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ABSTRACT

The main part of the book centers on the discussion of the engines in an airplane. After describing the terms and concepts of power, jets, and rockets, the author describes the reciprocating engines. The description of diesel engines helps to explain why these are not used in airplanes. The discussion of the carburetor is followed by a discussion of the lubrication system. Lubrication is an important feature in the smooth functioning of aircraft, not only because of lubrication properties but because of its complementary role in cooling down the heat released in engines. The chapter on reaction engines describes the operation of the jet in theory and gives examples of how the different types of jet engines operate. Rocket engines are also explained briefly. The book is to be used for the Air Force ROTC program only. (PS)

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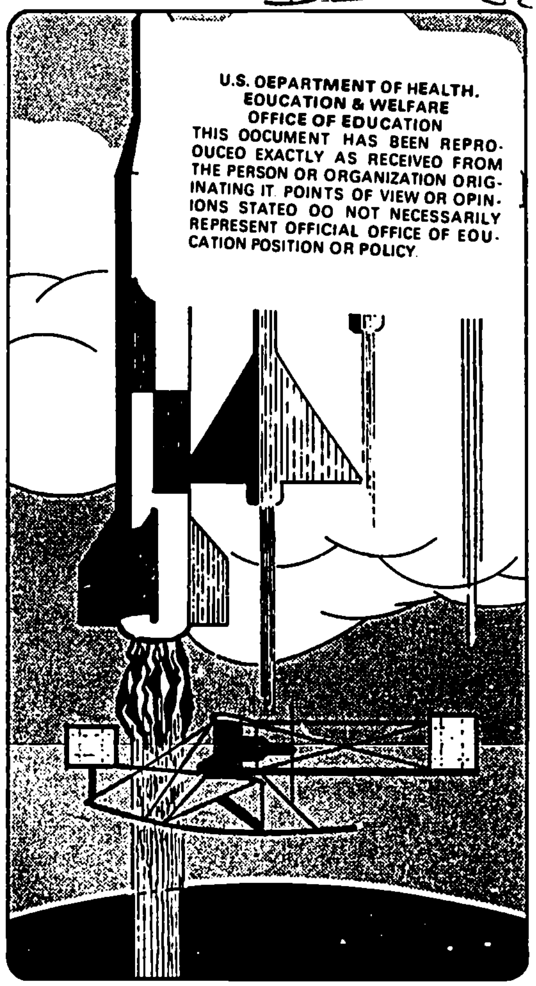

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Air Force Junior ROTC
Air University/Maxwell Air Force Base, Alabama

AEROSPACE EDUCATION II

Propulsion Systems for Aircraft

T. E. MACKIN
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AIR FORCE JUNIOR ROTC
AIR UNIVERSITY
MAXWELL AIR FORCE BASE, ALABAMA

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This publication has been reviewed and approved by competent personnel of the preparing command in accordance with current directives on doctrine, policy, essentiality, propriety, and quality.

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Preface

ONE OF MAN'S most persistent dreams is to be able to fly through the air unencumbered, like a bird. This was true hundreds of years ago, probably even back beyond the dawn of history. Evidence of the dream can be found in the fact that the gods of ancient civilizations were endowed with the power of flight. Men in these early civilizations gave to their man-like gods abilities that simple, ordinary men could not have—including the ability to fly.

The dream held true in later days also, as we can see from the many preserved drawings of human beings before, during, and after the days of Leonardo da Vinci. Even this Italian genius, whose abilities in many fields amaze sophisticated modern men, thought about, experimented with, and designed machines to allow man to leave the ground. Da Vinci and most other early theorists thought in terms of bird-like wings, operated by the muscle power of the man wearing them.

The dream exists even today, as we can see by the popularity of skydiving. This is the sport of parachutists who delight in jumping from planes, then soaring through the skies alone for as long as possible without opening their parachutes.

But accompanying this ancient dream has always been a rude awakening to the fact that man is just not built for flying. His body is too heavy to be held aloft by his arms. His arms are arms, not wings. And even with wing-like devices to hold him up, man is just not strong enough to build up the force it takes to keep himself in the air. Still, man does not concede that he is never to fly by himself, without mechanical assistance. (The skydiver is an example of this fact.) Even today, grown men fly kites and envy the paper birds they put aloft.

In his secret mind, man probably believes that he will one day overcome his ground-bound design and soar off by himself. After all, he reasons, the bumblebee defies all the rules of aeronautical design, and still flies. So why not man? In the meantime, however, man has accepted a compromise: if he has not yet found a way to fly under his own power, he will do the next best thing—he will use his machines for power.

Only through the use of machines has man so far been able to even partially fulfill his dream of controlled, continuing flight. After countless centuries of gazing at the sky and envying the birds, it is only within this century that man has made any real success of his ancient dream.

It is the purpose of this volume to trace the development of the power machines that man uses to propel his flying machines through the air; to study these propulsion machines as they exist today; and to look at probable future developments that will take man far, far beyond the range of the birds he envies.

Contents

Chapter 1

Power in Flight

THIS CHAPTER traces the historical development of engines used to power aircraft. It gives a brief review of developments in air theory, lighter-than-air craft, and glider flight, always considering that successful powered flight incorporated advances in all of these areas. Upon completion of this chapter, you should be able to: (1) explain the main differences between internal and external combustion engines and the reasons external combustion engines proved impractical for powering aircraft; (2) tell why the internal combustion engine was so long in developing and why it was the key to powered flight; (3) explain the terms "horsepower" and "thrust" and how they are related; and (4) perform the function necessary to compare a piston engine's power to that of a jet engine.

THE SUCCESSFUL FLIGHT of powered aircraft had to await developments in several fields. The theory of flight, for instance, underwent many changes as man continued to experiment with kites and gliders, to study bird flight and the movement of sailing ships, and to think about the nature of air itself.

As an adjunct to the accumulation of knowledge came physical developments. One of the most significant developments was the invention of the steam engine in the late eighteenth century. This new device represented man's first successful harnessing of mechanical power for useful work. It freed man from dependence on power from animals, wind, and falling water, and turned his thinking in new directions.

The steam engine was a revolutionary invention, and is still in use today. As important as the steam engine was, it had a number of basic characteristics which made it unsuitable for aircraft power. For one thing, the steam engine was too bulky. For another, it was not responsive enough to the pilot's control. It was too heavy. Moreover, it required external combustion.

External combustion meant that the fire that heated the water and turned it into steam was located outside the engine itself. This feature was more than just an inconvenience for someone who intended to fly through the air under power of a steam engine. (Some steam engines were used in the early days of ballooning, but they were soon abandoned.)

Improvements in the steam engine led eventually to the development of the internal combustion engine, which was a very significant development in the evolution of mechanical power. One of the most important characteristics of the new engine was provision for the burning process to take place inside the engine. The internal combustion engine eventually was to provide the power for man's first successful controlled, powered flight of a heavier-than-air craft.

The development of the internal combustion engine spurred the development of new metals that were strong enough and light enough to withstand the stresses of heat and pressure in the engine, while providing sufficient power to fly an airplane. Along with the development of this new kind of engine came new thought on how power can best be produced and used.

As you have seen in previous study in the Aerospace Education course, the road to successful flight was paved with many ideas from many men over a period of many years.

The Wright brothers collected the recorded progress in all of the fields of aviation thought, then added knowledge of their own to the pool of information. The collective knowledge produced by centuries of work by a number of people all over the world was responsible for the first controlled, powered, heavier-than-air flight on 17 December 1903. That historic flight lasted 12 seconds. The Wright brothers' "Flyer," with Orville at the controls, attained a forward speed of seven miles an hour, and covered a distance of about 120 feet.

Those figures do not sound like much today. In fact, they were far surpassed by the Wrights themselves before that day was over. And after that day, aircraft improvement literally flew forward at an astonishing rate.

But Orville Wright's flight represented the first successful application of the distilled knowledge of centuries of thinking, countless groping experiments, and an unknown number of unsuccessful attempts by men who would have been well satisfied to fly for 12 seconds at 7 miles an hour.

Let us briefly review that history.

AIR THEORY

For centuries before the Wrights, man had used the wind for power. Wind in the sails of ships moved those ships farther and faster than humans could row. But no one knew how to use the same wind force for flight. Ancient thinkers on the matter of flying thought that air was a sustaining force—that is, that air supported the birds, and held them up in the air. They differed on how the birds moved through the air. Some thinkers believed the birds swam through the air like a man swims through the water. Others believed the bird's forward motion was caused by the air closing around the bird's body, "squeezing" the body forward.

Leonardo da Vinci, 1452 to 1519, subscribed to the "swimming" theory, but he recognized that air hinders flight instead of helping it. Da Vinci was among the first to realize that air could be compressed, and that this compressibility acts to block flight. He made long studies of birds, and as a result, became a proponent of "streamlining" to cut down wind resistance as much as possible. Among da Vinci's drawings are plans for a parachute; for a kind of helicopter, which could pull itself through the air with a propeller-like screw, much as later boats would push themselves through water; and for an "ornithopter," a device with bird-like wings that man could flap with his muscle power, through a system of pulleys. This wing-flapping idea seems to have been most common among early would-be aviators. (The word "aviator," as a matter of fact, is derived from the Latin word, "avis," which means "bird.")

