

Powerplants and Performance Factors

In the previous chapter, the balance of forces acting on an aircraft in level flight was discussed. It was pointed out that for an aircraft to remain in level flight, a thrust must be provided 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. In all cases, the heat energy is released at a point in the cycle where the pressure is high, relative to atmospheric pressure. These engines are customarily divided into groups or classes, depending upon the:

Working fluid used in the engine cycle

Means by which the mechanical energy is converted into a propulsion force.

Method of compressing the working fluid in the engine.

The propulsive force is obtained by the displacement of a working fluid (not necessarily the same fluid used with the engine) in a direction opposite to that in which the aircraft is propelled. This is an application of Newton's second law of motion (Chapter 3). Air is the principal fluid used for propulsion in every type of power plant except the rocket.

The propellers of aircraft powered by reciprocating or turboprop engines accelerate a large mass of air through a small velocity change and are examples of engines in which the fluid (air) used for the propulsive force is different from that used within the engine to produce the mechanical energy. Turbojets, ramjets, and pulsejets accelerate a smaller quantity of air through velocity change and are examples of engines which use the same working fluid for propulsive force that is used within the engine. A rocket carries its own oxidizer rather than using air. It discharges the

gaseous products of combustion through the exhaust nozzle at an extremely high velocity.

There are four basic methods of compressing the working fluid before the addition of heat:

Positive-displacement, piston-type compression (reciprocating engine).

Variable-displacement, blower-type compression (turbine engine).

Ram compression produced by forward flight speed (ramjet).

Compression produced by combustion (pulsejet and rocket).

It is possible to combine some of the above methods, such as the reciprocating engine-turbo-supercharger combination and the turbojet-afterburner combination. This chapter will cover the reciprocating engine, the gas turbine engine, the turboprop power unit, and the turbofan engine.

Since both engine design and operation have as their ultimate objective the efficient and reliable production of power, it may not be altogether inappropriate at this point to inject a definition of power, together with a brief description of the methods by which it is measured and produced, and also to conduct an investigation of some of the limitations to which the application of power is subjected. An understanding of such terms as *indicated horsepower, torque, brake mean effective pressure, and normal rated power* should give you a better understanding of some of the problems fundamental to powerplant design and operation.

POWER AND ITS MEASUREMENT

Force

The definition of power involves the three basic ideas of *force, distance, and time*. The

concepts of time and distance are deceptively elusive, and do not permit a ready definition, but their meanings will nonetheless be generally obvious. Force masquerades in a variety of disguises—mechanical, electrical, chemical—but essentially it is anything which tends to produce, restrict, or change motion. Thus, force may be a pressure, a weight, or a tension. Motion is not necessarily implied, since two or more forces acting simultaneously on a body may be so balanced as to render the body immobile.

Work

To many individuals, work is the effort expended between “punching the clock” in the morning and “ringing out” at night, and is measured in terms of fatigue, boredom, or dollars and cents. The engineer’s definition, while it lacks human interest, is somewhat more precise. For him, *work is the product of a force and the distance through which it acts*, or:

$$\text{Work} = \text{force} \times \text{distance}$$

(in the direction of the force).

If a weight of 50 pounds is raised a distance of 11 feet, the work done is 50 pounds \times 11 feet = 550 foot-pounds. (See figure 7-1). The same amount of work, 550 foot-pounds, will be done if a 10-pound weight is raised 55 feet.

Power

Power is the rate of doing work, in other words,

the amount of work done in a certain length of time. Thus,

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

If you were to climb four flights of stairs, the work done (that is, the product of your weight and the total height of the stairs) would be the same regardless of the rate of ascent. On the other hand, if you were to first saunter slowly up the four flights and a little later to run up them, in say, one-third of your original climbing time, pulse and perspiration should convince you that you developed considerably more power during the rapid ascent than during the leisurely climb.

Power is expressed in a number of units—horsepower, kilowatts, BTU per minute, and the like, of which the first named is perhaps the most familiar. One *horsepower* (hp) is defined as *work at the rate of 550 ft-lb per second, or 33,000 ft-lb per minute*.

$$\begin{aligned} \text{Horsepower} &= \frac{\text{No. ft-lb per sec}}{550} \\ &= \frac{\text{No. ft-lb per min}}{33,000} \end{aligned}$$

Thus, if an engine is doing work at the rate of 16,500 ft-lb per second, or 990,000 ft-lb per minute, it is developing 30 hp.

Torque

So far, the discussion of dividing work by time has considered that the force factor of work was

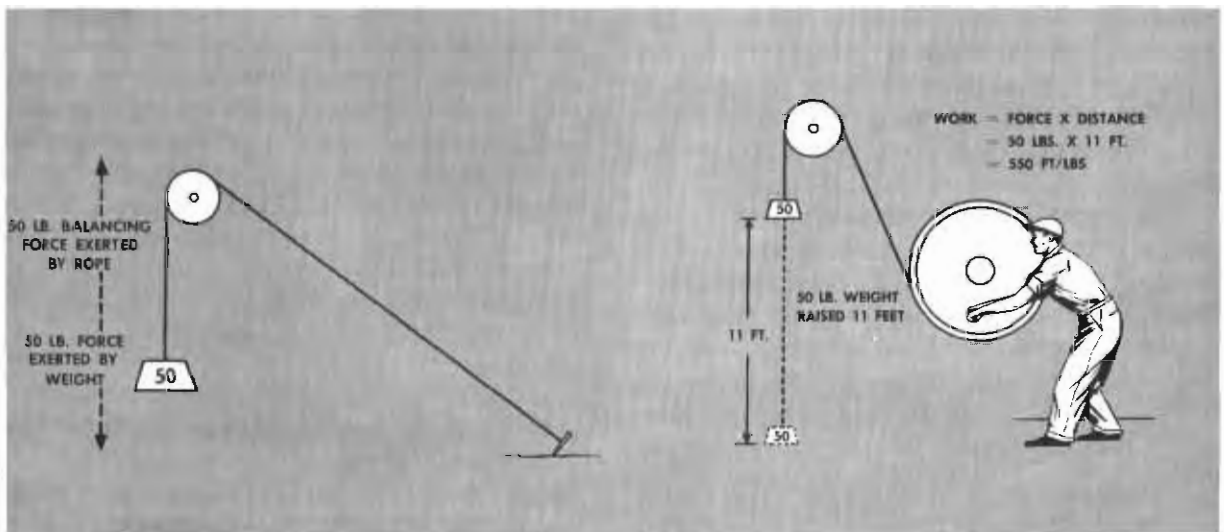


Figure 7-1. Work

acting in a straight line only. The form of energy existing in a rotating shaft does not lend itself to this elementary concept; therefore, the analysis must go further so that the power output of an engine can be described and measured. If the force applied to the crankshaft through the link- rods were considered as being constantly exerted at the end of a lever and at right angles to the lever, there would be a tendency to twist the shaft. This twisting tendency causes the shaft to rotate and the rate of rotation increases until an equal and opposite force is established in the propeller because of the reaction of the blades with the air. (See figure 7-2). If this equilibrium condition is at 2000 rpm, the power formula can be worked as follows:

$$\text{Force} = 20,000 \text{ lb}$$

$$\begin{aligned} \text{Distance} &= 2 \times \pi \times \text{radius} \times \text{number} \\ &\quad \text{of revolutions} \\ &= 2 \times 3.1416 \times \frac{3}{12} \text{ ft} \times 2000 \\ &= 3142 \text{ ft} \end{aligned}$$

$$\text{Time} = 1 \text{ Minute}$$

And,

$$\begin{aligned} \text{hp} &= \frac{\text{ft-lbs per min}}{33,000} \\ &= \frac{20,000 \text{ lb} \times 3142 \text{ ft}}{1 \text{ min} \times 33,000} = 1904 \end{aligned}$$

The bending moment imposed by the lever on the shaft by the 20,000 lb force acting at 3 inches from the shaft center is known as *torque*. Those who have hand-cranked automobiles or outboard motors have applied torque by exerting push or pull at right angles to a lever attached to a rotating shaft.

$$\text{Torque} = \text{force} \times \text{distance} = \text{lb-ft}$$

where the distance is measured in a plane which is at right angle to the center line of the shaft, and the force is at right angle to the distance.

In the example cited, the torque is equal to 20,000 lbs \times .25 ft, or 5000 lb-ft. Also note that 5000 lb-ft of torque would be obtained if a 1000-lb force were applied with a 5-ft arm or a 40,000-lb force were applied with an arm of 1½ inches. The torque at the shaft is the same, provided the product of the force times the lever arm remains the same.

Torque is a measure of energy or the ability to do work, and is properly, though not constantly, expressed in *lb-ft*. It is not to be confused with work, which is expressed in *ft-lb*. It is possible

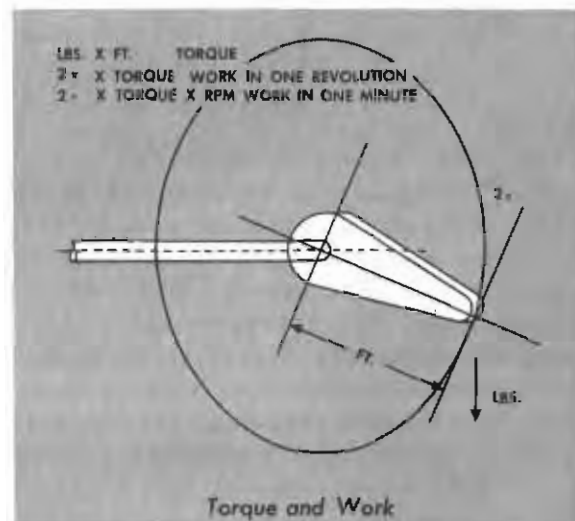
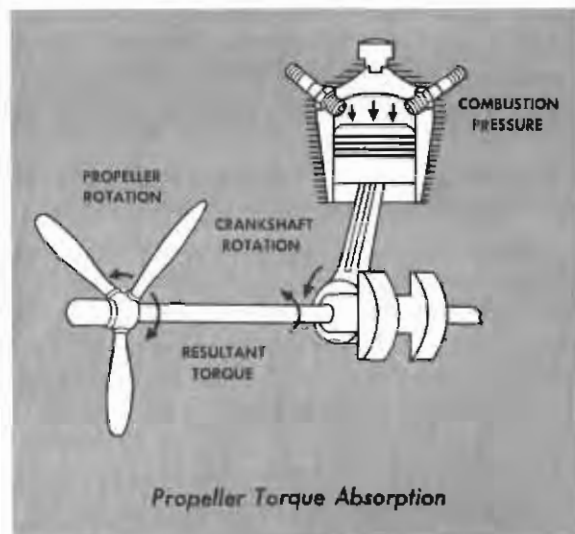
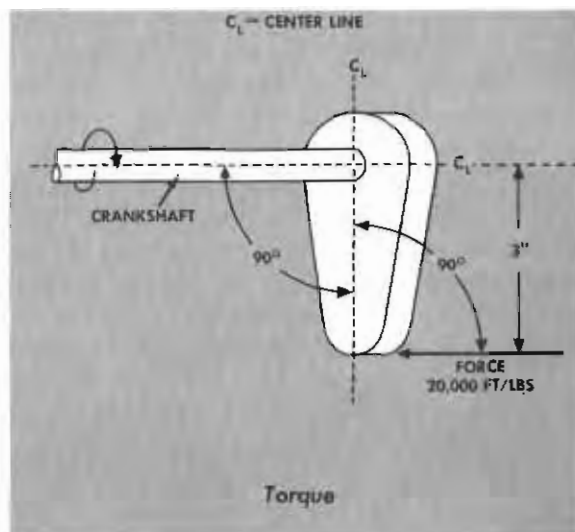


Figure 7-2. Torque Principles and Applications

to have torque (lb-ft) without motion in which case no work (ft-lb) is performed.

The horsepower equation can be reworked so that the useful engine output can be expressed in terms of rpm and torque.

Since torque is expressed in lb-ft, it contains a force value and also a distance value. This distance is the lever arm and the force is that which is applied at the end of the lever. In one revolution, this force moves around the circumference of a circle whose radius is equal to the lever arm. In other words, the force does work equal to $2\pi \times 3f$ where 3 is the distance from the center of rotation in feet and f is the applied force in pounds. But $3f$ is the torque developed, therefore, the work done per revolution is $2\pi T$ with units in ft-lbs. The work done in 10 revolutions would be $60\pi T$ ft-lbs. If a shaft were being turned at a speed of 10 rpm then the work done in a minute would be $60\pi T$ ft-lbs. The power developed is then $\frac{60\pi T}{33,000}$ in terms of hp. If a shaft were being turned at the speed of n rpm then the work done in a minute would be $2n\pi T$ ft-lbs and the power developed would be $\frac{2n\pi T}{33,000}$ in terms of hp. This equals:

$$\frac{T \times n}{5252}$$

therefore, the power (in hp) equals:

$$\frac{T \times n}{5252}$$

Since we generally use rpm for the rotational speed, we can substitute it for n and the equation becomes:

$$\text{Power (in hp)} = \frac{T \times \text{rpm}}{5252} \text{ (torque in lb-ft)}$$

$$\text{Power (in hp)} = \frac{T \times \text{rpm}}{63024} \text{ (torque in lb-in)}$$

These two equations apply to the power present in any rotating shaft regardless of the kind of power-producing unit that is causing the shaft to rotate. To measure the power delivered by the shaft, it is only necessary to have means for measuring rpm and torque. The more directly these two factors are measured, the greater is the accuracy of determining the power. The tachometer measures rpm directly. The tachometer generator is driven by the crankshaft through a train of gears and the only inaccuracies are instrument errors.

As long as the torque increase is proportional to the rpm decrease, the horsepower to the shaft remains unchanged. This can be seen from the equation since torque and rpm are the only variables. If the change in rpm is inversely proportional to the change in torque, their products remain unchanged. Therefore bhp remains unchanged.

Unlike rpm and manifold pressure, torque is not easily measured. While the sole use of manifold pressure as a measure of torque permits safe engine control where great accuracy is not required, the indirect relationship between manifold pressure and torque has its shortcomings. Torque changes with manifold pressure, but the relationship is not precise and significant changes of torque can be experienced without a corresponding change in manifold pressure and vice versa. The key to accurate power determination and precise powerplant management is a means of measuring torque directly.

In the laboratory, torque is measured by a device used to absorb the engine's power output. The earliest method employed was the *Prony brake*, which regulated the rpm and torque load with a brake or friction device. The force required to restrain the brake from turning could be measured and the power output calculated. The Prony brake has been replaced by hydraulic and electrical devices, but the principle remains the same and the term *brake horsepower* (bhp) is still used to refer to that part of the engine's output that can be measured by a brake.

A brake cannot be used for power measurement in flight, because the brake absorbs all of the power output. Actually, the propeller is the brake while in flight, and torque could be calculated if blade characteristics, blade angle, air density, and airspeed could be accounted for accurately. However, this would still be an indirect measure of torque.

The planetary reduction gear system of a reciprocating engine makes it possible to measure torque directly because a force proportional to torque is present in one of its fixed members. Solving the hp equation for torque:

$$\text{Torque} = \text{hp} \times \frac{63,024}{\text{rpm}} \quad (41)$$

The change of torque from the crankshaft to the propeller shaft will be as follows:

$$\begin{aligned} \text{Torque prop shaft} &= \frac{\text{hp} \times 63,024}{\text{rpm prop shaft}} \\ &= \frac{\text{rpm crankshaft}}{\text{rpm prop shaft}} = \frac{1}{\text{gear ratio}} \end{aligned}$$

Assigning a value of 1 to the crankshaft torque, the propeller shaft torque for an engine with .375 propeller reduction ratio will then be 1/.375 or 2.667. As these two torques oppose each other, an additional torque acting in the same direction as that of the crankshaft and equal to the difference between the propeller and crankshaft torques must be present to maintain equilibrium, as shown in figure 7-3.

This balancing force is present in the fixed gear of the planetary gear system. (See figure 7-4). This proves very useful since the necessary immobility of this gear allows it to be restrained by devices which will register the magnitude of the restraining force on an instrument.

Usually the fixed gear is held rigidly in the reduction gear housing and the restraining torque is transferred to the housing without being measured. In an engine incorporating a torquemeter, the fixed gear floats and tends to move in a direction opposite to that of the crankshaft and propeller shaft.

