced. The engine r.p.m. reading should be repeated to check parts replaced as a result of the above tests.

The jetcal analyzer is used for engine tabbing because engine speed and exhaust temperature are extremely critical in engine operation. When the engine is to be checked and tabbed, the most convenient way to do this is to put the switchbox in the EGT circuit and make the connections for the r.p.m. check at the beginning of the test.

The switchbox is used either to switch the EGT indicator into the circuit or to switch the temperature indication of the engine thermocouple harness to the jetcal potentiometer. However, temperature readings from the aircraft thermocouple harness can be made by connecting the check cable (with or without adapter) to the engine junction box (see figure 10–73). The aircraft EGT indicator must be used when the engine is started to be able to detect a hot start.

The engine is started and brought to the speed specified in applicable technical instructions. During tabbing procedures, all engine speed readings are made on the r.p.m. check in the jetcal analyzer, and engine temperature readings are made on the jetcal potentiometer. This is necessary because engine temperature and speed must be read accurately during engine tabbing to assure that the engine is operating at optimum engine conditions.

If the temperature reading is not within the tolerances stated in applicable instructions, the engine is stopped and tabs are added or removed as required. The engine is run-up and r.p.m. and temperature readings are again taken to make sure that the tabs added or removed bring the tailpipe temperature within tolerance.

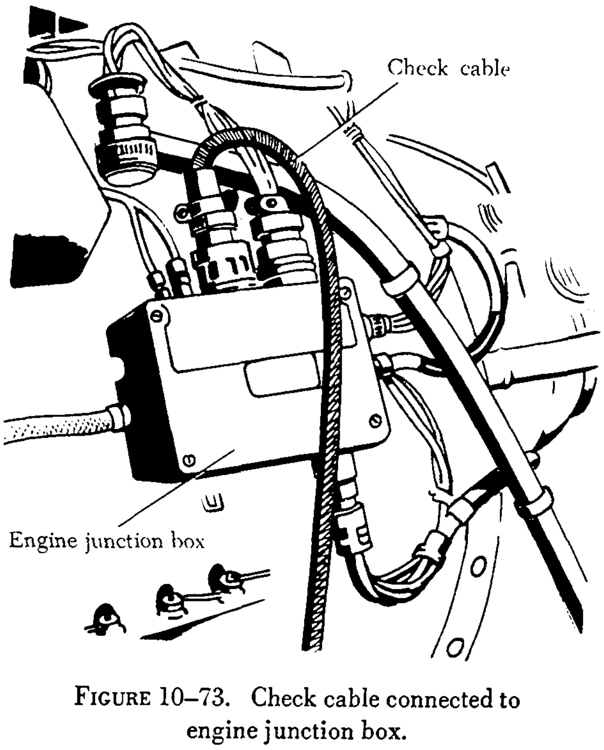


FIGURE 10–73. Check cable connected to engine junction box.

SPECTROMETRIC OIL ANALYSIS PROGRAM

The spectrometric oil analysis program has been used by branches of aviation for several years. It is based on the fact that each element will display a certain pattern of light when a sample is used in a spectrometer. It is applicable to either reciprocating or turbine engines.

The spectrometric analysis for metal content is possible because metallic atoms and ions emit characteristic light spectra when vaporized in an electric arc or spark. The spectrum produced by each metal is unique for that metal. The position or wave length of a spectral line will identify the particular metal, and the intensity of the line can be used to measure the quantity of the metal in a sample.

How the Analyzer Works

Periodic samples of used oil are taken from all equipment protected by the program and sent to an oil analysis laboratory. Here is a brief description of how the spectrometer measures the wear metals present in the used oil samples:

(1) A film of the used oil sample is picked on the rim of a rotating, high-purity, graphite disc electrode. (See figure 10–74.)

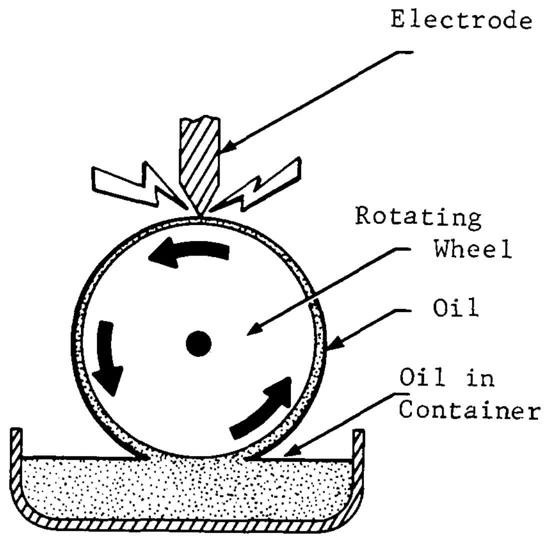


FIGURE 10–74. Oil Sample

(2) Precisely controlled, high voltage, ac spark discharge is initiated between the vertical electrode and the rotating disc electrode burning the small film of oil.

(3) Light from the burning oil passes through a slit which is positioned precisely to the wave length for the particular wear metal being monitored. (See figure 10–75.)