In 1680, a biologist named G. A. Borelli published a work explaining, among other things, that man's muscles alone would never be able to power a heavier-than-air craft through the air. Borelli explained that man had a poor ratio of power to weight, as compared with the bird. This biological explanation did not convince everybody, though. Some "birdmen" persisted in their attempts to get off the ground with bird-like wings. There is no record that any of them succeeded.

What they could not know was that the bird's wing was far from the simple flapping "arm" they saw. In fact, modern high-speed photography has revealed that the outer primary feathers of a bird's wings function as propellers do to drive the bird forward. Men of Borelli's time knew virtually nothing about aerodynamics, however, and saw only simple flapping when they looked at a wing in operation.

Many of the air-minded thinkers after Borelli's day turned their minds to flying lighter-than-air craft, or balloons. A major problem with the balloons was how to control their direction of flight. More than a century elapsed between the publication of Borelli's work and the invention of the steam engine. The greater part of another century had gone before the steam engine was used to propel balloons.

The first aircraft engine was a steam engine developed in 1851 by Henri Giffard of France. The engine weighed about 350 pounds and developed 3 horsepower. In September 1852, a cigar-shaped balloon flew at 6 miles an hour for 17 miles under the power of Giffard's engine, which drove directional propellers.

Internal Combustion Engines

From the time the steam engine was invented, scientists worked constantly to improve it. Their experiments led away from external combustion and toward the development of the internal combustion engine.

It is impossible to attribute to one man the invention of the internal combustion engine. Its development was made possible by an accumulation of knowledge in mechanical skills, thermodynamics (the effects of heat), experience, and the availability of materials.

The first record of the internal combustion gasoline engine was reported in 1820 by an Englishman named W. Cecil. The engine was put into production in 1823 by another Englishman, Samuel Brown. Cecil's engine operated on a vacuum system. The fuel burned inside the engine. As the heated air cooled, it produced a vacuum and the vacuum was used for power.

Later experiments showed that better power could be obtained by using the expansion force of the burning gases, instead of using the vacuum of the cooling gases. As a further refinement, in 1838, William Barnett of England suggested that the gasoline would produce more power if it were compressed before it was ignited.

POWER IN FLIGHT

The first really practical internal combustion engine was designed in 1860 by the Frenchman, J.J.E. Lenoir. Two years later, another Frenchman, Alphonse Beau de Rochas, came out with a theory for a four-cycle engine. His engine would have four steps: one for intake of the fuel; one for compression of the fuel; one for ignition of the fuel (the power step); and one for the spent gases to be exhausted.

A German named Nikolaus Otto applied the de Rochas theory to real engines in 1876. He began manufacturing them in the United States in 1878. Finally, Gottlieb Daimler made a valuable contribution to the propulsion field when he devised a high-speed internal combustion engine in 1883.

The internal combustion engine was to be the key to powered, heavier-than-air flight.

POWERED FLIGHT

The first internal combustion engine used on an airship, as balloons were called then, used coal gas for fuel. It was devised by Paul Haenlein of Germany in 1872, and had four cylinders. Eleven years later, Albert and Gaston Tissandier of France used an electrically-driven engine providing 1.5 horsepower on an airship.

The first use of a gasoline-burning internal combustion engine on an airship came in 1897. David Schwartz of Germany built the engine and installed it on a controllable balloon, or dirigible, made of aluminum.

A Brazilian, Alberto Santos-Dumont, and a German count, Ferdinand von Zeppelin, both worked on lighter-than-air craft (dirigibles) powered by internal combustion engines. Santos-Dumont started his experiments in 1898. Three years later, his dirigible flew a distance of seven miles in 29 minutes, 31 seconds. The 12-horsepower engine could move the 110-foot-long dirigible at 15 miles an hour. Count Zeppelin built a huge dirigible (420 feet long) in 1900 and powered it with two internal combustion benzine engines, developing 16 horsepower each.

The future, however, belonged not to the dirigible, but to the heavy aircraft.

Gliders

While the balloons supplied increasing information on engine design, valuable information on aircraft design was being gathered by glider builders.

Sir George Caley of England carried out pioneering experiments with gliders in the years around 1800. Later, the name of Germany's Otto Lilienthal became the foremost name among glider experimenters. Lilienthal, beginning in 1871, compiled a vast amount of information on aerodynamic principles through his work with gliders. Two of Lilienthal's disciples, Percy Pilcher of England and Octave Chanute of France and the United States, also made important contributions to airplane design through glider work in the last decade of the nineteenth century.

The marriage of the internal combustion engine to an air frame that incorporated these aerodynamic principles resulted eventually in a heavier-than-air machine.

More Power

Continuing advancement of the internal combustion engine nearly brought to Samuel Langley, an American, the historic honor of producing the first successful heavier-than-air craft. Langley, Director of the Smithsonian Institution in Washington, D.C., produced a series of powered model airplanes. The fifth model flew for about a minute and a half and covered nearly three-quarters of a mile. As a result of his experimentation in 1898, Congress awarded him a grant to develop a full-size aircraft.

Langley hired Charles M. Manly of Cornell University to build an engine for the full-size aircraft. Manly responded with a four-cylinder engine, weighing about 151 pounds and developing 52.4 horsepower. This engine was a marvel for that time, and the weight-to-power ratio is good even today.

With Manly at the controls. Langley's "Aerodrome" was launched in October of 1903 from a houseboat on the Potomac River. Part of the aircraft's structure snagged on the launching gear. Manly and the "Aerodrome" plunged into the river.

The plane was repaired, and on 8 December 1903, Manly made another try. His reward was another dunk into the river and hoots of derision from the Nation. the latter shared with Langley.

Nine days later, Orville Wright lifted off a launching rail at Kitty Hawk, North Carolina, in the "Flyer," while brother Wilbur stood by.

Success

The Wright brothers' flight was no accident. It was the result of long, hard work, of study of everything they could find on aeronautics, of building gliders and testing them, of constructing a wind tunnel to try out their ideas. When they could not find written material on information they needed, they experimented and developed their own ideas. When they could not find parts they needed, they built their own. For example, they came up short in their search for propeller information, so they had to experiment and design their own. The same was true with the engine. After searching for a suitable engine to power the "Flyer," the Wrights decided they must build their own. All known engines (Manly's was not "known" at that time) were rejected because they were too heavy or lacked sufficient power. Finally, they powered the "Flyer" with a gasoline-burning internal combustion engine, which was built with the assistance of Charles Taylor, the Wrights' mechanic. The engine had four cylinders, weighed 170 pounds, and developed 12 horsepower. It drove two wooden propellers.

The Wrights put in many hard hours of work over several years on their way to their date with history. And they arrived on time.

Jets

Jet propulsion has a different history. The theory of jet power has been around for centuries, but it was not until after Isaac Newton published his ideas on motion in 1687 that the jet was considered feasible as a propulsion device. More than 200 years elapsed after Newton, however, before anyone considered using a jet engine on an aircraft.

Actually, despite the fact that the principle of jet propulsion was known when the aircraft was first flown, the principle was not applied to aircraft for almost forty years. The reason for this delay includes the fact that when aircraft first began to fly, the only known jet engines were of the external combustion type, which were too bulky and lacked power; and that internal combustion jet engines could not be developed until man had come up with metals strong enough to withstand the tremendous heats and pressures produced inside such engines.

An American, Sanford Moss, contributed substantially to the jet engine, but more or less incidentally. Moss did research on the gas turbine, which was to play a big role in the jet engine's development. The turbine is a mechanical wheel-like device that spins in reaction to a fluid flow over or through it. Although the concept of a turbine was not new, Moss did much to perfect the idea. He experimented successsfully with the gas turbine in 1902.

An English Air Force officer named Frank Whittle combined the gas turbine and an air compressor to make a jet engine in 1930. But progress stalled until World War II came along. The English successfully flew a jet aircraft in May of 1941, thanks to Whittle.*

But he was not the first. The world's first jet aircraft flew in Germany in August, 1939. The engine was designed by Pabst von Ohain. A year later, an Italian jet aircraft built by Caproni flew 130 miles from Milan to Rome.

Whittle's ideas were imported by the United States and eventually emerged in the form of the P–80 Shooting Star jet aircraft in 1944. This was America's first operational jet aircraft.

The development of the jet leaped forward after World War II.

Rockets

The history of rocketry is long, and originated in China. Rockets were first used as toys, but can hardly be considered as such today.

Three men are credited with pioneering rocket flight and space exploration. They are Robert Goddard, an American, known as the Father of Rocketry; Herman Oberth, a German; and Konstantin Tsiolkovsky, a Russian. All three did their work in this century.

The rocket has become the key to future space travel, and its development has proceeded apace since Russia first launched an earth satellite in 1957.

POWER TERMS

In the discussion of propulsion systems, two terms will be used to describe the power output of the engine system. These terms are horsepower, used to evaluate the reciprocating engine; and thrust, used to rate the jet and rocket engines.