The mechanical arrangement of parts required to measure these reactions differs somewhat for various engine models, but the basic principles of operation are the same, as shown in the ac-

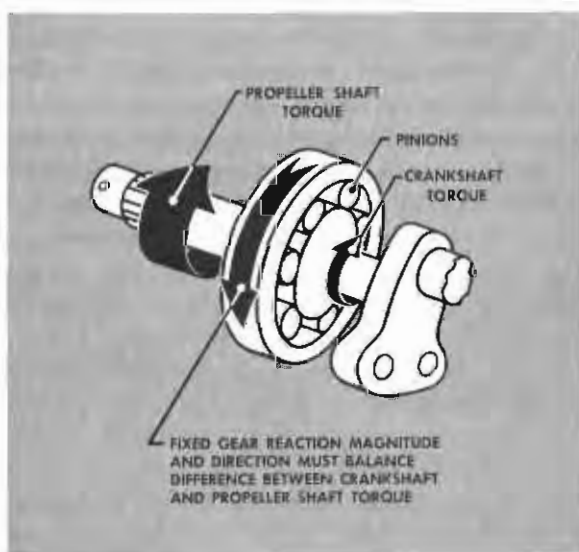


Figure 7-3. Torque Forces in Reduction Gear

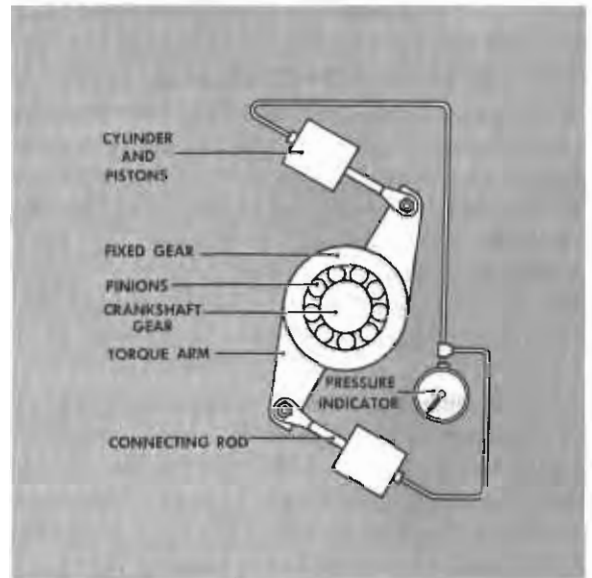


Figure 7-4. Basic Torquemeter Components

companying sketch. In R-4360 and R-2800 engines, the tendency of the fixed gear to rotate is translated into a tendency to move fore and aft with a helical spline mating the fixed gear and the reduction gear housing. The motion due to driving torque is opposed by oil pressure acting on pistons which apply force to the fixed gear. Motion in the opposite direction, which may be created by propeller windmilling, is restrained by stops. The pressure of the oil against these pistons is a direct measure of the force tending to rotate the fixed gear and so is a direct measure of the torque being delivered by the engine to the propeller.

Use of the Torquemeter

Although the manifold pressure indication can be used to show the power input to the engine, the rpm indication cannot be used as a valid indication of power output because engine rpm is maintained by the propeller to a preselected setting. A torquemeter installation, however, shows the torque applied to the propeller shaft, from which the actual bhp developed by the engine can be calculated.

On aircraft having engines equipped with torquemeters, the engineer establishes a power setting by first selecting the desired mp and rpm settings; then by using the torquemeter he can

determine the actual bhp being developed. Because of the many variables that affect the bhp developed by the engine, such as carburetor air temperature (cat), cylinder head temperature (cht), exhaust back pressure, and fuel-air ratio, the calculation of engine power without the use of the torquemeter leaves much to be desired, especially when accuracy in determining engine power development is of vital importance to the success of long-range cruise control missions. Basic torquemeter components are illustrated in figure 7-4.

The torquemeter oil pressure indication provides the operator with a direct measurement of the torque being transmitted by the crankshaft to the propeller shaft. This torque pressure, when multiplied by the rpm of the engine and a suitable factor, called the K factor, provides a quick and easy method of arriving at the actual brake horsepower an engine is developing. The K factor is a specific numerical value which takes into account the design features of the torquemeter and propeller reduction gears, and integrates them with the basic horsepower formula. Without this numerical constant, an almost endless list of computations would be necessary to determine the brake horsepower of an engine for any given rpm. Inasmuch as different engines use different torquemeter systems and have different speed ratios between the crankshaft and propeller shaft, a K factor has been worked out for each engine type and model by the manufacturer.

The differences in K factors for the same engine type can be shown by comparing those for two models of the Pratt and Whitney Wasp Major engine (R-4360 series). On the R-4360-35 and -41 engines, which have a propeller reduction gear ratio of 375:1, the K factor is .0043. On the R-4360-20W engines, with a reduction gear ratio of 425:1, the K factor is .00533. This K factor can be found in the *Pilot's Handbook of Operating Instructions* for the particular aircraft concerned. The K factor varies in accordance with the crankshaft to propeller shaft ratio.

The torquemeter measures the torque delivered to the propeller, but it does not measure the torque being furnished to drive the accessories. When the torquemeter is used for making power settings or for comparing the performance of the engine against established ratings, the power being absorbed by the operation of the various engine accessories must be taken into account.

On aircraft equipped with a torquemeter installation, the manifold pressure gage is used to determine power input, and the torquemeter gage indication is used to measure the power output.

In establishing various power settings, the engineer is concerned with three engine instruments: *the manifold pressure gage, the tachometer, and the torquemeter gage.* He establishes the desired manifold pressure and rpm setting; then for this power setting, the torquemeter pressure gage should indicate a torque value in psi that lies within prescribed limits. The actual bhp being delivered to the propeller shaft regardless of carburetor air temperature, cylinder head temperature, oil temperature, fuel-air mixture strength, impeller drive ratio, exhaust back pressure, altitude, and relative humidity can be found by using the following formula:

$$\text{rpm} \times \text{torque pressure} \times K = \text{bhp}$$

As a typical example let us use actual values in the formula. Assuming that the aircraft is equipped with R-4360-20W engines, the indicated engine speed is 2700 rpm, and the torque pressure reading is 216 psi, the solution to the problem would be:

$$2700 \times 216 \times .00533 = 3108.456 \text{ bhp}$$

From this -1 technical order in the operating instructions for a particular aircraft, the engineer can find the minimum power requirement that an engine must meet for takeoff. The minimum torque pressure required for takeoff changes slightly with small changes in several varying factors, such as the carburetor air temperature. Possessing these facts, the engineer can easily compute the bhp required for a particular takeoff. The flight manuals for the specific aircraft will specify the percent of decrease in torque pressure allowed on any one engine. The percent used will be established by local policy. Using the 6 to 10 percent allowable decrease, the engineer can determine exactly the minimum torque pressure on any one engine that must be developed to assure a safe takeoff.

The -1 technical order also includes many operational charts. These numerous charts inform the engineer of the performance that can be expected of the engines at various power settings, and cover a wide range of engine performance requirements. For example, the charts show such performance information as estimated takeoff bhp, fuel flow for various power settings, takeoff and

climb data, air speed calculations, and special power settings that are necessary to compensate for engine failure. From these charts, pilots and flight engineers can determine the desired performance level an engine should reach under various instrument indications and decide whether or not the engine performance meets the desired standards.

As stated before, the relationship expressed in the previous equation is very important for it shows that bhp is a function of both torque and rpm. For example, an engine conceivably could deliver the same bhp at the propeller shaft under each of the following conditions:

bhp	rpm	torque (lb/ft)
1900	2700	3694
1900	2200	4535
1900	1700	5868

Since the constant-speed propeller permits separate control of torque and rpm, a decision must be made by the flight engineer as to which combination to use for any particular power output condition. The basis for determining these combinations in the cruise range of power settings has been determined by cylinder pressures.

FACTORS AFFECTING POWER OUTPUT

Piston Displacement

The specific volume swept out by a piston as it moves from bottom to top center is known as *piston displacement* and is expressed in cubic inches. When other factors remain constant, the greater the piston displacement, the greater the maximum horsepower an engine can develop. The piston displacement of one cylinder is 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; the total piston displacement is found by multiplying the displacement of one cylinder by the number of engine cylinders. For example, the Wasp Major, whose piston is 5.75 inches in diameter and whose stroke is 6 inches, has a displacement of 155.7 cubic inches per cylinder.

$$\begin{aligned} \text{Cross section area of bore} \times \text{stroke} \\ \text{length} &= \text{Displacement} \\ \frac{1}{4}\pi \times D^2 \times L &= 0.7854 \times 5.75 \times 6 \\ 5.75 \times 6.00 &= 155.7 \end{aligned} \quad (42)$$

And from the second formula, we find that the 28-cylinder Wasp Major's total piston displacement is 4359.6 cubic inches:

$$155.7 \times 28 = 4359.6$$

Compression Ratio

All internal combustion engines must compress the fuel-air mixture so that a reasonable amount of work results 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 7-5) 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 "compression 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 120 cubic inches of space in the cylinder when the piston is at the bottom of the stroke and there are 20 cubic inches of space when the piston is at the top of the stroke, the compression

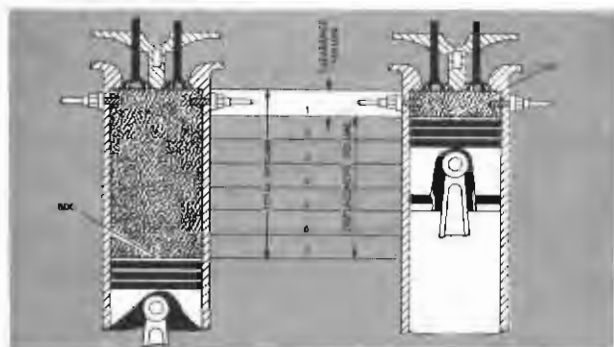


Figure 7-5.
Compression Ratio

ratio is 120 to 20. If this ratio is expressed in fraction form, it is $\frac{120}{20}$, or 6 to 1, usually represented as 6:1.

To understand more thoroughly the limitation placed on compression ratios, you must understand manifold pressure and its effect on compression pressures. *Manifold pressure* (mp) is the average absolute pressure of the air or fuel-air charge in the intake manifold and is measured in 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.

Compression ratio, manifold pressure, rpm, valve timing, and air temperature, in combination, determine the pressure near the end of the intake stroke and just before ignition takes place. Compression ratio and valve timing are the fixed factors, while manifold pressure, rpm, and air temperature are the variable factors. Manifold pressure is influenced by throttle setting and by altitude. Ambient air temperature depends on the altitude and existing climatic condition.

For any given rpm, the major variable is manifold pressure and this factor can be critical during ignition. Without going into great detail we have 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 (knock) occurs and produces 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 with low compression ratio. A higher temperature is developed and more heat is converted into useful work, but also more heat is absorbed by the cylinder walls and is lost. This occurs with the

same fuel charge at the same fuel-air ratio; therefore, engine efficiency increases.

When a manufacturer increases the compression ratio enough to obtain greater fuel economy and more efficient engine operation at high altitudes, he does so at the expense of maximum power at lower altitudes. Here again, a compromise is needed between the demand for fuel economy and the demand for maximum horsepower without knock. In high-compression engines, knock (detonation) at high manifold pressure is suppressed by injecting antiknock fluid into the fuel-air mixture to reduce the temperature of the charge.

Cylinder Pressures and Engine Speed

In any reciprocating-type engine, the speed and the pressure developed within the cylinder during the power stroke are two variable factors which have a major effect on the power output. As the average positive pressure on the piston becomes greater, more power is delivered. As engine speed is increased more power events occur per unit of time. Both of these increases result in increased power output.

Cylinder Effective Pressures

During a cycle of an internal combustion engine, the pressure within the combustion chamber varies considerably. To simplify the discussion of the pressure, a mean effective pressure is defined. Remember that mean effective pressure is not found in the engine; it is a mathematical device only. Since the total power output of the engine (indicated horsepower) is divided between friction horsepower and brake horsepower, the mean effective pressure is also called indicated mean effective pressure and is separated into *friction mean effective pressure* (fmep), and *brake mean effective pressure* (bmep).

The total average pressure produced in the combustion chamber during the operating cycle is called indicated mean effective pressure (imep). Imep is the pressure which produces the theoretical power known as indicated horsepower (ihp).

The portion of imep that is used to overcome the friction of moving parts in an engine and its accessories is called friction mean effective pressure (fmep). Fmep is the pressure that produces friction horsepower (fhp).

The portion of the imep that produces the use-

ful power at the propeller shaft is known as brake mean effective pressure (bme_p). The power that this pressure develops is applied to the propeller shaft and is called brake horsepower (bhp).

In formula form,

$$\text{imep} = \text{fmep} + \text{bme}_p \quad (43)$$

Although ime_p, bme_p, and fmep have no real measurable existence in the cylinder, they provide the design engineers with a convenient means of representing pressure limits and rating engine performance throughout the entire operating range.

To see how these pressures affect the power output of an engine, let us examine their relationship to horsepower calculations.

HORSEPOWER CALCULATIONS

In the calculation of aircraft engine horsepower, three "types" of horsepower are usually considered. These are *indicated horsepower* (ihp), *friction horsepower* (fhp), and *brake horsepower* (bhp), each of which is expressed as a numerical value.

Indicated Horsepower

Indicated horsepower (ihp) is the theoretical horsepower developed by a frictionless engine. This horsepower is calculated as a function of the actual cylinder pressure as recorded during engine operation. To facilitate the indicated horsepower calculations, a mechanical indicating device, attached to the engine cylinder, scribes the actual

pressures existing in the cylinder during the complete operating cycle. This pressure variation can be represented by the kind of graph shown in figure 7-6. Notice that the cylinder pressure rises on the compression stroke, reaches a peak just after the ignition event, 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 averaging is the mathematics referred to earlier.) This average pressure is known as indicated mean effective pressure (ime_p) and is inserted in the indicated horsepower calculation with other engine specifications. If the characteristics and the ime_p of an engine are known, it is possible to calculate the indicated horsepower rating.

The indicated horsepower of an engine can be found by computing the foot-pounds of work that the engine does in one minute and dividing this value by 33,000 (the number of foot-pounds per minute in one horsepower).

In formula form,

$$\text{ihp} = \frac{\text{Number of foot-pounds produced/min}}{33,000 \text{ foot-pounds/min}}$$

Since the foot-pounds of work per minute produced by the engine depend upon piston displacement, compression ratio, engine rpm, and indicated mean effective pressure, letter symbols for these factors can be substituted in the numerator of the formula.

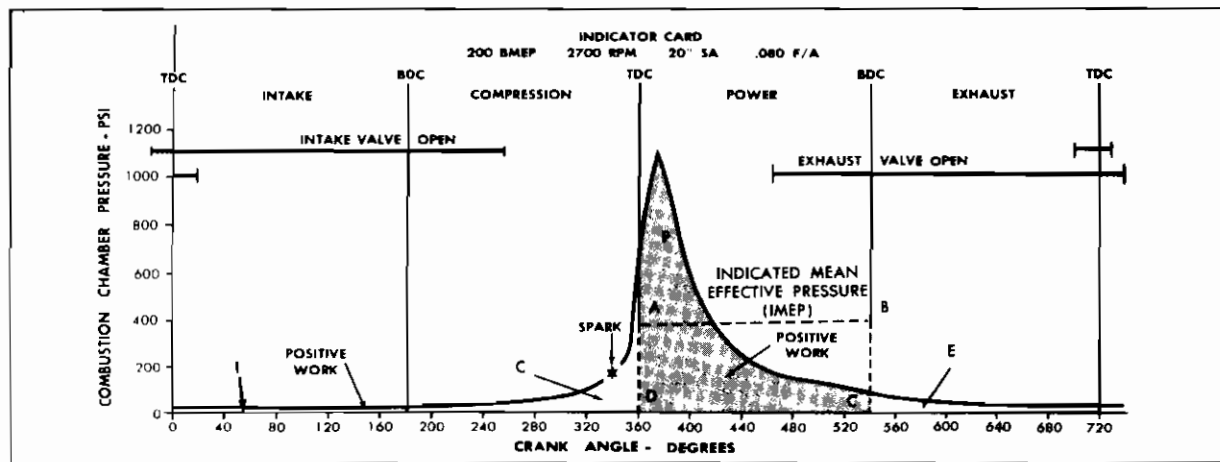


Figure 7-6. Variations in Combustion Chamber Pressure

The formula now reads:

$$\text{ihp} = \frac{\text{PLANR}}{33,000}$$

where

- P = imep in psi (pounds/sq in)
- L = Length of stroke in feet
- A = Cross-sectional area of the bore or piston
- N = Number of power strokes per minute, or $\frac{\text{rpm}}{2}$
- R = Number of cylinders
- 33 000 = Number of ft-lbs/min in one horsepower

What is the ihp of an R-4360 engine operating at 2000 rpm and developing an imep of 165 lbs/sq in. The engine has 28 cylinders, a bore of 5.75", and a stroke of 6".

$$P = 165$$

$$L = \frac{6}{12} = .5$$

$$A = 25.95 \quad (A = \frac{1}{4}\pi \times D^2) = .7854 \times 5.75 \times 5.75 = 25.95$$

$$N = \frac{2000}{2} = 1000$$

$$R = 28$$

Substituting in the formula,

$$\text{ihp} = \frac{165 \times .5 \times 25.95 \times 1000 \times 28}{33,000 \text{ ft lbs/min}}$$

$$\text{ihp} = 1820$$

This and other horsepower equations can be simplified by restating them in terms of engine displacement. Since the displacement of any engine is always known, it can be reduced to a simple constant. The displacement of any engine is the cross-sectional area of the bore in square inches times the length of stroke in inches times the number of cylinders. By rewriting the basic horsepower formula to obtain the proper dimensional values needed,

$$\text{ihp} = \frac{\text{imep}}{33,000} \frac{L}{12} \frac{A}{1} \frac{R}{1} \frac{\text{rpm}}{2}$$

where imep = P (as previously stated)

L — Length of stroke in inches (L/12 is the length of stroke in feet; this retains the value of the original equation.)

$$\frac{\text{rpm}}{2} = N \text{ (as previously stated)}$$

In this representation of the equation, you can see that the values of L, A, and R in the numerator, when multiplied, represent piston displacement; consequently they may be replaced by "displacement." Multiplying through in the denominator, $33,000 \times 12 \times 2 = 792,000$.