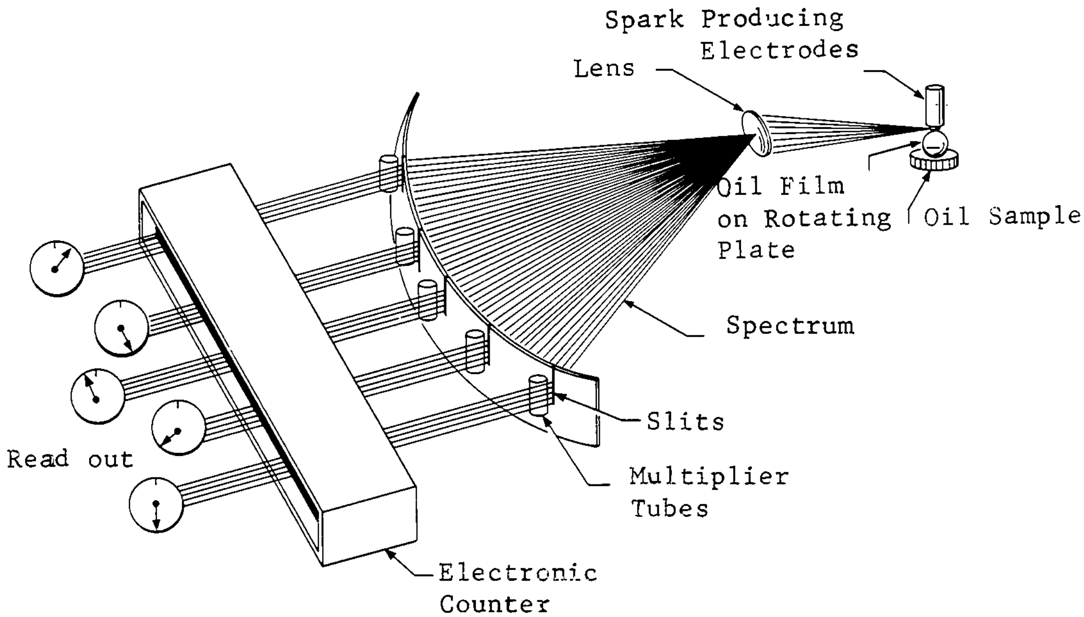


FIGURE 10–75. Spectrometic Analysis of Metals

(4) As the light passes through the slits, photomultiplier tubes transform the light waves electronically into energy which automatically prints the analytical results in parts per million on punch cards on the laboratory record sheets.

(5) The results are interpreted and when a sharp trend or abnormal concentration of metal is present, the participant is notified by telephone or message, depending on the urgency.

Application

Under certain conditions and within certain limitations, the internal condition of any mechanical system can be evaluated by the spectrometric analysis of lubricating oil samples. The concept and application are based on the following facts:

(1) The components of aircraft mechanical systems contain aluminum, iron, chromium, silver, copper, tin, magnesium, lead and nickel as the predominant alloying elements.

(2) The moving contact between the metallic components of any mechanical system is always accompanied by friction. Even though this friction is reduced by a thin film of oil, some microscopic particles of metal do wear away and are carried in suspension in the oil. Thus, a potential source of information exists that relates directly to the condition of the system. The chemical identity of the worn surfaces and the particles worn from those surfaces will always be the same. If the rate of each kind of metal particle can be measured and established as being normal or abnormal, then the rate of wear of the contacting surfaces will also be established as normal or abnormal. The chemical identity of the abnormally produced particles will provide clues to the identity of the components being worn.

Under most conditions, the rate of wear will remain constant and quite slow. The wear metal particles will be microscopic in size so that the particles will remain in suspension in the lubricating system.

Any condition, which alters or increases the normal friction between the moving parts, will also accelerate the rate of wear and increase the quantity of wear particles produced. If the condition is not discovered and corrected, the wear process will continue to accelerate, usually with secondary damage to other parts of the system and eventual failure of the entire system will occur.

Measurement of the Metals

The important wear metals produced in an oil lubrication mechanical system can be separately measured in extremely low concentrations by the spectrometric analysis of oil samples taken from the system.

Silver is accurately measured in concentrations down to one-half part by weight of silver in 1,000,000 parts of oil. Most other metals are measured accurately in concentrations down to two or three parts per million. The maximum amount of normal wear has been determined for each metal of the particular system in the program. This amount is called its threshold limit of contamination and is measured by weight in parts per million (PPM).

It must be understood that the wear metals present are of such microscopic size that they can not be seen by the naked eye, cannot be felt with the fingers, and flow freely through the system filters. As an example, wear metals one-tenth the size of a grain of talcum powder, are easily measured by the spectrometer. The spectrometer therefore measures the particles that move in suspension in the oil and are too small to appear on either the oil screen or chip detector.

Advantages

The Oil Analysis Program is not a cure-all, as normal maintenance practices must still be followed. There are several side benefits of the program worth mentioning, however.

Analysis of oil samples after a maintenance action has been accomplished can be used as a quality control tool by maintenance. An analysis which continues to show abnormal concentrations of wear metals present in the system would be positive proof that maintenance had not corrected the discrepancy and further trouble-shooting techniques must be employed.

Analysis of samples from engines on test stands has reduced the possibility of installing a newly overhauled engine in the aircraft that contains discrepancies not detected by test stand instruments.

Spectrometric oil analysis has been used mainly in analyzing conditions of reciprocating, turbo-prop and turbo-jet engines and helicopter transmissions. Impending failures were predicted before advancing to inflight failures. Numerous reciprocating engines have been repaired in the field by replacement of a cylinder instead of replacement of an entire engine. The technique is also applicable to constant speed drives, cabin superchargers, gear boxes, hydraulic systems, and other oil-wetted mechanical systems.

*U.S. Government Printing Office: 1996 - 405-571/55757