Horsepower is more or less an artificial word, invented to rate an engine's power in relation to the more familiar power source of earlier days. To understand horsepower, however, it is necessary first to understand the term work as used in a physical sense. Work is described as the exertion of a force over a given distance. It is measured in foot-pounds.

* For more details on Air Commodore Whittle, see the booklet. *The Coming of the Aerospace Age*, AE I, p. 76.

Work is the product of force, or weight, times the distance that weight is lifted. Time is not a factor in finding the amount of work done. The formula for determining work is expressed $W = F \times D$.

When James Watt was looking for a way to evaluate the power of his steam engine, he decided to rate the engine against a familiar power source, a horse. Watt hitched a brewery horse to a load and prodded the animal to his best effort in lifting that load. Watt found that the best that horse could do was to lift the 150-pound load three and two-thirds feet in an average second.

Using the formula for determining work, Watt found that the horse had performed about 550 foot-pounds of work per second. One horsepower, then, became equivalent to 550 ft-lb/sec.

The formula for determining horsepower is hp $= \frac{\text{number of ft-lb/sec}}{550}$ With today's big engines, manufacturers have found it more conventient to figure the horsepower by the amount of work done per minute. rather than per second.

This formula is stated, hp $= \frac{\text{number of ft-lb/min}}{33.000}$ and the figure 33,000 is merely 550 (one horsepower in seconds) multiplied by 60 seconds.

If an engine is capable of lifting 1,000 pounds of weight a distance of 25 feet in 10 seconds, the same weight could be lifted 2.5 feet in one second. Multiplying 2.5 feet times 1,000 pounds, we find that the engine performs 2,500 ft-lb of work per second. The horsepower rating, then would be: $\frac{2,500}{550} = 4.5$ hp.

Thrust

The power of jet and rocket engines is expressed in terms of thrust, instead of in horsepower.

Jet engines operate on the principles of Newton's second and third laws of motion (force is proportional to the product of mass and acceleration, and for every action there is an equal and opposite reaction).

In the jet, the "force" in Newton's second law is the power that moves the "mass" of air toward the rear of the engine. The "acceleration" is the increase in speed of the air mass from the time just before it enters the jet engine until the time it exhausts.

The formula for determining thrust is Force (in pounds) = Mass (in slugs) times Acceleration (in feet per second), or $F = MA$. To find the power rating of the jet engine, we substitute the word

Thrust for the word Force in the equation, since the two mean the same thing in this case.

Mass in slugs is equal to the weight of the air in pounds divided by the normal acceleration caused by gravity (32.2 feet per second). Our equation now reads, $T = \frac{\text{Weight}}{32.2} \times$ acceleration.

Acceleration of the air mass can be determined by subtracting the velocity of the air before it enters the engine (V_1) from the velocity of the air as it leaves the engine (V_2), and dividing the remainder by the time required to change the velocity. Assume that the aircraft (and the engine) is standing still. V_1 would then be, for our purposes, zero. If the exhaust velocity (V_2) is 1,500 feet per second, then the rate of velocity increase (acceleration) would be 1,500 feet per second per second. This would usually be stated 1,500 ft/sec^2.

Imagine, then, a jet engine capable of handling 150 pounds of air per second, and producing an exhaust velocity of 1,500 feet per second. Assume that the engine is stationary, making V_1 zero. The thrust could then be computed as follows:

$$T = \frac{150}{32.2} \times (1{,}500 - 0)$$
$$T = 4.65 \times 1{,}500$$
$$T = 6{,}975 \text{ pounds}$$

Thrust Horsepower

To get an idea of how thrust of a jet engine compares to horsepower of a reciprocating engine, we may use a formula for determining the unit called thrust horsepower (thp).

This formula is stated, thrust horsepower $= \frac{\text{thrust} \times \text{airspeed}}{375}$

The figure "375" in the formula is horsepower in mile-pounds per hour, and is simply an expansion of the more familiar 550 ft-lb/sec, or 33,000 ft-lb/min.

Thus, if a jet aircraft requires 10,000 pounds of thrust to travel at a speed of 800 miles per hour, the thrust horsepower would be

$$\text{thp} = \frac{10{,}000 \times 800}{375}$$

$$\text{thp} = 21{,}333$$

REVIEW QUESTIONS

1. Name one basic difference between the steam engine and the engine used to power the Wright brothers' "Flyer."
2. What was the contribution of balloon fliers to successful heavier-than-air flight? What was the contribution of glider fliers?
3. How did Charles Manly's engine, which he used on the "Aerodrome," compare with the engine that powered the Wright brothers' "Flyer?"
4. The theory of jet power is very old. Why was jet propulsion not used to power aircraft in the early days of aviation?
5. Name three men who were instrumental in the development of the modern rocket.
6. What term is used to evaluate the performance of the reciprocating engine? The jet engine?
7. What formulas are used to find horsepower or thrust ratings for engines? How do "horsepower" and "thrust" compare?

THINGS TO DO

1. The development of internal combustion engines forced the development of metals and other materials capable of withstanding the stresses of heat and pressure of the new engine. Modern jet and rocket engines develop heat and pressures much greater than the first internal combustion engines. Find some good examples of new materials developed as a direct result of modern propulsion systems. List some uses for these new materials in areas other than propulsion systems.
2. Although the first men to achieve powered flight were Americans, their biggest acclaim and the most immediate follow-up to their accomplishment came from Europe. Similarly, pioneering work in rocketry was done in the United States, but Europe made far more early use of it than America. Find out what historical and social factors led to this situation. Speculate on whether any of the same or similar factors are at work today, or whether the situation has been reversed. Explain your deductions and observations.

SUGGESTIONS FOR FURTHER READING

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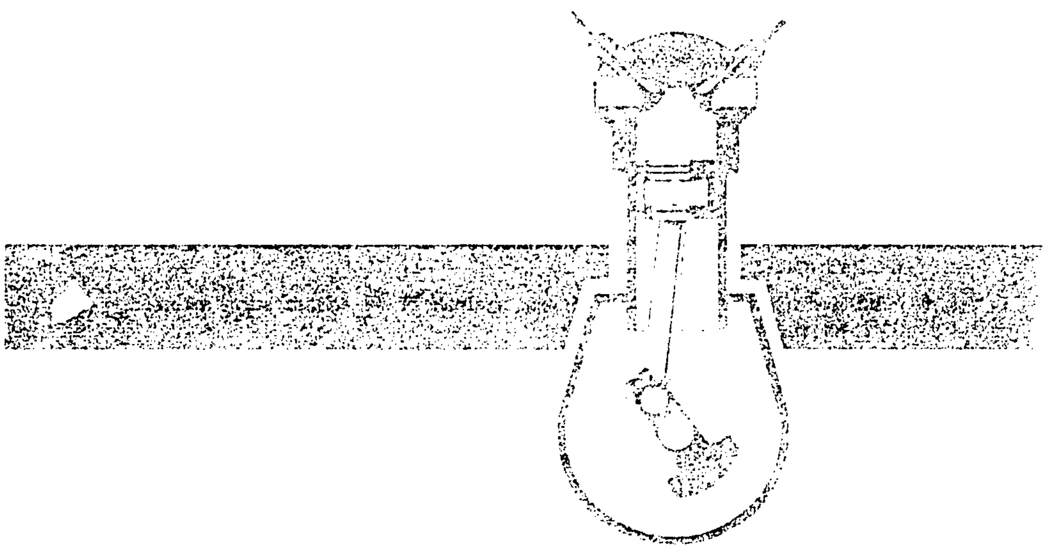

Chapter 2

Reciprocating Engines

THIS CHAPTER is concerned with the performance of the reciprocating engine, the numerically dominant engine in aviation today. It reviews the mechanical functioning of the reciprocating engine, beginning with the power cycle and including the necessity and means of cooling the engine. When you finish this chapter, you should be able to: (1) describe the power cycle of the reciprocating engine, explaining what happens during each step; (2) explain how diesel engines differ from reciprocating engines and why diesels are not used in aircraft; (3) explain the differing characteristics of in-line and radial engines and their relative advantages and disadvantages; and (4) describe clearly the workings of air cooling and liquid cooling systems in reciprocating aircraft engines and tell which is preferred and why.

THE AGE of the jet aircraft has had a profound influence on the thinking of air-minded Americans. The jet suggests speed and glamor and, indeed, it provides both. But in the field of general aviation—that is, all aviation except commercial airlines and military aviation—more than 99 percent of all aircraft are powered by the "old-fashioned" propulsion system of piston engine and propeller. This engine, where the power is produced by the back-and-forth motion of the pistons, is called a reciprocating engine.