Therefore the formula can be written

$$\text{ihp} = \frac{\text{imep} \times \text{piston displacement} \times \text{rpm}}{792,000} \quad (44)$$

Applying the formula to a particular engine; for example, the R-4360 engine.

$$\text{ihp} = \frac{\text{imep} \times 4359.6 \times \text{rpm}}{792,000}$$

Note that the actual displacement is 4359.6 cubic inches.

The formula can be simplified further by dividing the piston displacement (4359.6) into the constant factor 792,000 to obtain a single numerical value called the engine K factor (mentioned earlier).

The K factor for the R-4360 is 181.5 and is used in the formulas as follows:

$$\text{ihp} = \frac{\text{imep} \times \text{rpm}}{181.5}$$

$$\text{or imep} = \frac{\text{ihp} \times 181.5}{\text{rpm}}$$

$$\text{or rpm} = \frac{\text{ihp} \times 181.5}{P \text{ (imep)}}$$

This engine K factor varies from one engine to another, depending on the piston displacement and reduction gear ratio.

Friction Horsepower and Brake Horsepower

Friction horsepower can be calculated two different ways. When the engine is run for brake horsepower computation, either on a Prony brake or dynamometer setup, a reverse arrangement may be used to find out how much power is necessary to turn the engine over without the cylinders firing. The other way is to find the ihp as previously discussed, and then compute the bhp with a dynamometer or torque system, and the difference between the two is the friction horsepower.

$$\text{ihp} - \text{bhp} = \text{fhp} \quad (45)$$

The equation that was used to determine ihp may be converted to find bhp by substituting bmep for imep in the equation. This substitution is possible because bmep bears the same relationship to imep as bhp does to ihp. Thus, in equation form,

$$\text{bhp} = \frac{\text{PLANR}}{33,000}$$

where

$$P = \text{bmep}$$

Substituting piston displacement in the formula,

$$\text{bhp} = \frac{\text{bmep} \times \text{displacement} \times \text{rpm}}{792,000}$$

Substituting the engine constant K,

$$\text{bhp} = \frac{\text{bmep} \times \text{rpm}}{K (181.5)}$$

POWER CONTROL

Most reciprocating-engine-powered aircraft are equipped with either a bmep gauge system or a torquemeter gage system. Regardless of which system is used, the indications on the instrument serve the same purpose. This indication is a measurement of the torque delivered by the pressure exerted by the pistons, through the crankshaft, reduction gears, and to the propeller shaft. This power available at the propeller shaft is known as bhp and is developed by the bmep.

Why is bmep so important and why are we so concerned about it? Bmep is important because efficient power application comes with engine operation at or near maximum allowable bmep for a given engine speed. This type of operation is particularly applicable in the cruising range, where no sudden increase in power is anticipated which might exceed safe bmep limits.

Most modern aircraft powered by reciprocating engines are equipped with the variable-pitch propeller and the necessary controls. This arrangement permits the operator to vary the propeller blade angle (pitch) to conform to the load on the engine, and thus change the bmep to make most efficient use of the power produced.

As the propeller blade angle is increased and the throttle position not changed, a greater load is imposed on the engine, and the engine rpm tends to decrease, just as your automobile engine tends to slow down during a long uphill pull at a constant throttle setting. As the blade angle is decreased, with the throttle position still unchanged, the engine rpm increases as the load is relieved. The same effect is observed as you descend on a long grade in your automobile or as you depress the clutch pedal without taking your foot from the throttle.

When rpm is varied at the same throttle setting, the length of time the intake and exhaust valves are open is also changed. Therefore, as the engine rpm is decreased with the propeller, a greater volume of charge enters the cylinders, higher bmep occurs, and greater power per power stroke is produced.

The advantages of this type of power control (maximum bhp at a minimum rpm) is that reciprocating and centrifugal loads as well as friction losses are minimized, fuel and oil consumption is decreased, and wear is reduced. However, a decrease in rpm at a constant throttle setting means

that the cylinder pressure increases in proportion to the increased mass of the charge. Therefore, if the engine rpm is reduced excessively with the propeller control, the specified maximum pressure (expressed as maximum bmep) for the particular power setting is exceeded, and detonation, excessive bearing loads, and higher cylinder head temperatures result.

From the foregoing discussion, you should understand that bmep is, as the name implies, the resultant pressure that delivers the torque which is transmitted to the propeller shaft. Thus torque and torque pressures which are measured through the torque system are related to bmep. Regardless of the type of indicator used to show the output of the engine, whether it is a torque gage, or a bmep gage, the reading on the indicator is determined by two variable factors, rpm and torque.

Torque and rpm are independently controlled by the engineer and he has a wide variety of combinations to use for a required power. The engineer has a formula for his use in determining bhp:

$$\text{bhp} = \text{TOP (psi)} \times \text{rpm} \times \text{K} \quad (46)$$

where

TOP = Torque oil pressure in psi (also abbreviated tpsi)

K = Engine constant (available from the -1 technical order.)

A theoretical approach to setting up power, without considering all the factors, would favor minimum rpm and a correspondingly high torque or bmep, because this combination would produce the required output and deliver it to the propeller with the least input.

Since fuel consumption is determined by input, range should increase if a given power output were to be obtained with the minimum rpm and maximum torque or bmep. However, practical considerations require a slight modification of the theory. The high propeller blade angle required to absorb such a heavy torque loading at low rpm results in a serious loss of propulsive efficiency. While the engine would be giving its output at a very low brake specific fuel consumption, the propeller could not translate this into low-thrust specific fuel consumption, and miles per pound of fuel would diminish. The continuous high torque would result in high continuous stresses on all of the power transmission system from the piston to the propeller shaft. Experience

over the years has proved that these loads must be limited.

To avoid "flogging" a laboring engine, the engineer may turn to the other extreme of high rpm and low torque only to run into another set of difficulties. Higher rpm results in greater fhp. Accordingly, if 1800 bhp must be maintained, the ihp must be increased and as a result the fuel consumption is greater, since it is ihp, not bhp, that governs fuel flow. High rpm also leads to greater reciprocating loads, and the faster the engine operates, the sooner it wears itself out. At the same time, the higher internal impeller speeds may mean that critical charge temperatures are being approached. Proper operation clearly lies somewhere between the two extremes. Recent experience in testing and service operation proves that most reciprocating engines can be safely operated with good durability standards in the cruising range, using 115/145 fuel (discussed later in this chapter under "Aviation Fuels") for prolonged periods, with the cylinder pressures and temperatures represented by a bmep of 150-160 psi.

ENGINE EFFICIENCY

In addition to power output, there is another factor which is closely related to engine operation. This factor is *efficiency*, which can be defined in general as a comparison of "output" to "input." In other words, *efficiency is output divided by input* and is expressed in percent. Specifically, there are three efficiencies commonly referred to in connection with engine operation: *thermal efficiency, mechanical efficiency, and volumetric efficiency.*

Thermal Efficiency

Any study of engines and power involves consideration of heat, the source of power. The heat produced by the burning of gasoline in the cylinders causes rapid expansion of the gases in the cylinders. The force exerted by the expanding gases moves the pistons and creates mechanical energy.

It has long been known that mechanical work may be converted into heat, and that a given amount of heat contains the energy equivalent to a certain amount of mechanical work. In other words, heat and work are theoretically inter-

changeable and bear a fixed relation to each other. Heat may therefore be measured in work units—for example, foot-pounds—as well as in heat units. The British thermal unit of heat (BTU) is the quantity of heat required to raise the temperature of 1 pound of water 1° F. It is equivalent to 778 foot-pounds of mechanical work. A pound of petroleum fuel, when burned with enough air to consume it completely, gives up about 20,000 BTU, the equivalent of 15,560,000 foot-pounds 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 engines use equal amounts of fuel, the engine which converts into work the greater part of the energy in the fuel (that is, which has the higher thermal efficiency) delivers the greater amount of power. 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 twofold, and it constitutes one of the most desirable features in the performance of an aircraft engine.

Of the total heat, 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. See figure 7-7). 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 percent of the total heat of combustion which is turned into mechanical work is approximately constant, but the higher the compression ratio, the more heat that is developed and the more useful work that is done. This heat factor is a limiting factor, for the extremely high temperature created by high compression ratios causes the material in the cylinder to deteriorate rapidly and the fuel to detonate.

Thermal efficiency is computed on the basis of the equation:

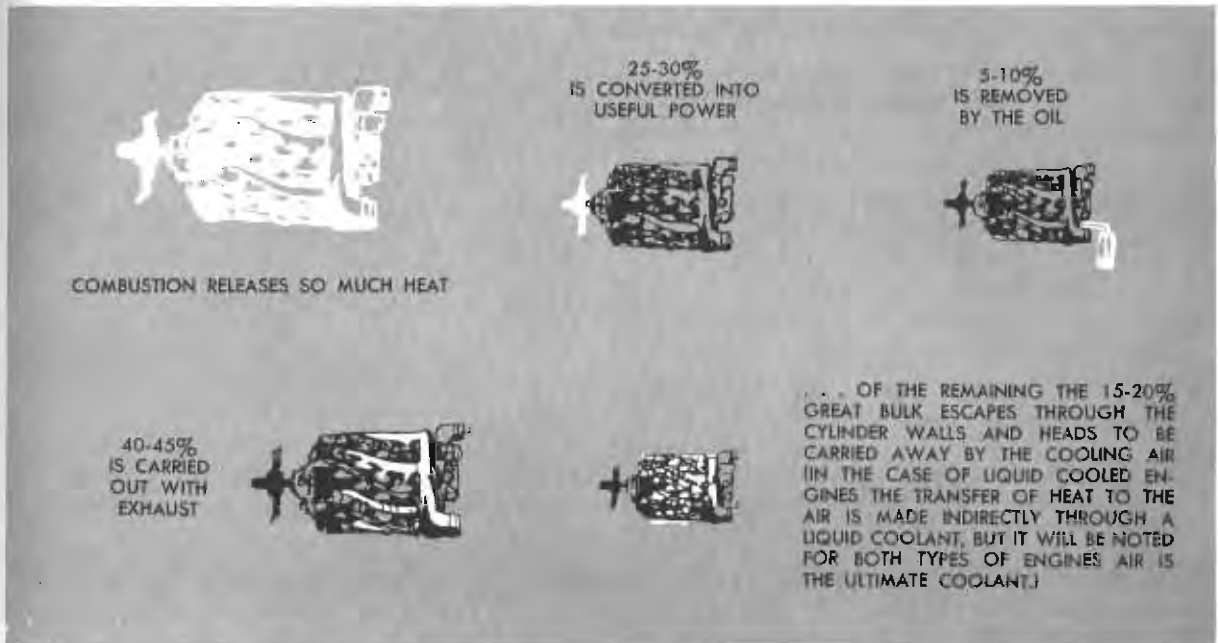


Figure 7-7. Heat Disposal of Typical Reciprocating Engine

$$\text{Thermal efficiency} = \frac{\text{Horsepower} \times 33,000 \text{ ft lbs/min}}{\text{fuel wt/min} \times 20,000 \text{ BTU} \times 778 \text{ ft lbs work}} \quad (47)$$

Thermal efficiency is about 18% for the average service-type engine running at full power. At lower powers, the thermal efficiency may reach 30%, and on some engines it may reach 35% or 40%.

Mechanical Efficiency

Another engine efficiency closely linked to thermal efficiency is *mechanical efficiency*. It is expressed in percent and it is the *ratio of shaft output (brake horsepower) to power developed in the cylinders (indicated horsepower)*.

Mathematically,

$$\text{Mechanical efficiency} = \frac{\text{brake horsepower}}{\text{indicated horsepower}} \quad (48)$$

The mechanical efficiency of the average high-output engine approaches 90%. The loss of 10% or more is caused by the use of energy to overcome friction. In the design of an aircraft, an engine is required that will supply the amount of power needed for the desired performance. Such specialized military aircraft as fighters or interceptors are powered relatively high in order to obtain high rates of climb and good maneuver-

ability. For bombardment- or transport-type aircraft, the powerplant is selected on the basis of cruising flight, since range is the more important factor.

Volumetric Efficiency

A third engine efficiency that must be considered is *Volumetric Efficiency*. Here we have to consider the weight of the charge which under standard sea-level atmospheric conditions of pressure and temperature has a volume equal to engine displacement. Remember, for each two crankshaft revolutions, a volume of charge equal to engine displacement goes into the engine, regardless of manifold pressure. It is the weight of this volume that governs power output. An engine drawing in less weight of charge than this has a volumetric efficiency lower than 100%. An engine equipped with an impeller may have a volumetric efficiency greater than 100%. The equation for volumetric efficiency is:

$$\text{Volumetric efficiency} = \frac{\text{volume of charge (corrected to standard sea-level pressure and temperature)}}{\text{piston displacement}} \quad (49)$$

The factors which tend to decrease volumetric efficiency may be divided into two general groups:

those that impede the charge from getting into the cylinder, and those that limit its weight by increasing its temperature. They are:

- High engine speed
- Long intake pipes of small diameter, with bends and the like.
- Part-throttle operation
- Too high carburetor air temperature
- Too high cylinder head temperature
- Incomplete scavenging of exhaust gases
- Improper valve timing

Factors Affecting Efficiency

The power produced and the efficiency and dependability of an engine depend on the amount and condition of the air charge entering the cylinders, the amount of fuel burned with the air charge, and the nature of the combustion process. This statement refers to an integrated engine control team which must be managed and fully understood by the flight engineer. For example, the amount of the air charge that enters the engine cylinders depends primarily on the pressure of the air charge (manifold pressure) and the duration of the intake event (rpm). These functions are controlled by the combined positions of the throttle control, the propeller control, and the turbosupercharger control. The condition of the charge is regulated by such air-conditioning devices as the intercooler and preheater. The amount of fuel burned with the air charge is controlled by the carburetor which measures the airflow established by the throttle, propeller rpm control, and turbosupercharger to meter and fix fuel in the proper proportion. The nature of the combustion process is affected by the fuel-air ratio, valve timing, ignition timing, and cylinder head temperature.

Since proper management of aircraft engine controls depends on an understanding of the control systems, a discussion of each of the factors affecting efficiency follows.

MANIFOLD PRESSURE. Manifold pressure is sometimes thought of as another expression for power. From previous discussion, however, it is known that rpm and manifold pressure are equally important, and that the latter quantity must be corrected for carburetor air temperature, exhaust back pressure, fuel-air ratio, and spark advance before stating that a specific power is being obtained. Furthermore, engine calibration cannot be

completely accurate without accounting for cylinder head temperature, oil temperature, valve clearances, atmospheric humidity, and other items that define the standard conditions of the engine specification.

The units in the induction system control the weight of the air charge consumed by the engine. In the elementary induction system, the air is drawn from the outside by the pumping action of the pistons. At sea level with full throttle and maximum rpm, the manifold pressure would be less than 30 inches Hg (no internal blower) and maximum horsepower would be produced. With increasing altitude, the manifold pressure would fall off with the atmospheric pressure and the power would decrease accordingly. At 10,000 feet, full throttle power would be approximately 71% of that developed at sea level; at 20,000 feet, full throttle power would be about 48% of that developed at sea level.