THE RECIPROCATING ENGINE

The reciprocating engine is dominant in general aviation not only because it has been around longer than the jet, but because it is

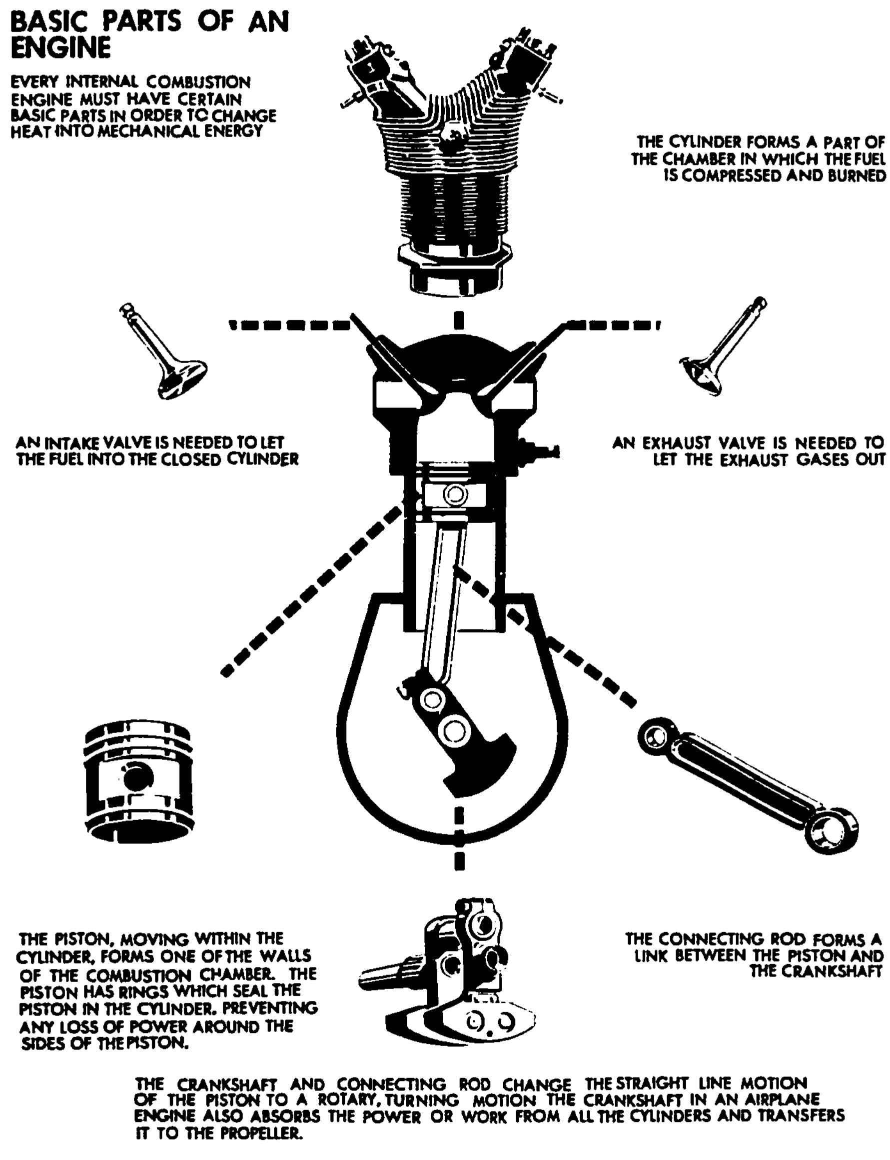

Figure 1. Basic Parts of an Engine.

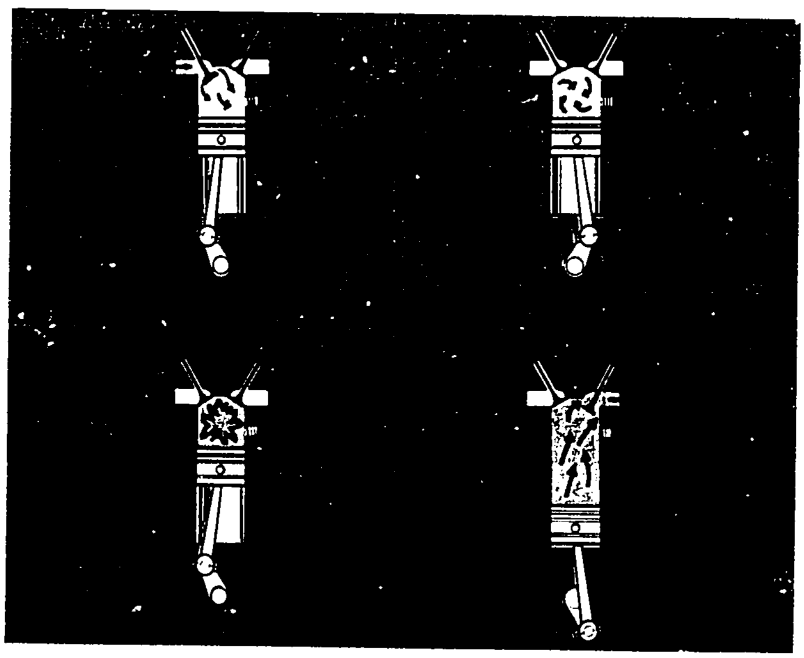

Figure 2. Four-stroke Engine Cycle.

well suited for the job it is called on to perform; that is, to deliver efficient, reliable, economical service at speeds below the speed of sound and at altitudes below 40,000 feet. Because of the dominance of this engine. it is important that we know something about it. In many ways, you will find that the aircraft's reciprocating engine is similar to the engine in most automobiles, with the main differences being that the aircraft engines are more powerful, more rugged, and lighter for the horsepower they develop. We will begin our study of the reciprocating engine by examining the mechanical system, where the power is developed.

The Mechanical System

Reciprocating engines used in aircraft have certain mechanical parts vital to their operation. These parts may be arranged in any of several different ways. but the design of the parts themselves remains more or less standard. These vital parts include the cylinder; the piston; the connecting rod; the crankshaft; and the valves. (Fig. 1).

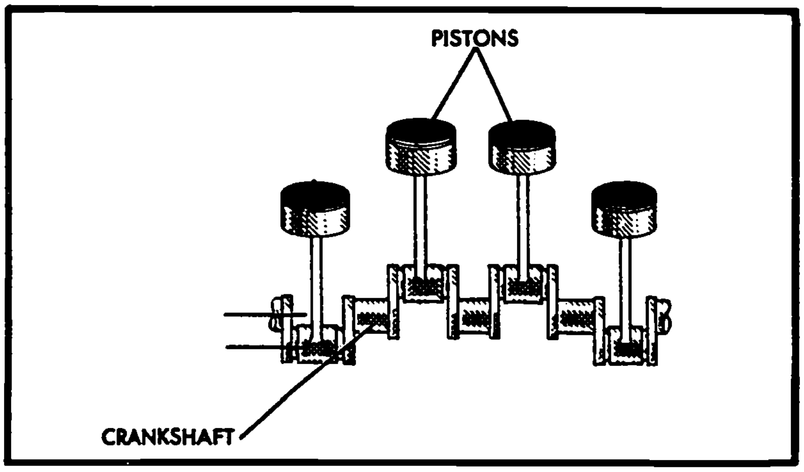

Figure 3. Piston-Crankshaft Connections.

Reciprocating engines used to power aircraft operate on what is called the four-stroke cycle. This means that the piston makes four strokes—movements from top center to bottom center of the cylinder, or from bottom center to top center—to accomplish the five stages in each complete action cycle.

The five steps in each cycle are: (1) intake, (2) compression, (3) ignition, (4) power, and (5) exhaust. The third step, ignition, occurs just before the end of the compression step and is thus considered as a part of the piston's second stroke. (Fig. 2)

The cylinder is the combustion chamber in which the engine's power is developed. The piston is designed to fit into the hollow cylinder snugly, but not so snugly as to prevent free up-and-down action by the piston. A connecting rod links the piston to the crankshaft, outside the cylinder. The crankshaft is so designed as to convert the piston's up-and-down motion into the circular motion required to turn the propeller, which is attached to the end of the crankshaft. The crankshaft is not straight, but has throws or bends in it. The connecting rods are attached to these throws. (Fig. 3)

At the top of the cylinder, in the cylinder head, are located two valves, an intake valve and an exhaust valve. The opening and closing of these valves allows the fuel to enter the cylinder and the exhaust gases to leave it. This opening and closing is regulated by rings or lobes on a cam shaft, which is located adjacent to the crankshaft. The cam shaft is connected to the crankshaft through a series of gears.

This camshaft-crankshaft connection provides synchronization of both shafts, the valves and the piston. The rings on the cam shaft—the cam rings—are made off-round, or eccentric. By pressing and releasing the tops of the valves in a timed sequence, the cam rings act to insure that each valve opens and closes at the proper time in the cycle.

With all of this in mind, then, let us look at the action that produces the power that drives the propeller.

Intake Stroke.—The piston begins the cycle from the location at top center of the cylinder. As the piston moves downward, toward the bottom of the cylinder and toward the crankshaft, the intake valve at the top of the cylinder and above the piston opens. This is due to the reduced pressure inside the cylinder, caused by the movement of the piston. The increased volume inside the cylinder and the lowered pressure force the pre-mixed fuel and air mixture to enter the cylinder through the intake valve.

Compression Stroke.—The piston reverses its direction starting back toward the top of the cylinder. Both the intake and the exhaust valves are closed, due to the cam ring action. The piston decreases the volume inside the cylinder, compressing the fuel mixture into a small space. Just prior to the end of this stroke, about 20 or 30 degrees from the top of the cylinder, a spark from the spark plug ignites the fuel. The momentum of the piston's upward movement carries the piston to the top of the stroke.

Power Stroke.—The fuel mixture, ignited by the spark, is burning now as the piston again reverses its direction. The burning fuel forms a large volume of gas, which creates tremendous pressure. This pressure drives the piston down forcefully. This power stroke is the whole reason for an engine.

Exhaust Stroke.—Slightly before the piston reaches its downward limit and reverses direction once more, the exhaust valve at the top of the cylinder opens. As the piston moves upward on its final stroke of the cycle, it forces the spent gases out of the cylinder. As the piston reaches the top of its final stroke, the exhaust valve closes and the cycle begins again.

This four-stroke cycle occurs at the same time in the other cylinders of the engine, but no two cylinders are at the same stage of the cycle at the same time. The cylinders are timed to fire in sequence to insure a smooth flow of power to the crankshaft and from it to the propeller.

Each cylinder goes through a complete cycle approximately 1,000 times every minute the engine is in operation. An engine with 18 cylinders, then, furnishes the propeller with about 300 power strokes per second.

Diesel Engines

The aircraft engines we are discussing use a mixture of gasoline and air for fuel. You may be familiar with another type of engine, the diesel. This is the powerful engine used on railroad trains and most heavy trucks today. Diesel engines are not used on modern aircraft, primarily because they are too heavy.

The diesel engine, named after Rudolf Diesel, its inventor, works on much the same same principle as does the four-stroke cycle gasoline engine we have been discussing. But its fuel is an oil that is not nearly as combustible as is gasoline. In fact, there is no explosion as such in the operation of a diesel engine. The diesel has no need for spark plugs and carburetors.

A basic difference in the operation of gasoline and diesel engines is that on the compression stroke of the diesel, no fuel is yet in the cylinder. The piston compresses air only.

Compressing a gas, such as air, makes the gas hot. In the gasoline engine, the gasoline-air mixture may be compressed to about one-ninth its original volume. If compressed more than that, it will explode. The explosion would, of course, prevent the piston from reaching the top of the cylinder and the engine would not work.

In the diesel engine, however, the air in the cylinder is compressed to about one-fifteenth its original volume. The temperature of the air in the cylinder rises above the burning point of the fuel oil. At the top of the compression stroke, the fuel oil is injected under pressure into the cylinder and burns immediately. The expanding gases force the piston down and supply the power, just as in the gasoline engine.

The diesel would seem to offer advantages for use in aircraft. Since the fuel oil is not as combustible, it would be less likely to explode in case of a crash. Moreover, it is cheaper than gasoline. But although the diesel provides more power per cylinder than does the gasoline engine, it does not provide as much power per pound of weight. The reason for this is that the diesel engine must be built very strongly—and very heavily—to withstand the tremendous pressures of the compression inside the cylinders. For this reason, the diesel is considered too heavy for aircraft use. The diesel engine also is more sluggish than the gasoline engine and does not react as quickly to the throttle. It is better suited to use where weight is not too important and where economy is needed.

Types of Reciprocating Engines

A constant concern of engine manufacturers is the problem of how to get more horsepower from their engines. With the reciprocating engine, there are two basic ways to accomplish this end. One way is to increase the number of cylinders in the engine.

The practical limitations on increasing the size of the individual cylinders are so restrictive that manufacturers have concentrated on the other method, the development of multi-cylinder engines. Not

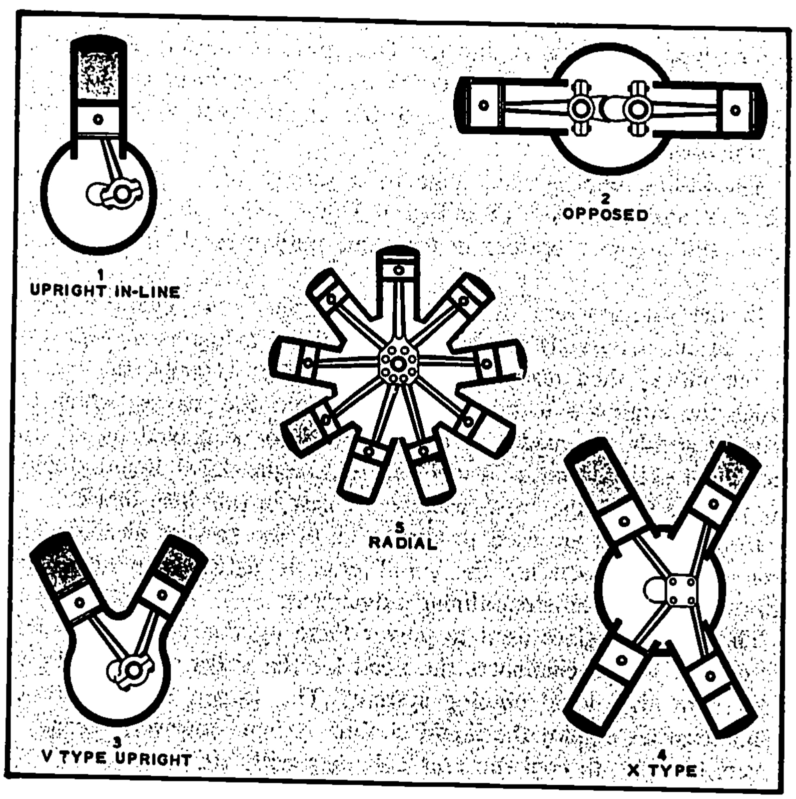

Figure 4. Types of Engine Designs.

the least advantage in using this method is the added smoothness of power supply, brought about because of the added number of power strokes per revolution of the crankshaft.

Manufacturers have come up with several different engine designs and configurations to accommodate the addition of cylinders. The most common designs in use today are the in-line and the radial engines. (Fig. 4)

In-line engines.—The in-line engine is one in which the cylinders are located in a row, one behind the other, along the crankcase (the casing through which the crankshaft runs). The cylinders, then, are in line, hence the name of the engine.

To accommodate the additional cylinders, the crankshaft must be lengthened and its number of bends (throws) must be increased.

If the cylinders are located above the crankcase, the engine type is called *upright*. If the cylinders are below the crankcase, the engine type is called *inverted*.

One type of in-line engine has two rows, or banks, of cylinders, one row on each side of the crankcase. The rows of cylinders are directly opposite each other, and the engine type is called *horizontal opposed*.

The in-line engines can come in a variety of designs, including the "V" and the "X." (See Fig. 4.) But these different arrangements still are put together in the same fundamental "in line" manner.

In the manufacture of the in-line engines, the cylinder heads may be cut separately or the whole bank of cylinders may be cast in one block, then machined to specification. Usually, the way in which the engine is to be cooled determines the way in which the cylinder heads are made. If the engine is to be cooled by air, the individual cylinder heads usually are cast separately. If liquid cooling is to be used, the heads usually are cast in one long block.

In-line engines are used in almost all of the smaller aircraft. The type of engine used for the small craft is usually the horizontal opposed, due to its streamlining advantages.

The in-line engines used to power these light aircraft are usually air cooled, which eliminates the need for the extra weight and machinery of the liquid cooling system. The larger, more powerful in-line engines employ the liquid cooling system, however, because it is very difficult to cool the rear cylinders with air.

Due to these cooling difficulties, the air-cooled in-line engine of the opposed type rarely produces more than 250-300 horsepower.

This limitation is the result of the limitation on the number of cylinders which can be cooled by the air system.

The in-line engine is usually a very compact package with a small diameter. The liquid cooled version offers very good, even cooling for the individual cylinders. This normally increases the life of the engine and reduces engine failure.

Where more horsepower is essential—in the larger aircraft, for instance—the radial engine is used.

Radial engines.—The radial engine features a crankshaft with only one throw. The cylinders are arranged around the crankshaft in a circle in such a manner that all the cylinders and connecting rods contribute their power through the single throw. One of the cylinders is designated as the master cylinder. The connecting rod from the piston in this cylinder is called the master rod, and attaches to the throw of the crankshaft.

Other connecting rods, called articulating or link rods, connect the other pistons to the large end of the master rod. The master rod, however, is the only rod that is connected directly to the crankshaft itself.

The radial engine always has an odd number of cylinders in each bank. This feature is required by the firing order of the four-stroke cycle. The maximum number of cylinders in each bank is usually nine. Where more power is needed from an engine, additional banks of cylinders may be added behind the first bank.

Where more banks are added, the crankshaft must be lengthened to accommodate the master cylinders in each additional bank. These extra banks operate in the same manner as does the original. In effect, a radial engine with two banks of cylinders is two engines working together, one behind the other. The design of the radial engine features fewer working parts and less weight than that of an in-line engine developing comparable power.