The basic reason for this feeble performance is that the elementary induction system with its limited capacity can take in only a fixed volume of the atmosphere. The same volume of air decreases in weight as the altitude is increased. If more power is needed, more air must be pumped. Increasing the engine speed above maximum rated rpm is a possibility, but the structural loads on the rotating, reciprocating, and supporting parts would become excessive. Adding to the basic engine volume by increasing the bore and stroke or the number of cylinders could result in an engine of impractical weight and bulk.

The best method of producing the needed rate of airflow is to pack more weight of charge or air into the cylinder. This was first accomplished by internal supercharging.

The internal supercharger, figure 7-8, is a boost pump in the airstream directly ahead of and in series with the piston and cylinder. Its rotating member, the impeller, is driven by the crankshaft through a gear train which may have either a fixed ratio or a variable ratio. As the air charge passes through the impeller, it is compressed by being accelerated to a high velocity as it is thrown outward from the impeller. The air then passes through an expanding passage called the diffuser. As the air passes through the diffuser, its velocity decreases. This process changes the velocity energy to pressure energy. In addition, the diffusing passages are arranged to direct air into the intake manifold passages to aid in proper air distribution.

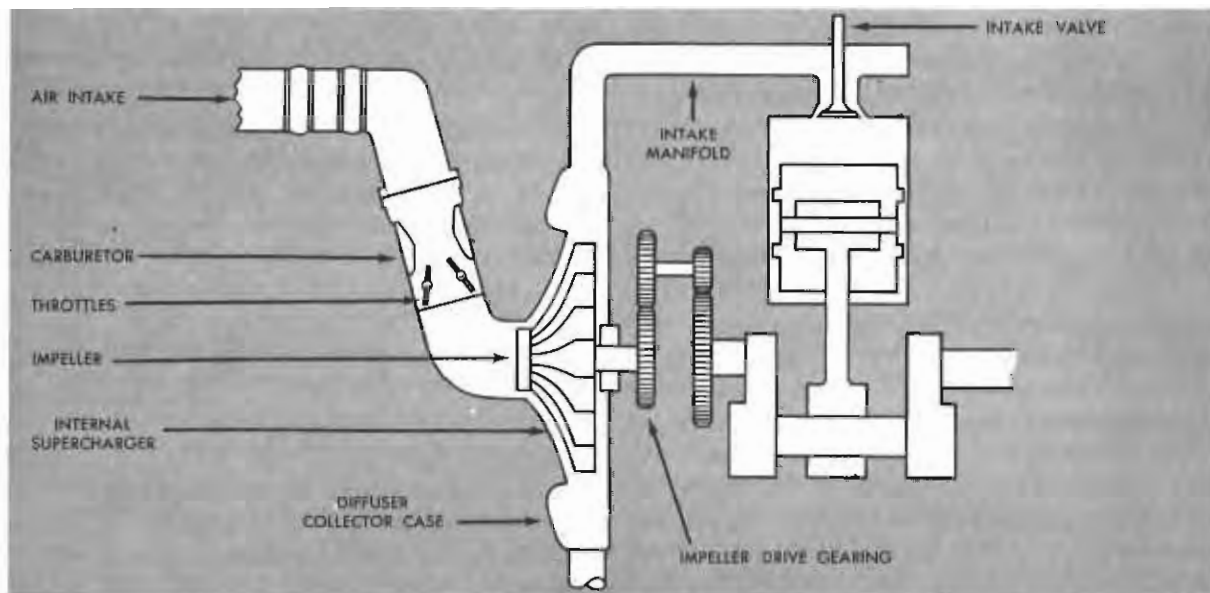


Figure 7-8. Internal Supercharger

An internally supercharged aircraft engine can be termed a ground-boosted engine, that is, maximum operating conditions prevail at sea level. However, the moment the engine leaves the ground, the pounds-per-hour air consumption falls off as the air density diminishes, and the power diminishes at the same rate as with an unsupercharged engine.

With only internal supercharging, the basic engine must be operated at times with power reduced below full capacity. This requires a direct means of reducing the weight of airflow. Rpm reduction is possible, but by itself cannot lower the output to the values desired for warmup, taxiing, and landing. If at any altitude, the same low pressure could be maintained ahead of the impeller, power could be conveniently controlled without resorting to extreme rpm changes or variation of altitude for the purpose of regulating airflow. The throttle, being a variable obstruction in the induction passage, provides the means for controlling the impeller entrance pressure and is, in effect, an altitude regulating valve for the engine air intake. At low altitude when the throttle is adjusted so that the downstream pressure is 13.75 inches Hg absolute, the internal supercharger "thinks" it is at 20,000 feet and produces the same manifold pressure that it would at that altitude where the same entrance pressure would be available with full throttle.

The present-day aircraft must have a powerplant that can sustain high power from start of takeoff to very high altitude. This implies that the weight of the fixed volume of air charge (engine displacement) must also be fixed in order to operate at all altitudes at high power. Throttle control of the air charge cannot attain high power; therefore, this can only be accomplished by supercharging, using power from an external source (the turbosupercharger) which must pump and compress the high volume of air necessary to maintain sea-level conditions at high altitudes for the few altitude reciprocating engine aircraft remaining in the Air Force inventory.

With a turbosupercharger, the same volume of air at a higher pressure is conducted through the manifold passage and into the cylinder during the intake stroke. The increase of pressure ahead of the cylinder increases the weight of each charge, but not in exactly direct proportion to the added manifold pressure because of the increase in the charge air temperature caused by the heat of compression. Fortunately the gain in density caused by the increased pressure is greater than the decrease in density caused by increased temperature. The net result is more weight packed into the fixed volume. This increase in weight of the air charge allows the cylinder to produce more horsepower. Not all of this added horsepower can go to the propeller, as some of the

power must be returned through the shaft to drive the internal supercharger which must now do more work with the heavier charge delivered to it.

The speed ratio of the supercharger is designed so that the maximum power can be obtained at sea level with maximum rpm. If the ratio were lower, insufficient air pumping capacity would result. If the ratio were higher, the cylinders would produce more power but a greater portion of this gain would need to be returned to the supercharger drive, and the fuel-consumption increase would be greater than the increase in performance at the propeller.

For carburetor engines in which the fuel is introduced at or ahead of the impeller, the internal supercharger performs the additional function of aiding fuel vaporization and distribution. The mechanical action of high-speed rotation and heat added by compression act upon the liquid fuel as it is discharged into the airflow so that the vaporization is nearly complete before the mixture enters the cylinders and the mixture is more evenly distributed to the cylinders of the engine.

HUMIDITY. The engine produces power in proportion to the amount of dry air consumed. As water vapor displaces dry air, its presence constitutes a loss of power-producing potential in the charge being pumped into the cylinders. The total pressure of the charge is the combination of the pressures of its component parts (nitrogen, oxygen, water vapor, and the like), and the manifold pressure gage, sensing total pressure only, is unable to reject vapor pressure and concentrate only on the pressure supplied by air.

Starting outside the induction system, if the barometer reads 29.5" Hg and .5" Hg vapor pressure is present, the dry air is responsible for a reading of 29.0" Hg. By the time the charge has passed through the induction system, the .5" Hg of vapor pressure is multiplied by the superchargers to about 1.02" Hg. Therefore, 60" Hg of manifold pressure represents only $60 \div 1.02$ or 58.98" Hg of power-producing charge—a loss of about 60 bhp per engine.

Since the carburetor cannot distinguish between water vapor and dry air, it meters fuel for the water vapor, thus furnishing too much fuel for the dry air actually taken in. This results in an additional loss of power for the prevailing manifold pressure. High humidity often accompanies high outside air temperatures so that the combina-

tion of these factors detracts from aircraft takeoff performance. The corrections outlined in the *Flight Handbook* are for the purpose of correcting the takeoff manifold pressure so that the true charge pressure is equal to that for which the engine is calibrated, and so that the maximum safe power is being delivered.

The humidity correction factor is used only during takeoff, since the moisture content of the atmosphere at higher operating levels is negligible. This correction should not be neglected by the engineer when he calculates beforehand what takeoff manifold pressure he will use.

CARBURETOR AIR TEMPERATURE. Carburetor air temperature (cat) affects power output because the power output of any engine varies directly with the weight of the charge in the cylinder at the time of combustion. The weight of air per given volume at constant pressure is a direct function of the temperature of the air. There are more molecules, and consequently more weight, of cold air in a given volume at a given pressure than there would be if the air were heated. From this you can see that the weight of the charge of fuel and air in the cylinder is greater when the charge is cold than when it is warm. Therefore, the bhp increases when the cat is low and decreases when it is high. How much this affects bhp can be computed mathematically or from a cat correction chart.

EXHAUST BACK PRESSURE. At sea level, when the combustion event is completed and the exhaust valve opens, the unsupercharged engine normally has difficulty in completely scavenging the residual gases in the cylinder because of the high normal atmospheric pressure of 29.92" Hg. As the altitude is increased, atmospheric pressure falls off until, at 18,000 feet, it is approximately 15" Hg. At this altitude, the exhaust back pressure (ebp) due to the atmosphere is approximately half that at sea level, and consequently the exhaust gases can be scavenged from the cylinder faster and more completely. With this better scavenging, a greater amount of charge can enter the cylinder, resulting in an increase in bmep and a corresponding increase in bhp output if the manifold pressure can be maintained at sea level value. Under average conditions, an increase of from 40 to 80 horsepower can be obtained by climbing to the critical altitude for the particular power setting.

CYLINDER HEAD AND OIL TEMPERATURES. High temperatures in the cylinder cause increased

pressure before combustion. Provided that the temperatures are not high enough to cause pre-ignition or detonation, this additional increase of pressure is desirable, for the more pressure (bmep) in the cylinder, the more the bhp output of the engine. However, the compression event heats the charge further and may cause it to preignite or detonate. This would heat the engine more, resulting in a vicious cycle leading to engine destruction. Thus, while cylinder head temperatures should be kept as near the maximum limit as possible for better thermal efficiency, temperatures should be carefully watched because sudden increases may approach the detonation range.

Oil temperature is an indication of engine cooling. With equipment having automatic-functioning oil cooler units, little can be done to vary oil temperatures other than to maintain a careful watch on the gages.

FUEL MIXTURE. The fuel (fuel-air) mixture is determined and regulated by either a carburetor or a master control unit. The function of each of these units is to mix fuel and air in the correct proportion to sustain efficient engine operation at all speeds.

Usable fuel-air ratios fall between .060 pounds of fuel per pound of air (leanest) and 0.12 pounds of fuel per pound of air (richest). The most efficient combustion occurs between .074 and .080. This range is called *best power*, since it produces greater power for a given airflow or manifold pressure.

To compensate for poor fuel distribution between cylinders in carburetor-equipped engines at low engine speeds, the fuel-air ratio must be quite high. In the normal cruising range, the ratio is at its minimum and gradually increases as horsepower increases until the point corresponding to rated power is reached, where the weight of fuel per weight of air is at its highest value. In order to attain the minimum specific fuel consumption (sfc) (pounds of fuel per horsepower per hour) an auto-lean range is built into the carburetor. On most aircraft, automatic carburetion is used, that is, the carburetor follows the auto-rich curve when the mixture control is set in auto-rich, and the auto-lean curve when it is set in auto-lean. These ratios are determined on test stands for best overall engine operation. The mechanical means employed in measuring air and metering fuel are not 100% perfect, and a tolerance of plus or minus 2% is usually assumed for

the carburetor. On some of the larger aircraft, the mixture control is manually controllable by the flight engineer. This control is used below the auto-lean setting to enable the flight engineer to control fuel flow when it varies excessively from prescribed limits. This, of course, is only possible on properly instrumented aircraft, that is, aircraft with fuel flowmeters and torqueometers.

Theoretically, there is only one fuel-air ratio (.067) which permits ideal combustion, one where every molecule of fuel properly combines with the oxygen in the air. Practically speaking, however, there are complications. Because of peculiarities of the engine, such as air-ducting, valve overlap, impeller speeds, air temperatures, and timing, test runs show best power at mixtures slightly richer than ideal, and best economy at mixtures slightly leaner than ideal. Besides, at higher airflows (and respectively higher horsepowers), heat liberation is increased and detonation is encountered. This increased temperature is detrimental to engine life, and, if maximum power is required, some means of controlling the temperature rise must be evolved. One of the most efficient means of reducing the temperature has been to increase the fuel-air ratio. The extra fuel acts as a cooling agent.

When the fuel is sprayed into the airstream, its evaporation causes a temperature drop in the mixture, which, in turn, reduces the cylinder temperatures. If more fuel is evaporated, cylinder temperatures are further reduced. This is the main reason for the increased fuel-air ratio at higher powers. The limitation of metering additional fuel for cooling purposes occurs at the point where the combustion becomes so incomplete and uneven that power is lost and the engine runs roughly. Engines that must produce higher powers than fuel enrichment cooling will permit are generally equipped with fluid (anti-detonant) injection.

VALVE TIMING. In the four-stroke cycle engine principle, we assume for convenience of explanation that the valves open and close exactly at the top and bottom center positions of the piston. In actual operation, the valves of an engine are timed to open and close at piston positions that provide the best efficiency and power output at cruising speeds.

In order to get maximum efficiency from the engine, as much of the exhaust gases as possible have to be expelled from the combustion chamber, so that a maximum amount of the new charge

can be packed into the cylinder. To accomplish this, both valves in the cylinder are momentarily open during the cycle so that the incoming fuel-air mixture can help scavenge the exhaust gases. This valve arrangement is known as *valve overlap*. Although valve overlap is advantageous at cruising speeds, it has an undesirable effect at idle and low speeds when manifold pressure is below outside atmospheric pressure. This effect causes a back-flow of air through the exhaust stack which opposes complete scavenging and dilutes the charge in the combustion chamber.

Ignition timing also has an important effect on engine efficiency and power output. Ignition must be timed so that the resulting peak pressure of combustion provides a maximum "push" to the piston just after top center on the power stroke. In order to achieve this desired peak pressure location, the ignition event must be timed before top center. Many factors tend to alter the actual point at which ignition occurs. These factors include rpm, manifold pressure, fuel-air ratio, carburetor air temperature, and cylinder head temperature.

ANTIDETONANT INJECTION

The use of overrich mixtures to suppress detonation has been a practical means of controlling detonation, but it does involve a measurable loss of engine efficiency. The added enrichment necessary at takeoff power results in a loss of about 6% of the power obtainable from the air-flow at that rpm and manifold pressure.

Antidetant injection (adi) makes possible such control of detonation that the power output of the engine can be increased beyond that obtainable from the fuel mentioned above. The antidetant fluid (water and alcohol) replaces the excess fuel as the antidetant factor. The carburetor, in fact, is cut back to the approximated .067—.080 mixture, and the added cooling is accomplished by the adi fluid. The charge is cooled better by a mixture of alcohol and water than by fuel because the two together require more heat per pound for vaporization than does fuel. This process increases the charge density.

It should be remembered, however, that there is a limit to the amount of antidetant (fuel, water, or alcohol) that can be added to the charge without causing an overcooling effect which results in poor engine operation. Thus, by using the proper amount of antidetant fluid to perform

the cooling function heretofore provided by excess fuel, the fuel-air ratio may be reduced to the best power mixture. Eight percent more power is obtainable from most engines with no increase in takeoff manifold pressure.

CONTROL OF DETONATION AND PREIGNITION

Detonation can be a limiting factor during almost all phases of engine operation. Its sustained occurrence in moderate form causes inefficient combustion and deterioration of combustion chamber parts. Short intervals of severe detonation can cause in-flight failure necessitating engine shut-down (see figure 7-9).

Automatic protection against detonation is provided by the fuel-air regulation of the carburetor if the mixture is *not* leaned out below the NORMAL position. This assumes, of course, that all other operating limits are observed. The NORMAL position is used during ground operation, takeoff, and landing. At these times the necessary margin of safety comes from the built-in characteristics of the carburetor and the ability of the engine to operate on the specified grade of fuel with cylinder head and carburetor air temperatures within maximum limits.

When the mixture is leaned from NORMAL, the built-in margin is being eliminated and the maintenance of detonation-free operation calls for the greatest possible application of judgment. Here, the engineer is the safety cushion. If the engineer has not accumulated experience upon which to base his judgment, he must rely on the experience of others. Detonation is a formidable opponent, being elusive and insidious at the same time—elusive because the limits confining its occurrence do not form an exact line but rather are a constantly shifting, vague boundary; insidious because its presence is not always apparent and the consequence of its occurrence may not be felt at once.