The radial engine is air cooled. Where more than one bank of cylinders is built into the engine, the air passes through the first bank and encounters a series of baffles. These baffles direct the air around and through the other banks of cylinders to cool the rear of the engine.

It is not uncommon to see radial engines with four banks of cylinders. Such engines can develop more than 3,500 horsepower each. When more power is needed, the radial engines may be used in sets of two, or even in groups of up to eight engines.

Performance of Reciprocating Engines

Manufacturers perfer the air-cooled radial engine for the heavier aircraft and the air-cooled inline engine for planes requiring less than 300 horsepower per engine.

The propulsion system composed of a reciprocating engine and propeller is efficient at speeds up to about 400 miles per hour and at altitudes below 40,000 feet. Such a system can create a large amount of thrust at low speeds and so can get an aircraft off the ground after a relatively short takeoff run. This propulsion system can carry more weight farther, and on less fuel, than any other kind of propulsion system in its speed range. It is dependable, and has become, through years of development, rugged and simple to maintain.

The propeller-reciprocating engine system of propulsion can provide very fast acceleration. The engine responds immediately and can change from a low to a high power output in a very short period of time. It is versatile and efficient. That is why, in this age of powerful and very fast jet planes and rockets, the propeller-driven aircraft, powered by the reciprocating engine, is still seeing extensive use.

HEAT AND COOLING

Reduced to basic essentials, the purpose of an engine is to produce energy, and this energy is in the form of heat. Without heat, the engine would not drive the propeller. But that same element—heat—is the primary source of wear and tear on the engine.

When the fuel and air mixture burns in the cylinder of an engine, about one-third of the resulting heat drives the piston downward. This is the only useful energy produced by the engine. Some two-thirds of the total heat produced is wasted. Of the lost portion of the heat, about one-half is pushed out into the atmosphere through the exhaust valve. The remaining heat—one-third of the total produced by the engine—does not escape and does not perform any productive work. Instead, it is trapped in the walls of the cylinder, in the piston, and in the lubricating oil of the engine. Unless this heat is disposed of, it can wreck the engine.

There are two ways to carry off the excess heat. One way is through the use of the air through which the engine is traveling; the other way is through the use of a liquid cooling agent carried along for the sole purpose of cooling the engine. Whichever way is used, special features are built into the engine to assist in the cooling.

One of the most noticeable of these features is the system of fins or flanges machined onto the head and barrel of the cylinders. These fins expose a broader surface to the cooling effects of the air or liquid coolant.

In the early days of aviation, the engines were exposed only to the direct air current through which the aircraft were flying. The air flowed over the engine, carrying off some of the excess heat, but that system proved effective only at a fairly low rate of revolutions per minute by the crankshaft.

The air cooling system developed along with the development of more powerful engines, which turned the crankshaft at a faster rate. The fins on the cylinders are an example. Another development was the enclosure of the engine in a cowling, or cover, with a system of cowling flaps and air baffles built in. This system slows down the air to the speed at which it does the best job of cooling. The cowling flaps control the volume of cooling air entering the cowling. The flaps can be operated or closed by the pilot. The air cooling system is effective not only at cruising speeds and normal altitudes, but on the ground and at high altitudes. (Fig. 5)

On the ground, the only air available to cool the engine is that produced by the propeller's action. In this situation the engine, as you can imagine, would tend to run hot. In contrast, the air at high altitudes is very cold, and, in addition, a greater volume of air is

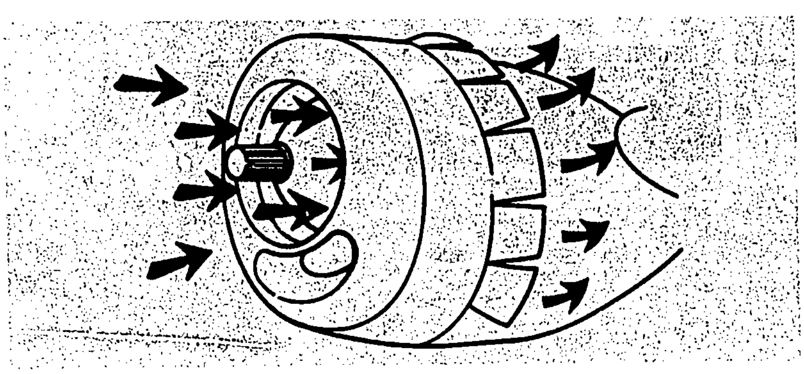

Figure 5. Air Cooling, with Cowling Flaps Open.

available due to the movement of the aircraft. In this situation, the engine would tend to run colder than its most efficient operating temperature. Since the pilot can control the opening and closing of the cowling flaps, however, he can increase or decrease the cooling ability of the air and keep his engine near to the most efficient temperature.

A recent development, called an augmenter tube, is now in use. This device is a tube placed behind the engine. The exhaust gases flow through the tube and, by use of Bernoulli's principle, create a pressure differential between the air inlet and the outlet. The result is a suction effect which pulls the air through the engine faster, and makes air cooling more effective on the ground.

The liquid cooling system on an aircraft works in much the same manner as does the liquid cooling system on most automobiles. In this system, the coolant flows in a blanket through the engine block and around the cylinders. The liquid—usually ethylene glycol on an aircraft—circulates through a system of pipes to a radiator. It is cooled in the radiator by air, then repeats its journey around the cylinders and through the engine block. (Fig. 6)

Proponents of the liquid cooling system claim that it cools more evenly, and therefore better, than does the air cooling system. It is more compact and usually can be built with a smaller frontal area.

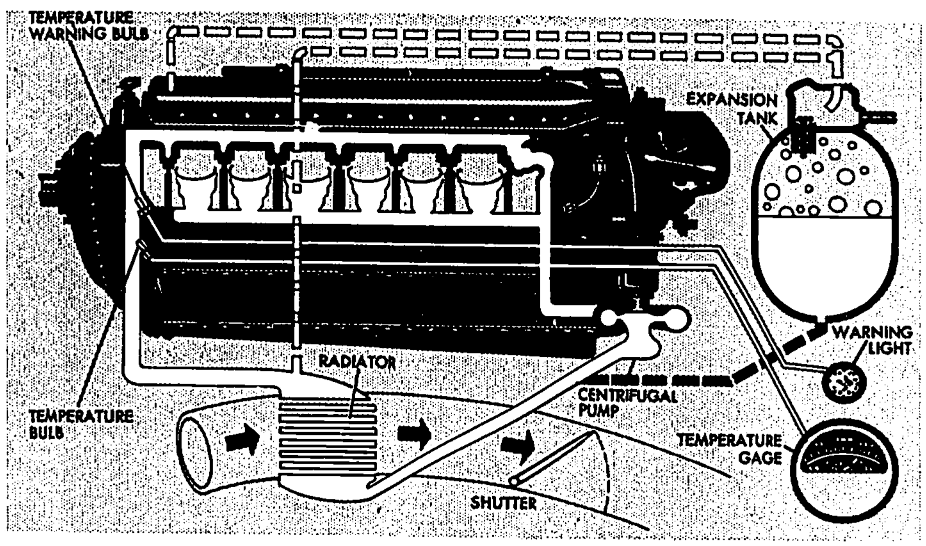

Figure 6. Liquid Cooling System.

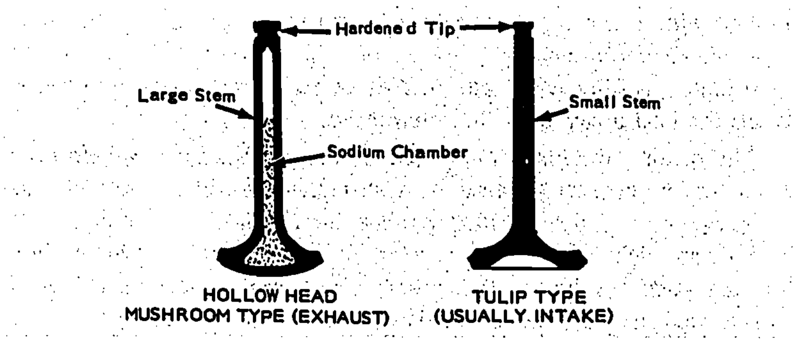

Figure 7. Cut-away Drawing of Valves.

But the liquid system is more costly to build and more complicated to maintain than is the air cooling system. In military aircraft, it is more vulnerable to enemy fire. For these reasons, the liquid cooling system has been nearly abandoned by United States engine manufacturers since World War II.

CONSTRUCTION MATERIALS

Since the heat generated in an engine is so intense, manufacturers must be careful in choosing materials that can withstand the heat and keep their strength and shape.

The cylinder is the seat of the engine's action, and is therefore subject to very high temperatures and pressures. The cylinder barrel and head must be very strong. The cylinder barrel is made of a high-grade steel alloy. It is machined to very close specifications. The inside of the cylinder barrel is highly polished and is harder than glass. The cylinder head is made of cast or forged aluminum alloy and is "shrunk" onto the cylinder barrel.