First, let it be understood that it is not the engine that detonates; it is the charge mixture that detonates. The visual account of what happens has been obtained in the laboratory by high-speed motion pictures taken through a quartz glass window opening on the combustion chamber. For a picture of normal combustion and detonation refer again to figure 7-9.

Let us analyze just what happens when detona-

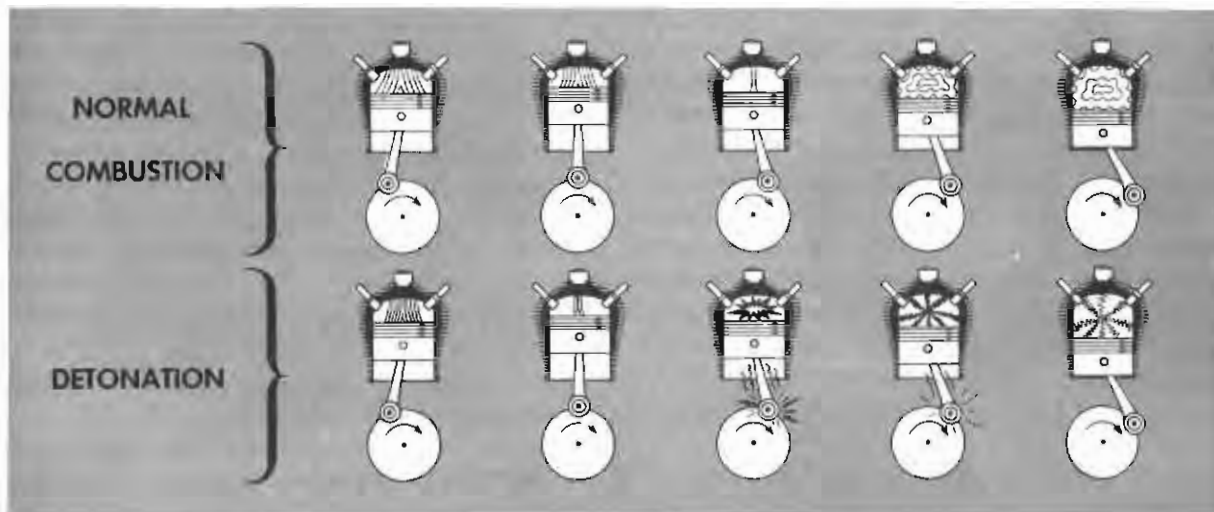


Figure 7-9. Normal Combustion and Detonation Contrasted

tion occurs. As the mixture passes through the engine induction system, it undergoes successive increases of temperature—first, because of supercharging, then because of cylinder compression, and finally from the heating and squeezing of the unburned portion of the charge by the advancing flame fronts during combustion. If, through these successive heat stages, the final “end zone” temperature is greater than the kindling temperature of the charge, all of the unburned charge spontaneously ignites and explodes. This results in an abnormal and uncontrollable rate of pressure rise, which takes place with sufficient rapidity to set up pressure waves within the combustion chamber. These waves travel at sonic velocity under the temperature conditions in the cylinder and cause the “ping” or “knock.”

Now that we have seen what detonation is and have analyzed why it happens, the next item of interest is what it does. The results of detonation vary widely. Light (incipient) detonation is not necessarily harmful. In fact, many engines are rated at maximum outputs with the full knowledge that this condition exists. Those responsible are satisfied that this degree of detonation is under control and does not lower the service life of the engine. This amount of detonation is never seen at the engineer’s station in the form of increased cylinder head temperature, loss of power, or rough operation.

As detonation becomes heavier, its ugly nature asserts itself. The hammer blows on the

pistons, chamber domes, and valves erode the surfaces and cause fatigue failures. These show up as cracked cylinder heads, broken spark plugs, dished piston heads, and dimpled exhaust valves. At best, these parts must be replaced at overhaul, but it is possible for erosion to progress to the point where the engine fails. Even this degree of detonation may not be apparent on the flight deck until the failure takes place. (See figure 7-10.)

Heavy detonation causes a rapid increase in the cylinder temperature. This, in turn, increases the intensity of detonation. A continuation of this cycle inevitably brings on early failure.

Apparent engine roughness does not necessarily indicate that detonation is present, but is probably a result of the damage caused by detonation or preignition. A rough-running engine should be checked carefully, and remedial action taken to provide smooth operation, otherwise the defect may lead to detonation, preignition, or other serious difficulty.

Preignition is closely related to detonation. The combustible mixture is unconcerned as to the source of heat for ignition. Any incandescent point, such as an eroded surface, a lead deposit, or a damaged spark plug or valve can remain hot enough during the exhaust and intake strokes to serve as an adequate spark. Preignition fires the charge prematurely. The combustion chamber and the cylinder walls are exposed to the flame for a longer period of time than normal, and the pressure rise of combustion acts entirely against

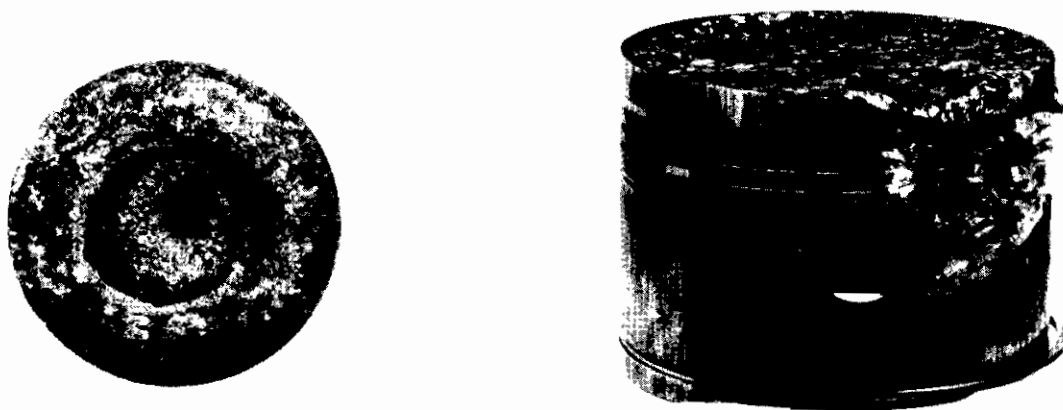


Figure 7-10. Effect of Detonation

the piston as it advances on the compression stroke. The results are loss of power and an increase of cylinder head and piston temperatures.

The loss of power can be seen on the torque-meter gage, but the temperature is noticed only in the event that the thermocoupled cylinders are the ones in trouble. Even then, there is no direct indication of the effect on the piston temperature.

The early combustion and resultant overheating of the cylinder walls and pistons with only moderately severe preignition may cause the cylinder wall lubrication to fail. Lubrication failure may, in turn, result in failure of the piston or the cylinder or both.

Preignition, by itself, does not mean that combustion is disorderly. However, the pressure increase during combustion and the temperature rise of the combustion chamber materials can bring about severe detonation. The combined effect of detonation and of preignition can quickly ruin a cylinder or piston (see figure 7-10).

Detonation can pave the way to preignition by its erosive action. The wearing away of smooth surfaces leaves rough points that become incandescent and serve as igniters.

Remember that detonation is basically a condition brought about by excessively high pressure and temperature. Whether combustion is normal or is accompanied by detonation depends upon the temperature of the unburned portion of the charge ahead of the flame fronts. If this temperature exceeds the kindling temperature of the grade of fuel used when mixed with air at that particular fuel-air ratio, detonation occurs.

SPARK PLUG FOULING

In order for the engine to operate efficiently, it is necessary, among other things, for the spark plugs to operate properly. Perhaps the most common spark plug malfunction which the flight engineer has to contend with is spark plug *fouling*. In the early stages, fouling causes misfiring; in the advanced stages, it does not allow the plug to fire at all, which results in a substantial loss in power.

There are several types of spark plug fouling; some are caused by lack of preventive procedures, others by lack of care in maintenance or preflight operation, and still others that result from excessive operating time and the need for routine plug replacement. In this discussion, fouling is considered to be any undesirable deposits that accumulate on the combustion end of the spark plug and cause misfiring. These deposits are principally made up of one or more of the following substances:

- Carbon from fuel or oil combustion
- Lead and its compounds from fuel additives
- Graphite from thread lubricant
- Preservative compounds in the oil
- Ice from cold false starts
- Miscellaneous substances (aluminum, sand, dust, etc)

Ignition checks and power checks give indications of malfunctions in the ignition system. Fouling, however, occurs at the combustion end of the spark plug, and standard checks do not always point immediately to the source of trouble. Regular monitoring of the spark plugs with the engine

analyzer provides a valuable means of determining the degree of fouling present.

Let us assume that an operating engine has been manually leaned for some time, and that a fairly thick deposit of lead salts has formed on the lower end of the insulator and increased the resistance to ground. Now assume that the power setting is rapidly changed to climb power with an auto-rich mixture setting and normal spark advance. The richer fuel-air ratio and the higher brake mean effective pressure causes a very sharp increase in combustion flame temperature, causing the spark plug temperature to rise rapidly. It has been established that, during any change of combustion chamber conditions, from 15 to 20 seconds is required for the ceramic insulator temperature to stabilize. Unfortunately, the 15 to 20 seconds is insufficient time for the deposits to burn off, but their temperature is increased suddenly, so that electrical resistance of the deposits drops. Misfiring frequently results from plug fouling during such an abrupt power change.

Usually the fouling is not complete, because when the cylinder fails to fire for a few cycles the plug temperature decreases, the lead compound resistance increases, and the cylinder again fires. Usually, this process continues until the lead deposits alter their thickness and composition sufficiently for the plug to become operative again.

Application of takeoff power after a long period of idling can result in this phenomenon, as evidenced by backfiring at takeoff which clears up without apparent reason. Sudden reductions in power have no adverse affect on spark plug operation. The above discussion indicates that fouled plugs respond to different antifouling practices, depending upon the type and amount of fouling present. A few common fouling conditions and their corrective measures are described to help you choose the proper corrective procedure.

Let us assume that the engine is operating in MANUAL LEAN with an advanced spark and that some of the plugs are lead fouled. Under such conditions, the air pressure resistance across the plug gap is high and the resistance of the lead deposit is low, causing the spark to run across the insulator to ground instead of arcing across the plug gap to ground. As the engineer, you must take the correct action to eliminate the lead so that the plugs will fire across the plug gaps.

A good corrective action for this condition would be to reduce the manifold pressure, place

the mixture control lever in the AUTO LEAN position, and the spark plug advance control in the NORMAL position. Reducing the manifold pressure by about 10" Hg reduces the electrical resistance at the plug gap, inducing the plug to fire. Advancing the mixture control to AUTO LEAN enriches the fuel-air mixture, making the charge easier to burn. Finally, the combination of richer mixtures and NORMAL spark advance reduces the temperature in the combustion chamber which, in turn, increases the electrical resistance of the lead deposits.

Another corrective action is to increase manifold pressure slowly, perhaps only two inches Hg every 5 minutes, which allows the ceramic temperatures to rise slowly, burning off lead deposits. This procedure has been known to clear plugs that were completely fouled and to permit return to manual lean operation in less than an hour. It represents, of course, a method of correcting an extreme condition of plug fouling.

Probably the best prevention method is that of making small power increases periodically which would cover a span of perhaps 3 to 5 minutes. For example, if we are cruising in normal spark advance, the rpm can be increased in 25 rpm increments, using three to six increments. This allows spark plug insulator temperatures to stabilize and affords the lead salts a chance to burn away.

Another undesirable characteristic of lead fouling is the ability of carbon to reduce lead salts to metallic lead. If the fuel-air ratio is very rich during idling or low-power ground operation, the combustion chamber becomes coated with a layer of finely divided carbon. When the power is increased rapidly for runup or takeoff, this carbon becomes very active chemically and changes the chemical composition of the lead salts to form small beads of metallic lead. These lead beads are highly conductive, and upon melting (320° C) may spread over the insulator tip to form a nearly continuous coating which is very effective in shorting the plug. This type of fouling cannot be cleared by further operation of the engine. For this reason, it is important that the carburetor be adjusted to maintain correct idle mixture.

The use of the fuel primer system to combat plug fouling is a debatable procedure. Most of the earlier theories claimed that benefit was derived from a *thermal shock*. However, tests have proven that there is little, if any, thermal

shock. For example, plugs were rigged with temperature indicators to show that a temperature of about 1500° F existed on the ceramic insulator at a near best power mixture. When fuel was added by the primer the ceramic insulator temperature dropped in a few seconds to about 1350° F. This in itself was not enough change to produce a thermal shock.

There is no such thing as *washing* the plugs clean. Using the primer to lower ceramic temperatures raises the electrical resistance in lead deposits, which helps the ailing plug to fire across the normal gap; however, the rich mixtures may introduce enough free carbon to reduce the lead salts to metallic lead. This may remain on the ceramic insulator to permanently short the plug.

CONTROL AND OPERATION OF THE RECIPROCATING POWERPLANT

Need for Operating Limits

Previous discussions have dealt with the various forces set up in the engine in the process of producing power. Pressures and stresses inside the engine increase as the throttles are advanced and the superchargers turn faster. Obviously, there is a limit to the stresses and pressures that can be safely imposed on the cylinders, pistons, link rods, bearings, and other engine parts.

The limits of operation within which the accepted degree of reliability can be obtained are known as *engine ratings*. Operation within the ratings assures reliability. Operation outside of these limits relies on margins of safety which may or may not exist.

Since reliability occupies a place of considerable importance, and since the ratings define the upper limits of reliable performance, they are a logical beginning for a discussion of engine operation.

Time-Limited Ratings

Time-limited ratings are possible because the aircraft engine, like most mechanical devices, is capable of sustaining an overload temporarily without impairing its reliability and without appreciably affecting its durability. Accordingly, several ratings have been established setting up limits within which the engine may be safely operated for restricted periods of time at powers and speeds greater than those permitted for maximum continuous operation.

While takeoff ratings demand the greatest power output, it is a condition with a definite time limit. To obtain this output on the basis of a continuous rating would require a much heavier engine; therefore, aircraft efficiency is increased by establishing a rating which permits the engine to meet takeoff requirements but limits this performance to a short period of time.

Tactical and combat requirements necessarily dictate the amount of power that is used in military operations. In meeting these demands, military personnel are naturally less concerned with the life of the engine than with the offensive or defensive advantage of an overload performance. The *military rating* establishes the maximum time-limited power for service aircraft. The suitability of the engine to operate at this power and for this time is specified in the procurement specifications. Military rating (power and rpm) is the same as the takeoff rating without water injection.

The conventional normal rated, takeoff, and military power ratings are based on peacetime concepts of engine reliability and durability. In wartime these considerations are not necessarily of first importance. Tactical and combat demands often warrant the use of powers in excess of those permitted under normal circumstances. These are known as *war emergency powers*. The performance available on such occasions is entirely regulated by the military services. Furthermore, demonstration of engine suitability for this power output is not a part of the basic procurement specification, but is determined by tests conducted under controlled circumstances.

An aircraft engine can actually be run continuously under overload conditions of power and speed for much longer periods than those permitted by the ratings. However, the period of reliable operation is considerably reduced. By imposing a time limit on takeoff and military power ratings, the cumulative effect of the overloads is distributed evenly over the period between overhauls, and the useful life of the engine is increased.

Maximum safe overspeed is dictated by the allowable reciprocating and centrifugal loads resulting from the high rpm which may be encountered during aircraft maneuvers. This speed is usually limited to seconds. See the appropriate technical order for procedures to be followed when engine speeds and manifold pressures exceed the limits.

Continuous ratings define the limitations of operation without time limitations.

Normal rated power is specified as the maximum output for all normal operations, such as routine climb and high-speed level flight. The fuel flow specified for the NORMAL mixture position and NORMAL spark are required when using this rating.

Cruise ratings may be specified for aircraft depending on the engine being used. Since each engine has its limitations, manual leaning of engine fuel flow may be practiced. In addition, the power range between normal rated power and the maximum power allowed for manual leaning is sometimes used for cruise.

Because of the tremendous variations in range, load, and time factors, more latitude in power settings is permitted than with certain other types of military aircraft. On the other hand, engine durability must be considered and everything possible must be done, consistent with accomplishment of the long-range mission, to keep the engines in good condition and to extend engine life.

The ability of the engine to give the necessary performance depends on how well it has been operated and maintained previously. It is in the cruise power range particularly that the engineer must display his ability and knowledge of power-plant performance in order to get to his destination and to return home safely.

AVIATION FUELS

To be suitable for use in a reciprocating aircraft engine, a fuel must meet rigid requirements. It must vaporize readily and must be capable of producing high power without detonation. The fuel must also be free of impurities which would interfere with the operation of the engine or the units in the fuel and induction systems.

Volatility

The property of a liquid which enables it to change readily into a vapor is known as *volatility*. This is an important property in fuel, since the fuel must be in the form of vapor to combine with oxygen during combustion. In addition, volatility affects engine performance since it determines how much fuel can be vaporized in the fuel-air mixture. This is particularly important when the engine

is operated on a rich mixture—a high proportion of fuel to air. Volatility is important also from the standpoint of economy, since fuel which does not completely vaporize is not only wasted but washes the lubricant from the cylinder walls. Although high volatility is desirable, the fuel must not vaporize so readily that it forms a vapor lock in the lines, pumps, or other units in the fuel system.

Octane Number and Performance Rating

Probably the most important property of fuel is its ability to burn readily even at a high temperature. The more compression the fuel can stand without detonation, the more power it can develop. Antiknock qualities of aviation fuels are designated by grades, such as 91/96, 100/130, and 115/145. The higher the grade, the more compression the fuel can stand without detonating. For those fuels that have designations consisting of two numbers, the first indicates the lean-mixture rating and the second the rich-mixture rating. Thus, grade 100/130 fuel has a lean-mixture rating of 100 and a rich-mixture rating of 130.

Two different scales are used to designate fuel grade. For fuels below grade 100, an *octane number* is used. The octane number is the percentage of iso-octane in a mixture of iso-octane and normal heptane which duplicates the knock characteristics of the particular fuel. Thus, grade 87 fuel has the same knock characteristics as a blend of 87 percent of iso-octane and 13 percent normal heptane. With the advent of fuels having anti-knock qualities superior to iso-octane, another scale has to be used. This scale represents the *performance rating* of the fuel—its knock-limited horsepower as compared to that of straight iso-octane or 100-octane fuel. For example, an engine which can deliver a knock-limited horsepower of 1000 with 100-octane fuel delivers a knock-limited horsepower of 1.3 times as much (1300 horsepower) with 130 performance number fuel.

Doped Fuels

With the development of bigger and better engines, the quest for better fuel began. Chemists learned that better fuel could be produced by the addition of small quantities of certain compounds to produce "doped" gasolines. The best known and most widely used of such additives is tetra-

ethyl lead, $Pb(C_2H_5)_4$, which gives *ethyl* gasoline its name. Tetraethyl lead is a colorless substance. The color of the ethyl gasolines is caused by the addition of a small quantity of dye, which distinguishes leaded gasolines from unleaded gasolines.

As an antiknock agent, tetraethyl lead is efficient, but it has the disadvantage of producing in the cylinders, after combustion has taken place, compounds which affect many of the alloys and metals used in engine construction. This effect, in turn, has again required design modifications. Another difficulty with using doped gasolines is associated with the high temperatures reached during combustion.

Owners of cars who use "ethyl" may be aware of one of those effects—the rapid pitting of exhaust valve seats and consequent loss of compression. Other additives including acetone peroxide and ethyl nitrate, have been tried but all have defects, the chief of which is that they are expensive and must be added to the gasoline in considerable quantities; but tetraethyl lead can be used in the proportion of several cubic centimeters per gallon of gasoline.

JET PROPULSION POWER UNIT

How does the jet engine propel an aircraft? Where and how is power produced in the jet engine? This section answers these and other questions concerning the application of the laws of physics to the operation of the jet engine. In addition, you may find it helpful to review the chapter which discussed basic physics. The formulas discussed should help you understand thrust ratings, thrust horsepower, and the variables affecting thrust output of the jet-propulsion engines.

Principles of Jet Propulsion

The principal of jet propulsion is expressed by Sir Isaac Newton's *third law of motion*, which states that *for every action there is an equal and opposite reaction*. In the case of the jet, the action is the rearward rush of a mass of air from the tailpipe, and the reaction is the forward motion of the aircraft.

All types of jet-propulsion engines—turbojet, pulsejet, ramjet, turboprop, and rocket—use this principle. These engines differ only in the method used to accelerate the huge mass of air or gas

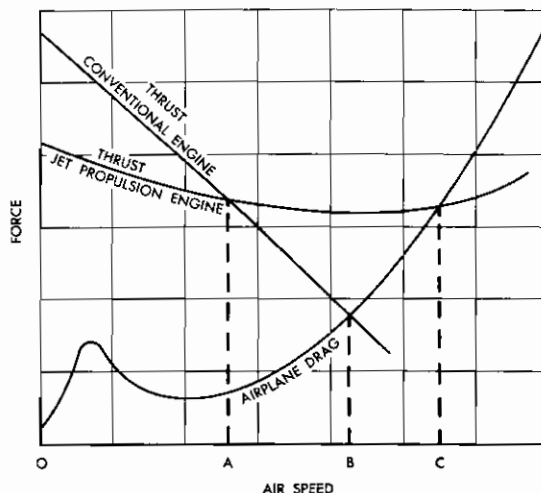


Figure 7-11. Thrust-Drag Chart

that produces the thrust force to propel the aircraft. See figure 7-11 for comparative thrust-drag values.

Rating the Jet Engine

The jet engine, being a reaction type of engine, produces thrust by the force of reaction. This thrust is a force and is expressed in pounds, and therefore the *jet engine power output is rated in pounds of thrust*. This rating is usually determined by the manufacturer, who operates the engine in a special test cell where the thrust output can be measured accurately.

Since a jet engine is rated in pounds of thrust and a conventional reciprocating engine is rated in brake horsepower (bhp), no direct comparison can be made between the two. One horsepower is a definite amount of work done in a period of time; it is equal to 33,000 foot-pounds of work per minute or 550 foot-pounds of work per second. (We will use this definition later to convert the jet thrust in pounds to thrust horsepower.)

Remember, however, that the brake horsepower of a reciprocating engine is converted into thrust by the propeller. This being the case, you can make a true comparison of the two types of engines only by comparing the thrust from the jet engine with the thrust from the propeller of the reciprocating engine.

The thrust output of the jet engine is affected by several factors, such as aircraft speed (ram pressure), altitude, and engine rotor shaft speed.

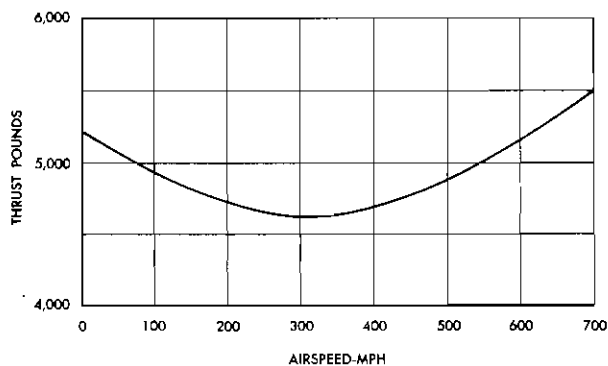


Figure 7-12. Thrust vs. Airspeed

You can see the relationships between the thrust output and aircraft speed in the *Thrust vs Airspeed* graph, figure 7-12. Notice that up to a speed of 300 mph the thrust gradually decreases, and from that speed on it gradually increases, and at the maximum airspeed shown on the chart, the thrust is actually more than the static thrust at zero forward speed.

The *Thrust vs Altitude* graph, figure 7-13, shows that as the aircraft increases in altitude, thrust takes a sharp drop. This factor determines the maximum altitude a jet-powered aircraft can attain.

Engine speed in revolutions per minute (rpm) directly affects the amount of thrust that a jet engine develops, as shown in figure 7-14. Note in this graph that there is little thrust developed at low engine rpm as compared to the higher engine rpm. For example, in the 10% range between 90% rpm and 100% rpm there is a thrust gain

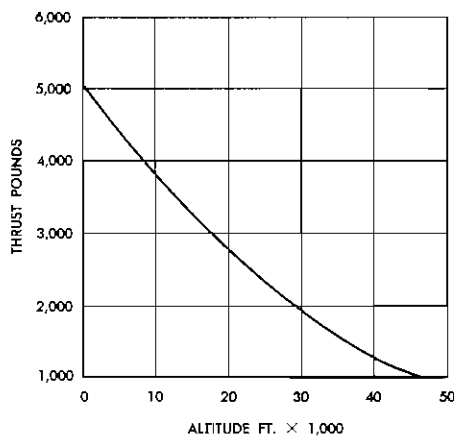


Figure 7-13. Thrust vs. Altitude

of over 1,500 pounds, while the total thrust up to 70% rpm is only 1,650 pounds. The engine indicator is calibrated to read in percent of rpm rather than in actual rpm.

Thrust Computation

In order for you to understand the basic formulas for computing *gross thrust*, *net thrust*, and *thrust horsepower*, you need to know the effect of gravity on an object or a mass. A free-falling object accelerates in accordance with the law of gravity at a constant rate of 32.16 feet per second per second until it reaches its terminal velocity (maximum speed) or strikes the earth, which ever occurs first. Since 32.16 feet per second per second is a constant acceleration, it is used to determine the amount of resistance an object offers to a force trying to put it into motion. This is accomplished by dividing the weight of the object by the acceleration constant. The quotient is called the mass of the object. Applying this to the second law of motion:

$$\text{Force of Action} = \frac{\text{weight}}{\text{gravity (32.16)}} \quad (50)$$

× change in velocity (acceleration of mass)

This can be written as

$$\text{Action} = \frac{W}{g} \times V_c$$

Since every action produces an opposite and equal reaction, if we use the letter "a" for acceleration, the *gross thrust* formula is:

$$\text{Gross thrust (reaction)} = \frac{W}{g} \times a \quad (51)$$

The gross thrust formula does not take into consideration the forward speed of an aircraft, which must be included in the computation of

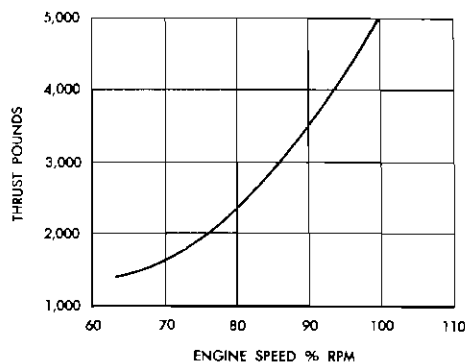


Figure 7-14. Thrust vs. RPM

new thrust. If the velocity of the aircraft is 400 miles per hour, the velocity of the aircraft must be subtracted from the velocity of the exhaust gases at the jet nozzle to determine the actual velocity change caused by the engine. This assumes that the air entering the jet engine is also traveling as fast as the aircraft. This can be expressed as an equation:

$$V_j - V_p = V_c \quad (52)$$

where V_j is the velocity of air leaving jet nozzle, V_p is the velocity of the aircraft or of the air entering the engine, and V_c is the actual velocity change. The *net thrust* formula becomes:

$$\text{Net thrust} = \frac{W}{g} (V_j - V_p) \quad (53)$$

Keep in mind that when the gross thrust is computed, the velocity of the air coming into the engine is disregarded, and the velocity of the gas leaving the engine is used as the acceleration factor. True acceleration of the gas is the difference in velocity between the incoming and outgoing air, and this difference is used in computing net thrust.

The equivalent *thrust horsepower* (thp) of a jet engine can be calculated by measuring how fast the jet engine is doing work. Power is a force applied through a distance in a given period of time. Therefore, the equivalent thrust horsepower which a jet engine is producing depends on the thrust developed multiplied by the distance the engine has moved in a given period of time. To determine the horsepower of the jet engine, the following formula is used:

$$\text{thp} = \frac{W}{g} (V_j - V_p) \times \frac{\text{velocity of aircraft in feet per second}}{550 \text{ foot-pounds per second}}$$

(In this formula, one horsepower, 33,000 foot-pounds per minute, has been reduced to foot-pounds per second by dividing by 60.) Since the velocity changes of the air and the aircraft speeds are expressed in units per second, the following equation results:

$$\text{thp} = \frac{\text{net thrust} \times V_p}{550} \quad (54)$$

For example, let us assume 4,000 pounds of thrust and an aircraft velocity of 375 miles per hour:

$$\begin{aligned} 375 \text{ mph} &= 1,980,000 \text{ feet per hour} \\ 1,980,000 \div 60 &= 33,000 \text{ feet per minute} \end{aligned}$$

$$33,000 \div 60 = 550 \text{ feet per second}$$

Substituting,

$$\text{Thrust horsepower} = \frac{4,000 \times 550}{550} = 4,000$$

Thus, 4,000 horsepower is developed by a jet engine delivering 4,000 pounds of thrust at an aircraft speed of 375 mph. This calculation shows that each pound of thrust is converted to the equivalent of one horsepower at 375 mph. What would be the result on the thp if the aircraft speed were increased to 750 mph?

If 750 mph equals 1,100 feet per second,

$$\text{thp} = \frac{4,000 \times 1,100}{550} = 8,000$$

Efficiency of Jet Engines

Internal-combustion engines in general have low thermal efficiency. The better reciprocating engines have a thermal efficiency of 18% to 34%, depending upon power settings and design characteristics. The better high-powered jet-propulsion engines seem at present to be somewhat less efficient than reciprocating engines when rated by the same thermal efficiency scale. Remember that the efficiency of jet and reciprocating engines can be compared if the power output of the reciprocating engine is converted to the thrust which the installed propeller produces. A comparison in terms of thrust shows that the jet engine produces more thrust but is less efficient in terms of thrust in relation to fuel consumed.

To find thermal efficiency in the gas turbine engine:

$$\begin{aligned} \text{Thermal efficiency} &= \frac{\text{net work}}{\text{energy in}} \quad (55) \\ &= \frac{\text{force} \times \text{velocity}}{\text{fuel flow} \times \text{heating value}} \end{aligned}$$

The three most important factors affecting the thermal efficiency are *turbine inlet temperature*, *compression ratio*, and the *component efficiencies of the compressor and the turbine*.

Classification of Turbojets

Turbojet engines are classified according to the type of compressor used: *centrifugal flow* or *axial flow*. In the centrifugal-flow engine, the compressor blows the air outward (perpendicular to the longitudinal axis of the engine) and then rearward into the combustion chambers. (See

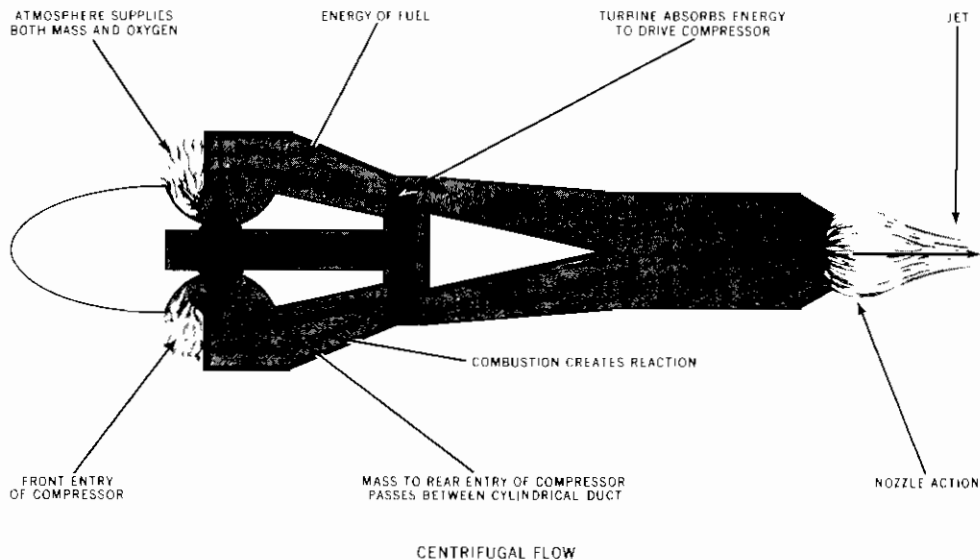


Figure 7-15. Flow of Gases Through Centrifugal Flow Engine

figure 7-15.) In the axial-flow engine, the compressor blows the air directly rearward (parallel to the longitudinal axis of the engine) into the combustion chambers. (See figure 7-16.) The accompanying illustrations show each type of turbojet engine. The obsolete centrifugal flow engine is described for historical purposes only.

Jet Engine Operation

The operation of both types of turbojet engines is basically the same, except for the direction of

airflow through the compressor. Using the axial-flow engine shown in the illustration, let us follow the flow of gases through the engine. The cycle starts at the inlet duct, from which the air is drawn through and accelerated by the two compressors. From the high-pressure compressor, the air passes through the diffuser case which reduces the velocity and increases the pressure of the air before it enters the burner cans (combustion chambers). In the burner cans, the air is mixed with fuel and the mixture is burned.