The shrinking process consists of heating the cylinder-head, then screwing it onto the cylinder barrel. The inside of the cylinder head is slightly smaller in diameter than is the outside of the cylinder barrel. Both are threaded. Heating expands the metal of the cylinder head so that it may be screwed onto the barrel. When the metal cools, the head is locked tightly into place.

The valves also are subjected to intense heat and high pressure. They are made of tungsten steel or chromium steel, which provide strength at high temperatures. The faces of the valves—that portion which is actually exposed to the heat inside the cylinder—are coated with a thin layer of stellite, which resists pitting and burning. The intake valve usually is solid, but the exhaust valve is hollow. The hollow is filled with salt solution of metallic sodium, which conducts the heat away from the valve head. (Fig. 7)

The pistons are made of forged or cast aluminum. Aluminum is used for the pistons because it is strong, it has compatible characteristics with the steel of the cylinder barrel, and because aluminum pistons are light enough to stop at the end of each stroke without causing undue stress on the other mechanical parts. Aluminum is also a good heat conductor and is therefore easy to cool.

The connecting rods are made of steel and the piston pins, which connect the connecting rods to the pistons, are made of tough nickel steel.

The heat on the crankshaft is primarily that produced by friction, and not by the action in the cylinder. But the crankshaft is subjected to the most violent twisting movement and must be made of very strong material to withstand the forces exerted on it. Therefore, the crankshaft is made of chromium steel. The crankcase is usually made of aluminum in smaller engines and of steel in the larger ones.

REVIEW QUESTIONS

1. **What are the principal parts of the reciprocating engine?**
2. **Name the five steps in the operation of the four-stroke engine.**
3. **What is the function of the cylinder in the reciprocating engine? What is the purpose of the crankshaft?**
4. **Describe the action of a four-stroke engine.**
5. **Why are Diesel engines not used in aircraft?**
6. **What is an "inline" engine? What is a "radial" engine? Name some advantages of each type.**
7. **Name some advantages of the propulsion system composed of a reciprocating engine and propeller.**
8. **What percentage of the heat developed in the chamber is used to drive the piston downward? What happens to the remaining heat?**
9. **What is a cowling? What is its function?**
10. **Name some materials used in the construction of the engine parts.**

THINGS TO DO

1. Diesel engines were tried experimentally on aircraft in the early 1940's, but were found unsuitable. Find out if advances in the development of strong, light-weight metals and improvements in diesel design have revived the prospects of diesel aircraft engines. Report to the class and explain your findings, whether positive or negative.

2. Recently, there has been developed an engine known as the rotating combustion engine. Plans for this engine include application to aircraft, automobiles, boats, and industrial uses. Find out and report on the operation of this engine and its current status. What are its prospects for wide acceptance?

SUGGESTIONS FOR FURTHER READING

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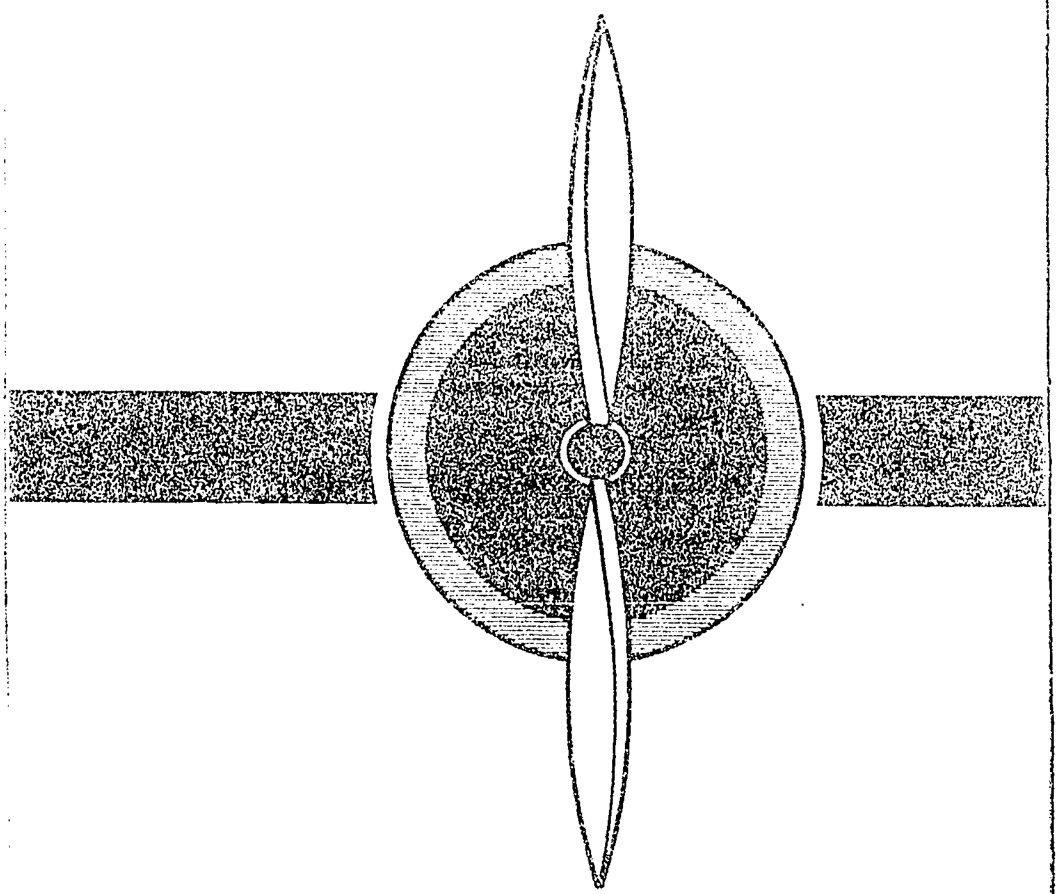
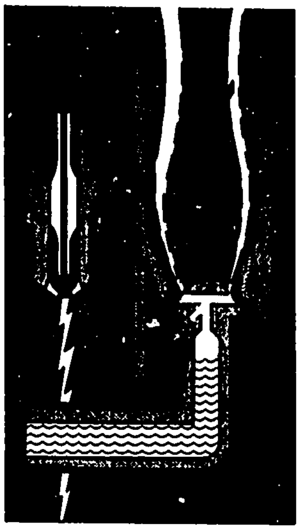


Chapter 3



Other Engine Systems

WHERE CHAPTER 2 considered the mechanical system of the reciprocating engine, this chapter considers other engine systems, namely the fuel system, with emphasis on carburetion; the ignition system; the lubrication system; and the propeller system, with some theoretical discussion of propellers. When you finish this chapter, you should be able to: (1) discuss the desirable qualities of gasoline and tell why it is the ideal fuel for aviation engines; (2) describe what happens in the carburetor, why this function is necessary, and how it occurs; (3) explain what happens in the operation of the ignition system; (4) explain the function of the lubricating system; and (5) describe the workings and limitations of the propeller.

THE CYLINDERS, pistons, valves, crankshaft, and related parts that we have discussed make up only one section of the engine, the section called the mechanical system. If fact, there are a number of engine sections which work together to provide power to move the aircraft. These different sections all must work properly within themselves and in cooperation with all the other sections if the total engine is to function well.

It is only for convenience in study that we divide the engine into its different systems. With that fact in mind, in this chapter we will examine engine sections other than the mechanical system and the cooling system. These other sections include the fuel system (including the carburetor), lubrication system, ignition system, and propeller system; their related parts; and their functions as parts of the whole engine.

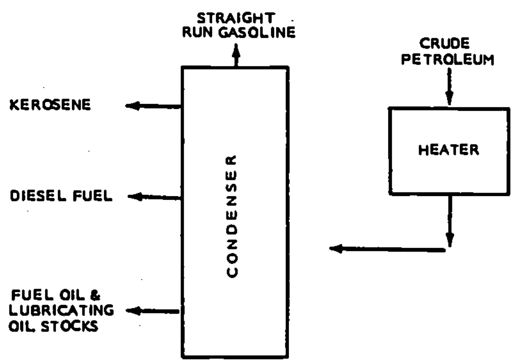


Figure 8. Products Derived from Petroleum.

FUELS

The fuels in use in today's aircraft are the result of extensive experimentation in search of the best fuel for the most reasonable price. The commonest forms of aircraft fuels are the hydrocarbons derived from petroleum.

"Hydrocarbon" is merely the descriptive name supplied by chemists to materials which contain only the chemical elements hydrogen and carbon in their structure. The principle hydrocarbon fuels in use in aircraft power today are gasoline and refined kerosene. These fuels, as well as diesel fuel, fuel oil, lubricating oils, and other produts, all are distilled from petroleum. (Fig. 8)

The petroleum-derived gasoline and kerosene used as aviation fuels offer several advantages:

1. They are volatile. They evaporate quickly and can be mixed easily with air to form a combustible mixture.

2. They have relatively low "flash points." That is, when they are mixed with air they ignite at relatively low temperatures. If the flash point of a fuel is too high, the result is difficulty in starting the engine.

3. Petroleum-based fuels have low freezing points. This is important when the aircraft is operating in the low temperatures of high-altitude flight. It also comes in handy when the fuel must be stored in the cold temperatures of the northern regions.