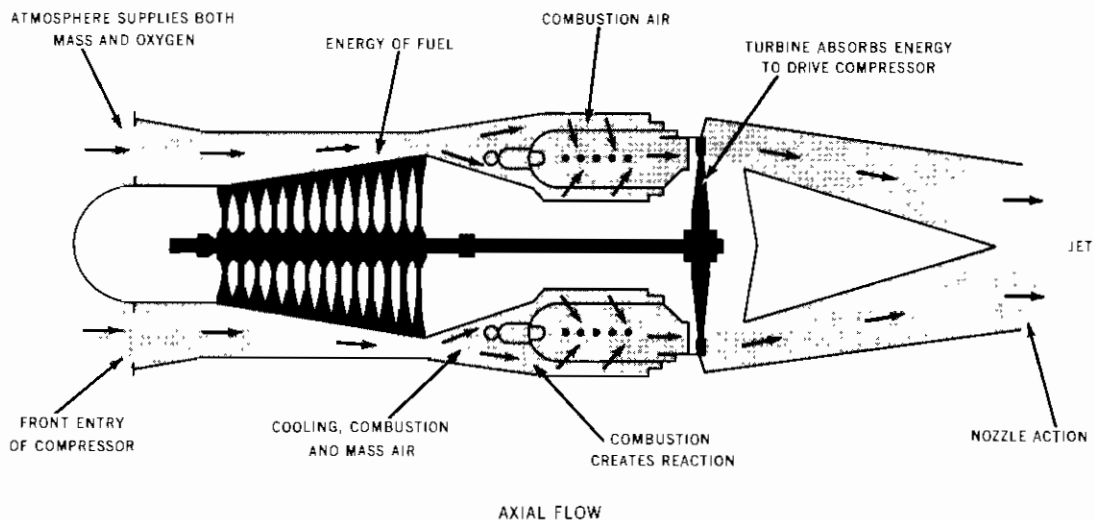


Figure 7-16. Axial Flow Engine

Ignition occurs first in the chambers containing the spark plugs, and then progresses into the other chambers through crossover tubes. The heat resulting from combustion accelerates the gases and forces them through the turbine wheels and out through the tailpipe. Nozzle diaphragms in front of each turbine wheel increase the velocity of the gases and direct them onto the turbine buckets at the most efficient angle to drive the turbines at high rpm. The first stage turbine drives the high-pressure compressor, and the second and third stage turbines drive the low-pressure compressor. The exhaust gases are expelled from the tailpipe at a tremendously high velocity, thus producing the thrust that moves the aircraft forward.

Jet Engine Construction

The typical axial-flow engine, shown in the illustration, consists of the following main components: *Inlet duct*, *compressor section* (N_1 and N_2 compressor), *combustion section* (diffuser case and burner cans), *turbine section* (1st, 2nd, and 3rd stage turbines), and *exhaust section* (tailpipe and exhaust cone).

FORWARD COMPRESSOR. The N_1 (forward) compressor is a low-speed, low-pressure compressor, which has nine stages of compression. It is connected to the No. 2 and 3 turbine wheels by a shaft running inside the first-stage turbine shaft and the high-pressure compressor. (See illustration.) The speed of the N_1 compressor is not governed in any way, but varies according to the load applied to it by the density (pressure, temperature, and humidity) of the incoming air. This compressor supplies air to the aft (high-pressure) compressor, called N_2 .

AFT COMPRESSOR. The N_2 (aft) compressor is a high-speed, high-pressure compressor, which has seven stages of compression, which give the engine a total of sixteen compression stages. It is driven by the first-stage turbine wheel with a hollow shaft running on the outside of the N_1 compressor shaft. The speed of the N_2 compressor is governed by the amount of fuel delivered to the combustion section. The amount of fuel, in turn, determines the speed of the first-stage turbine. Power is extracted at the aft end of the N_2 compressor by a bevel gear and tower shaft that operates the accessory section, which is mounted at the 0600 position under the compressor sec-

tion. Another advantage of the "two-spool" compressor used in this engine is that the starter brings only the N_2 compressor up to starting speed; therefore, the starter can be made smaller and lighter than those on other types of jet engines.

The compressors deliver air to the combustion section of the engine at a pressure ratio of approximately 10:1 at sea level and full power conditions.

COMBUSTION SECTION. The combustion section is a canannular type, having eight "cans" (chambers) in which combustion takes place. The cans are interconnected by crossover tubes to allow flame passage for starting. Fuel under pressure from the fuel control units is sprayed into the airstream by forty-eight dual-orifice fuel nozzles. The nozzles are arranged in clusters of six and protrude into the inlets of each of the eight cans. Exit ducts direct the hot gases from the combustion section onto the first stage turbine nozzle vanes.

TURBINE SECTION. The turbine nozzle vanes straighten the flow of gases, increase their velocity, and direct them onto the turbine wheel buckets at the most effective angle to obtain maximum efficiency. Each of the three turbine wheels has its own set of nozzle vanes. The nozzle vanes and turbine buckets are progressively larger from front to rear, exposing more surface to the exhaust gases as their velocity and power are reduced. The three turbine wheels convert part of the heat energy to mechanical energy to turn the compressors and required accessories. After leaving the last-stage turbine wheel, the gases are expelled into the atmosphere through the tailpipe or the afterburner.

EXHAUST SECTION. The purpose of the tailpipe is to cause the exhaust gases to converge into the smaller diameter of the tailpipe to increase the jet effect. The inner cone prevents too rapid expansion of the exhaust gases and prevents turbulence behind the rear turbine wheel. The exhaust cone, mounted in the center of the exhaust section, prevents too rapid expansion of the gases and reduces turbulence at the rear of the last-stage turbine wheel. On some engines, the cone is adjustable by means of spacers to aid in the control of exhaust-gas temperature.

In fighter aircraft, the engine is normally located in the fuselage, which allows the installation of an afterburner in place of the shorter conventional tailpipe assembly. The afterburner provides for additional thrust by serving as a large com-

bustion chamber, in which fuel and the oxygen remaining in the exhaust gases are mixed and burned. The resulting heat energy increases engine thrust by as much as 50%. This added thrust is used during takeoff and in maneuvers where maximum acceleration is required.

ENGINE SYSTEMS. The main systems of the engine include *fuel, oil, electrical, starting, anti-icing, and water injection.*

A hydromechanical fuel control unit, located below the compressor section and connected to a single cockpit control lever, automatically maintains the correct fuel flow in accordance with a preselected setting and changing atmospheric conditions. The other fuel system units are the engine-driven pump, pressurizing and dump valve (flow divider), fuel manifold, and fuel nozzles.

The engine is lubricated by a dry-sump oil system using an oil tank mounted on the engine. The capacity and design of the tank depend upon the aircraft installation. A single-element pump supplies oil under pressure to all components requiring lubrication. Scavenge pumps located throughout the engine return the oil through a cooler to the oil tank.

The electrical system provides power for ignition and for the operation of electrical and electronic control units. Ignition is supplied by two identical, high-energy, capacitor-type ignition units which furnish power to the igniter plugs located in no. 4 and no. 5 combustion chambers. The ignition unit input is received from a storage battery. Either an air-driven or engine-driven generator provides power in flight to operate aircraft electrical units.

Two types of starting systems are used: the fuel air (combustion) starter and the pneumatic starter. The fuel-air starter is self-supporting, but the pneumatic starter requires the use of auxiliary air pressure.

Water injection is provided on some nonafterburner-type engines to increase the thrust output for takeoff. The water, in the case of the C-135A, is pumped to the engine, where the flow is controlled by engine-mounted equipment. The injection manifold is mounted between the compressor front bearing support and the inlet guide vanes. One model of engine has another manifold located in the diffuser case of the engine to increase the amount of water flow.

The engine is anti-iced by 16th stage air piped into the inlet guide vanes and the compressor

front bearing support struts. Airflow is controlled by two shutoff valves and an air regulator that regulates the airflow in accordance with compressor discharge air temperatures.

TURBOPROP ENGINE

The turbojet engine excels the reciprocating engine in top speed and altitude performance. This great advantage is minimized only by the engine's limited takeoff and initial climb performance. In this respect, the reciprocating engine is superior to the jet engine. It follows, then, that the most versatile engine would combine the best characteristics of the turbojet and the propeller-equipped engines. In an attempt to combine in one engine the better characteristics of each type, the turboprop engine was developed.

As the name indicates, the turboprop engine has a propeller, and it has a gas turbine power section, which is similar in design and operation to the turbojet engines we have been discussing. The main difference is that more of the energy of the gases is harnessed by the turbine to drive not only the compressor and accessories, but a propeller as well. This leaves a small amount of energy in the gases to produce jet thrust. The turbine absorbs the gas energy, and this energy is transmitted forward through the turbine shaft to the compressor. The energy is carried forward from the compressor through a torque shaft to the reduction gear housing on the front end of the engine. The reduction gear assembly is necessary to keep the propeller speed within practical limits.

The turboprop offers several advantages over other types of engines: *economy of operation, minimum vibration, the advantage of the propeller for takeoff and landing on moderate-sized fields, and high power for low weight.* Even with the added weight of the extension shaft and reduction gear housing, this engine produces more than two and one-half horsepower per pound of weight, which is twice as much as most reciprocating engines.

Construction

The turboprop engine, figure 7-17, consists of three primary sections, the *power section, the torque meter section, and the reduction gear assembly.*

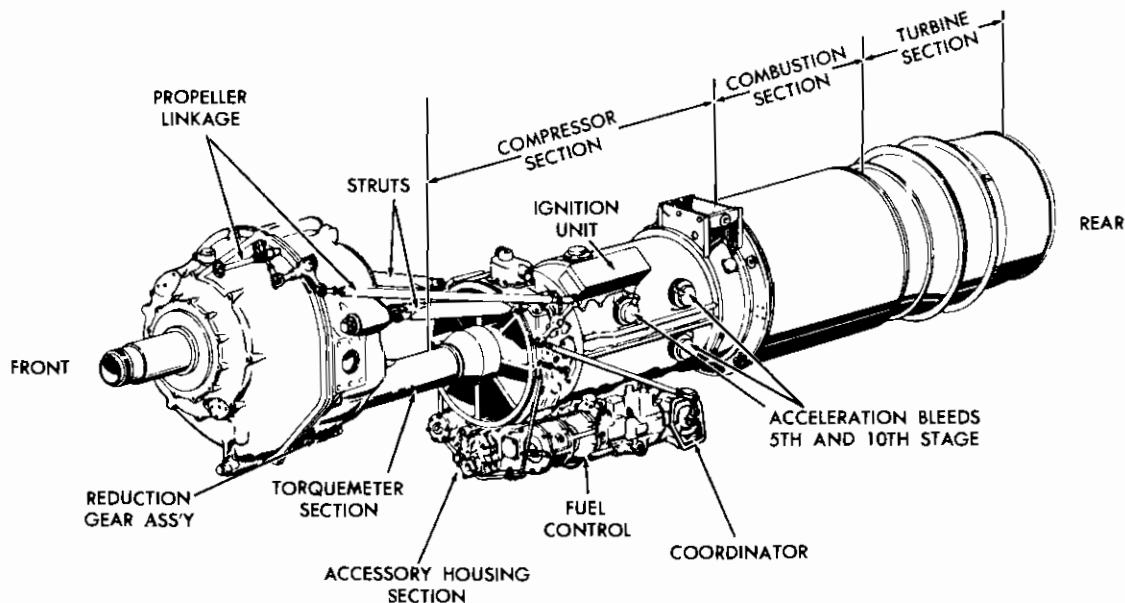


Figure 7-17. Turboprop Engine

POWER SECTION. The power section is a gas turbine engine, which has three main sections: compressor, combustion, and turbine, the same as any turbojet power unit.

TORQUEMETER SECTION. This section consists of the torquemeter housing and extension shaft, which connects the power section to the reduction gear assembly.

REDUCTION GEAR ASSEMBLY. This unit is used to reduce the high engine speed to a practical and usable propeller rpm. In one engine the reduction is from 13,820 to 1106.

SUPPORT UNITS. Engine support units, which are mounted on the compressor section, are the ignition unit, the accessories housing section, and the fuel control units, which function automatically to establish an operating condition selected with the power control lever.

Operation

The power section of the turboprop engine functions like any other turbojet engine. However, the engine has only two operating speeds, one for idling and one for flight operation. In one particular engine, the idle speed is $13,475 \pm 200$ rpm, which gives a propeller rpm of 1078. The flight rpm of this engine is 13,820, which gives a propeller rpm of 1106.

The operator has two control levers—the

condition lever and the *power lever*. The condition lever has four positions—AIR START, RUN, GROUND STOP, and FEATHER—and is used to preset the fuel control, the coordinator, and the propeller governor. When the engine is operating, the condition lever is in the RUN position. The power lever is operated in two ranges—flight range and taxi range.

If the pilot wants to increase airspeed, he must get more power, which he does as follows: He advances the power lever, which causes a new setting in the coordinator; the coordinator changes the fuel control setting to increase fuel flow. More fuel increases turbine inlet temperature and turbine rpm, which tends to cause the propeller to overspeed. The propeller governor senses the overspeed condition and increases the propeller blade angle to give the blades more "bite" and to hold propeller rpm at its fixed value of 1106. The pilot notes the increase in power and airspeed by higher readings on the turbine inlet temperature gage and the airspeed indicator.

The propeller control system also functions to automatically maintain propeller rpm when changes in atmospheric conditions or aircraft attitude tend to make the propeller go off-speed. For example, if the aircraft goes into a dive, the propeller tends to overspeed. The governor senses this condition and functions to increase blade

angle to hold the propeller onspeed. Similarly, if the aircraft is placed in a climb, the propeller tends to underspeed, and in this case blade angle is decreased so that the propeller remains onspeed.

Power Rating

Since the turboprop engine has a propeller, a torquemeter can be used to measure the load (torque) applied to the propeller by the engine. Two types of torquemeter systems are in use. In the engine just described, torque is electrically measured from the twist on the extension shaft inside the torquemeter housing. In another type, the torquemeter system is incorporated in the planetary gear system in the reduction gear assembly. This system is similar to the arrangement used in a reciprocating engine.

Direct measurement of torque on any turboprop engine is measurement of shaft horsepower and not jet thrust. Shaft horsepower (shp) may be computed by the formula following:

$$\text{shp} = \frac{T_i \times \text{rpm}}{63,025} \quad (56)$$

where T_i is in inch pounds.

The engine described here is rated at 3,750 equivalent shaft horsepower (eshp), which is a combination of shp and jet thrust.

$$\begin{array}{r} 3460 \text{ hp (shaft)} \\ 290 \text{ hp (jet thrust)} \\ \hline 3750 \text{ eshp} \end{array}$$

These figures are test cell computations, with the jet thrust converted to horsepower. Roughly $1 \text{ hp} = 2.5 \text{ lb thrust at zero ram}$. The thrust in the foregoing example was 726 lbs, and $726 \div 2.5 = 290 \text{ hp}$.

TURBOFAN ENGINE

Many modifications and configurations of the turbofan engine are being developed at a relatively rapid pace. Although the appearance of certain engine components as well as that of the engine may change with time, the principles of turbofan engine operation and performance, as covered here, remain substantially the same. (See figure 7-18.)

Operation

The turbofan is a turbine-powered engine which, to some extent, exhibits the desirable characteristics of both the turboprop and the turbojet engines. Operationally, the turbofan version of the gas turbine engine is similar to the turboprop, except that the ratio of secondary airflow to primary combustion airflow is much lower in the turbofan engine. Also, the geared propeller as found on the turboprop engine is replaced by a duct-enclosed, axial-flow fan which is driven at engine speed.

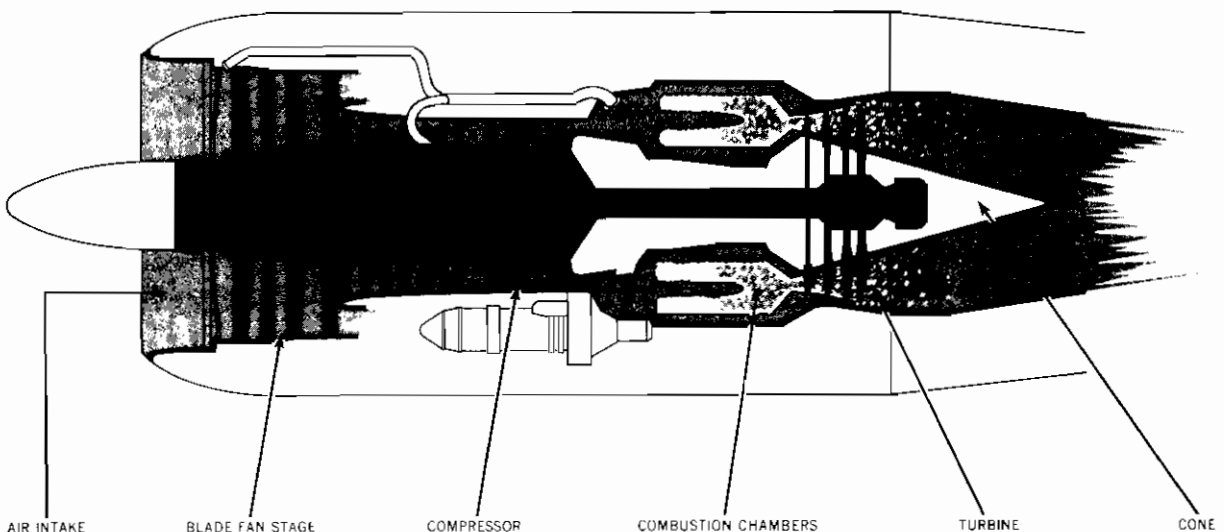


Figure 7-18. Turbofan Airflow

Construction

With the exception of the fan section, the turbofan engine sections are generally the same as those of the turboprop and turbojet engine sections covered previously in this manual; i. e., each basic gas-turbine engine consists of a compressor section, a combustion section, and a turbine section.

Turbofan engines may have their fan section located either forward of the compressor section or aft of the combustion section. By locating the fan in the forward portion of the gas-turbine engine, many advantages can be derived. First, greater dependability can be realized by operating the fan in the relatively cooler section of the engine. Also, in dual-compressor turbofan engines, the front-mounted fan operates with the slower-turning, low-pressure compressor which results in a lower fan tip speed and, consequently, a greater operational efficiency. Finally, foreign material drawn in through the engine intakes will likely be thrown radially outward by the front-mounted fan blades and pass through the fan discharge rather than through the engine exhaust (primary airstream).

The fan section consists of one or more stages of rotating blades and stationary vanes that are larger than the compressor stages to which they are attached. The air accelerated by the fan tips forms a secondary airstream which is ducted overboard without passing through the main engine. This fan discharge may be directed either to the outside directly behind the fan or to the rear of the engine. Air ducted to the rear may or may not mix with the turbine exhaust gases, depending on the engine construction. The bifurcated duct engine fan is driven by the same turbine that drives the compressor, whereas the annular duct engine fan utilizes a turbine separate from the one that operates the compressor.

The air passing through the center of the fan becomes the main airstream through the engine. This relatively larger air mass at lower velocities produced by the fan results in a greater propulsive efficiency of the engine.

Advantages

As stated previously, the turbofan engine is a compromise between the desirable performance characteristics of both the turboprop and turbojet engines. As a result, the turbofan engine does not attain the takeoff and low-speed performance of a turboprop engine of comparable size, nor the high-altitude, high-speed performance of a turbojet version of the same gas turbine; however, the turbofan exhibits an overall performance capability which makes it a very desirable powerplant for either short or long range passenger and cargo-type aircraft.

Turbofan vs Turboprop

A turbofan engine, when compared to a turboprop version of the same gas turbine is superior in the following respects:

- The turbofan engine performs more efficiently at airspeeds over 400 knots (cruising altitude), since propeller efficiency decreases rather rapidly at such speeds.
- The turbofan engine eliminates the maintenance complexity and weight inherent in turboprop reduction-gearing and pitch-governing systems.

Turbofan vs Turbojet

The turbofan engine is superior to the turbojet of comparable size in the following respects:

- Since the turbofan engine accelerates greater quantities of air at relatively lower velocities than its turbojet counterpart, the turbofan operates with greater thrust at lower airspeeds such as at takeoff or during climb and with lower thrust specific fuel consumption (TSFC).
- With greater thrust at lower airspeeds, a turbofan-powered aircraft can take off with a much higher gross weight than an equivalent turbojet-powered aircraft and requires less take-off roll.
- As a result of lower velocity exhaust gases, the turbofan engine operates at a lower noise-level than that inherent in turbojet engine operation.

Weight and Balance

There are many factors which are essential to the safe and efficient operation of an aircraft. One of these is the *balance* of the aircraft. That is, the weight of the aircraft must be distributed so that the center of gravity falls within specified limits. Maintaining the balance of small aircraft such as liaison and fighter types is comparatively simple because most of the weight is fixed. With transports and bombers, however, where a large percentage of the aircraft weight is in variable quantities such as fuel, crew members, equipment, bombs, and cargo, maintaining the balance of the aircraft involves precise mathematical calculations.

When an aircraft is not balanced correctly, several unsafe conditions are produced. These are: longitudinal instability in the form of light or reversed stick forces; increased takeoff distance, stalling speeds, and pilot's control forces; and decreased range, rate of climb, and structural safety factors.

The standardized weight and balance control system used by the Air Force makes it possible for the pilot or engineer to check the balance of his aircraft before takeoff and determine if the load is distributed properly. By performing a few simple calculations, facilitated by charts and balance computer (load adjuster), and by observing the clearance form prepared by the weight and balance technician, he can also find the following essential information: the probable landing weight, the center of gravity position prior to disposal of the load, and the center of gravity location after disposal of the load (fuel, bombs, cargo, etc.).

WEIGHT AND BALANCE TERMS

Like other technical subjects, weight and balance has a definite language all its own. This

language is composed of terms which the flight engineer must know to perform his duty efficiently. The terms are listed in alphabetical order—not necessarily in their order of importance—in the attachments to this manual.

We shall be using the terms relating to weight and balance continuously. Before proceeding with the text you should study the definitions in the attachment, then keep the attachment at hand for reference when needed.

PRINCIPLES OF BALANCE

The theory of aircraft weight and balance deals only with balance along the longitudinal axis of the aircraft. Lateral and vertical moments created by loading an aircraft are small because of the relatively small cross section of the fuselage. These conditions of unbalance are compensated for by the use of aileron trim tabs.

Aircraft balance is determined by the relationship of the center of gravity (CG) to the center of lift. Balance in flight is achieved on most aircraft with the CG forward of the center of lift because of a combination of the forces of lift, weight, thrust, and drag acting on the aircraft in flight.

The lift must be equal to the weight of the aircraft in level flight and greater than the weight in a climb. If the weight is greater than the lift, the aircraft loses altitude. The lift can be increased by increasing the angle of attack, up to certain limits (about 18°), or by increasing the power output of the engines.

FLIGHT ENGINEER DUTIES AND RESPONSIBILITIES

Weight and balance is of prime importance to the engineer, since it has a direct bearing on the predicted horsepower settings. It also affects the mechanical operation as well as the structural condition of his aircraft. At times, the engineer has to figure out the takeoff weight, CG, and landing weight in the absence of a weight and balance technician or loadmaster.

When the CG is not within proper limits, the aircraft does not perform according to the manufacturer's specifications. When this occurs, the engineer must make the necessary corrections by one of two methods or a combination of both. One method is a change of cargo position; the other method is a horsepower correction. If the cargo position cannot be changed, then the engineer must rely on the horsepower correction. What is known as *Performance Gross Weight* is calculated. This is the weight at which the aircraft is actually performing, and it is not necessarily the actual weight of the aircraft. This weight calculation is discussed in a later chapter.

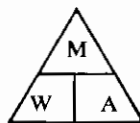
Fuel management is also a duty of the engineer. This job requires him to figure the fuel load and distribution of fuel throughout the tanks. Whenever an aircraft carries more fuel than the amount required for the mission, the payload is reduced. Some aircraft used by the United States Air Force have a distinct change in CG as fuel is consumed. Hence the flight engineer must know the CG position as the flight progresses.

FUNDAMENTALS OF WEIGHT AND BALANCE

The theory of aircraft weight and balance is that of the familiar steel-yard scale, which is in balance (equilibrium) when it rests on the fulcrum in a level position. It shows that the influence of weight is directly dependent upon the distance it is from the fulcrum and that for balance or equilibrium the weight must be distributed so the turning effect is the same on one side of the fulcrum as on the other side. A heavy weight near the fulcrum has the same effect as a lighter weight farther out on the bar. (See figure 8-1.)

The three items used in weight and balance calculations are *moment*, *weight*, and *arm*. The relationship of these terms can be shown by ar-

ranging them in a "mathematical tri-angle," as illustrated. In formula form, the terms are related as follows:



$$\text{Weight} \times \text{arm} = \text{Moment} \quad (57)$$

$$\text{Moment} \div \text{weight} = \text{Arm} \quad (58)$$

$$\text{Moment} \div \text{arm} = \text{Weight} \quad (59)$$

For a simple problem, let us find the CG of a plank, as shown in figure 8-2. Note that the reference datum (rd) line is at the left end of the plank, just as the rd line would be at or near the nose of an aircraft. This location makes all the moments positive (+), thus making the calculations easier.

Example: If we hang two weights from this plank, one 10" from the rd line and one 30" from the rd line, where will the plank balance?

$$\begin{array}{r} W \times A = M \\ 10 \text{ lb} \times 10 \text{ in} = 100 \text{ in-lb} \\ 10 \text{ lb} \times 30 \text{ in} = 300 \text{ in-lb} \\ \hline 20 \text{ lb} \qquad \qquad 400 \text{ in-lb} \end{array}$$

then, using total weight and total moment,

$$A = \frac{M}{W} = \frac{400}{20} = 20 \text{ inches}$$

The calculation shows that the plank will balance 20 inches from the rd line.

When the original object is balanced without the addition or removal of weight, the horizontal CG is at the fulcrum. Using an aircraft as an example, let us see how weight added gives a new CG. If the weight is added forward of the existing CG the CG is moved forward, and a noseheavy condition results if the new CG is forward of the center of lift. If the weight is added aft of the existing CG, a tailheavy condition results if the new CG is aft of the center of lift. In the loading of an aircraft, the added weight must be distributed so that the resultant CG falls within the specified limits; otherwise, the aircraft is not safe to fly.

In figure 8-3, you can see the original CG point along the horizontal plane. Add two weights of 50 lb and 10 lb and note the change.

$$\begin{array}{r} W \times A = M \\ 100 \text{ lb} \times 20 \text{ in} = 2000 \text{ in-lb} \\ 50 \text{ lb} \times 10 \text{ in} = 500 \text{ in-lb} \\ 10 \text{ lb} \times 35 \text{ in} = 350 \text{ in-lb} \\ \hline 160 \text{ lb} \qquad \qquad 2850 \text{ in-lb} \end{array}$$

$$A = \frac{M}{W} = \frac{2850}{160} = 17.81 \text{ in}$$

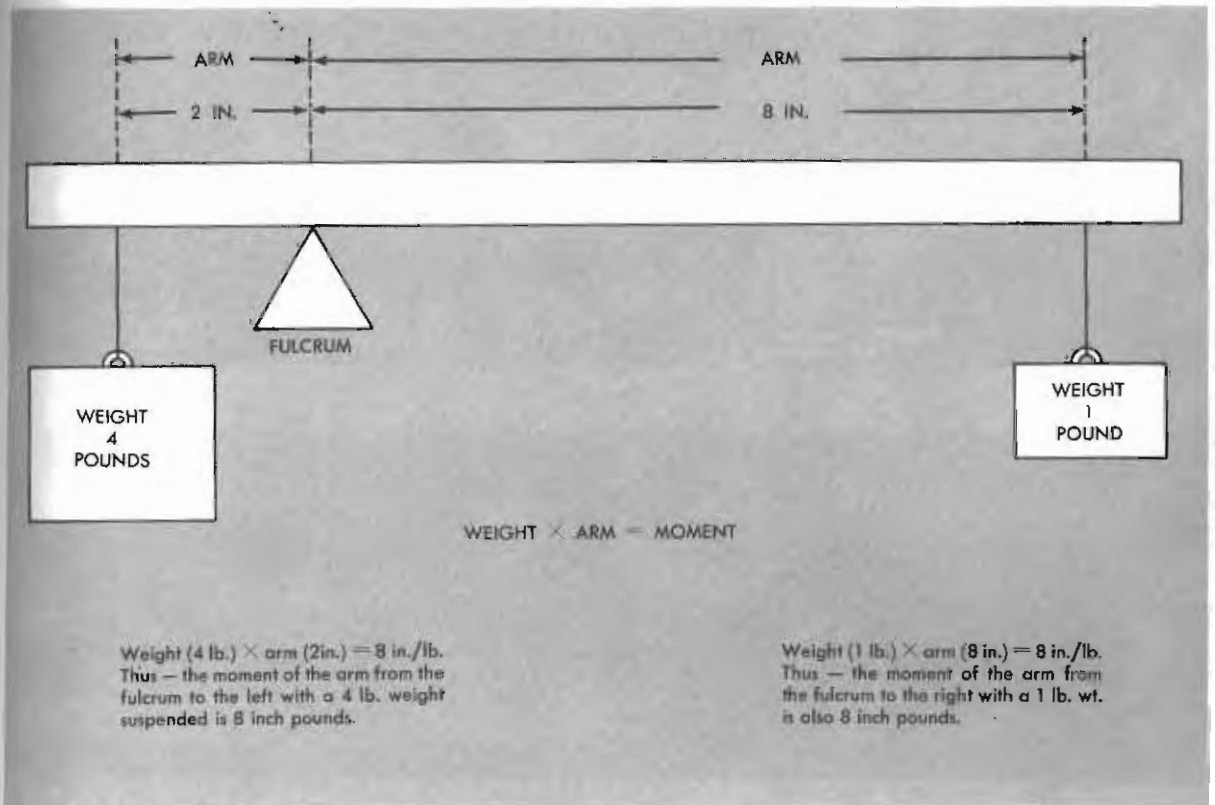


Figure 8-1. Theory of Balance

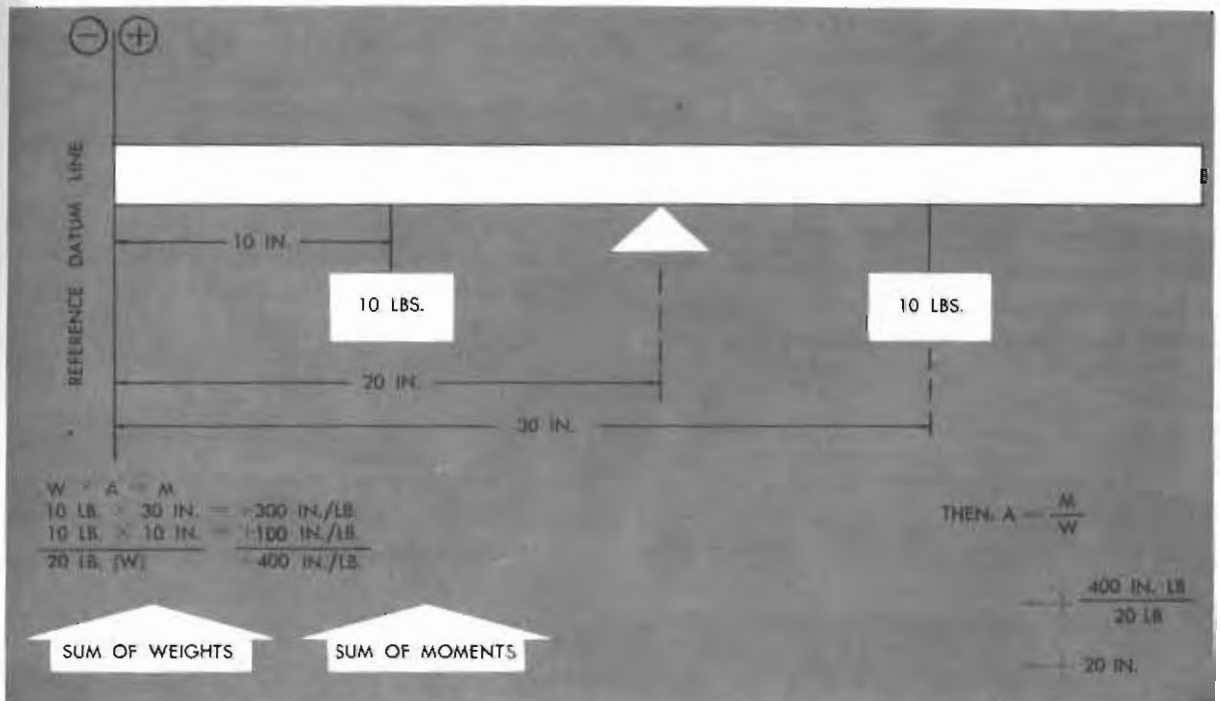


Figure 8-2. Balance Example