4. They have a relatively high heat content. This means there is much potential energy within the fuel which may be converted to

kinetic energy as the fuel burns. Potential energy is that energy which is at rest. Kinetic energy is energy actually at work.

5. The fuels are relatively stable. They can be easily handled under fairly simple safety precautions, and they will not deteriorate when stored over long periods of time.

6. They are readily available at relatively reasonable cost.

The petroleum from which gasoline and kerosene are derived, is found deposited in most regions of the world. Petroleum also is the source of automobile gasoline and other common fuels. But the fuels used in aircraft require stricter control in production than do the "ordinary" fuels used in automobiles. These controls are important because a failure in the engine of an aircraft can be much more serious than a failure in a car engine. A pilot cannot just pull over to the side of the road and call a mechanic.

Volatility

Aircraft fuel must be highly volatile so that the engine will start easily. But it must not be *too* volatile, or trouble can result.

One result of too much volatility is the *vapor lock*. In this condition, the gasoline "boils" in the fuel line before it reaches the carburetor. This "boiling" causes air bubbles to form in the fuel line. The air bubbles block or partially block the flow of the liquid fuel, so that an insufficient amount of fuel gets through to operate the engine.

Too much volatility also can lead to *carburetor icing*. We know from science that vaporization of a liquid requires heat. The heat used for vaporization of aircraft gasoline is taken from the air and from the metal surrounding the fuel. Gasoline of high volatility extracts this heat very quickly. When too much heat is taken from the metal parts for vaporization, the remaining cold will cause ice to form in the valves of the carburetor, and stop the proper operation of the carburetor. The carburetor, which will be explained more fully later in this book, is the device which mixes the fuel and air to the proper proportions for engine operation. If the carburetor does not operate as it should, the engine will fail. Various production tests are performed on aircraft fuels to insure that they are volatile enough for efficient engine operation but not too volatile for safe operation.

The octane rating of aircraft fuels also is important. In fact, manufacturers specify the octane rating of the fuels which will function best in each engine. The octane rating is simply a number describing the antiknock performance of the particular gasoline. A fuel of low antiknock value, used in a high-performance engine, may cause any of several dangerous consequences. Three types of "knock" are fuel knock, pre-ignition knock, and detonation.

Fuel knock is the result of uncontrolled burning of the fuel in the engine's cylinder. The fuel charge may burn evenly part of the way across the cylinder, then unevenly across the remainder. It may damage any of several vital engine parts.

Pre-ignition knock results when the compressed charge in the cylinder ignites before the electrical charge from the spark plug can jump the gap between the spark plug's electrodes, or points. This upsets the timing of the engine and also can cause damage.

Detonation is a severe fuel knock which creates pressures too extreme for the valves, the piston, and in some cases even the cylinder head to endure for any period of time. Detonation may be described as an uncontrolled explosion of the fuel in the cylinder,

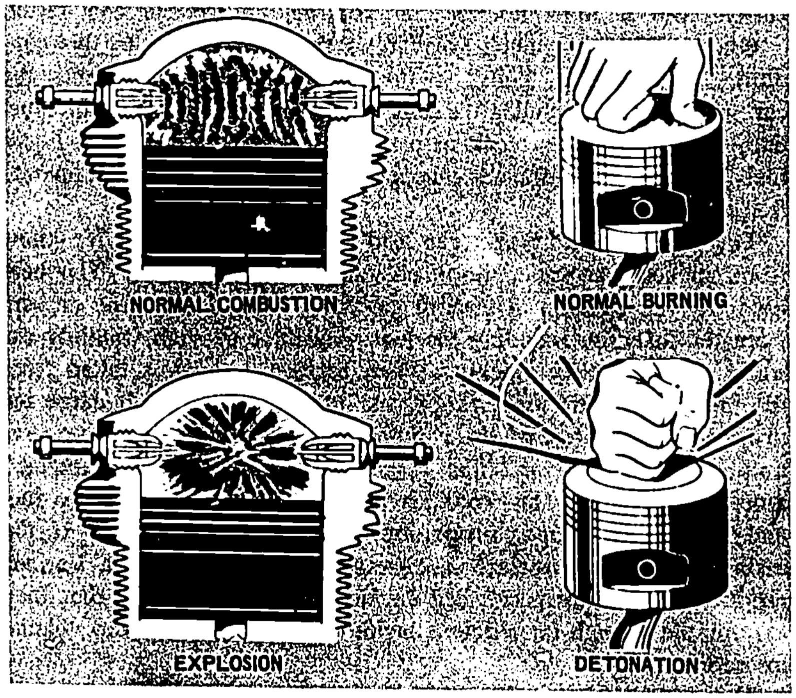


Figure 9. How Detonation Compares with Normal Burning.

due to spontaneous combustion. It can completely wreck the cylinder and its parts. (Fig. 9)

Fuel knock, pre-ignition knock and detonation may be caused by malfunctions of the mechanical part of the engine, but they may also result from the use of low-grade fuel. That is why the gasoline to be used must have the proper Octane Rating.

Octane Rating

The octane rating gets its name from one of the hydrocarbons contained in the fuel, called iso-octane. Iso-octane has high anti-knock properties, while the other common hydrocarbon in fuel, heptane, has low anti-knock properties.

The octane rating applied to a particular fuel originally indicated the percentage of iso-octane contained in the fuel. Because of its high anti-knock properties, pure iso-octane was arbitrarily given the number 100 to describe its anti-knock performance. For example, a gasoline rated 65 octane would be a mixture containing 65 percent iso-octane. But you may have seen fuels with octane ratings above 100. This is possible because chemists discovered that certain other elements blended into fuel with a high percentage of iso-octane actually could increase the anti-knock performance of the fuel beyond the level of pure iso-octane. The most commonly-used of these blending agents is tetra-ethyl lead.

Thus, a fuel with an octane rating of 130 would contain a high percentage of iso-octane, plus a quantity of another blending agent. The octane rating no longer describes merely the percentage of iso-octane in the fuel, but is a rating of the fuel's anti-knock performance.

Fuels with high octane ratings are used primarily in large engines specifically designed for them. The high anti-knock properties of this high-octane fuel allows higher compression of the fuel in the cylinder before it is ignited. The higher compression in turn yields a stronger "explosion" of the fuel charge when it is ignited, and higher power from each cylinder.

Now that we know the nature of the aircraft's fuel, let us see how that fuel finds its way into the engine and through the fuel system.

THE FUEL SYSTEM

The fuel system is a network of tanks, lines, gauges, pumps, strainers and screens. Its purpose is to deliver to the carburetor a steady flow of clean fuel under constant pressure. This delivery must continue at all operational altitudes of the airplane, and in all of the plane's positions, or attitudes, including diving, climbing or even flying upside down as well as level flight. To be sure these requirements are met, gravity-feed or mechanical pumping is employed.

FUEL FEEDING

The gravity-feed fuel system, the simplest type used, is common in small planes whose engines have relatively low horsepower. In this system, the fuel tank is located above the level of the carburetor inlet. The pressure behind the fuel flowing through the lines is built up by the weight of the fuel behind it, flowing from the higher level of the tank to the lower level of the carburetor inlet.

The gravity-feed fuel system is light-weight, easy to maintain and simple in design and operation. But it is not suited for high-powered aircraft.

The force-feed fuel system features an engine-driven pump which draws the fuel from the tank and forces it into the carburetor. The use of the pump means that the tanks do not have to be located above the carburetor inlet, but may be placed wherever there is ample and convenient space. A hand operated pump, called a wobble pump, is included for use in case of emergencies, if the engine-driven pump fails. The pumps may be arranged side by side, or parallel, or in series. The series arrangement is preferred for use in fast-climbing aircraft. (Fig. 10)

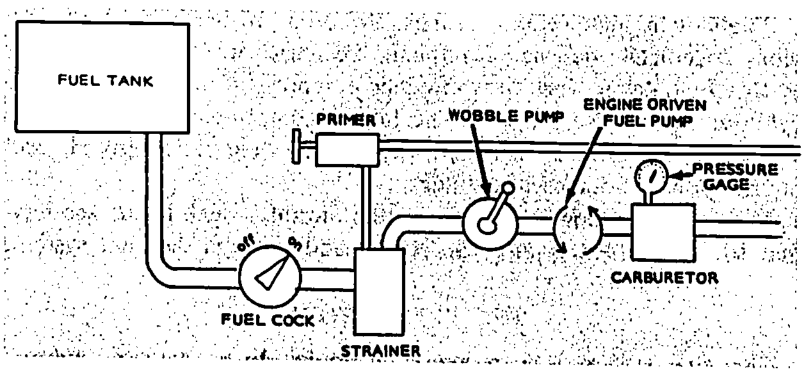


Figure 10. Fuel System with Pumps in Series.

The force, or pressure, system is used in larger planes with more than one engine. This type of system makes possible the high fuel pressure required by many modern aircraft carburetors. Since the constant supply of fuel is assured, the plane has more maneuverability.

A series of strainers and screens is included in the fuel system to assure that water, dirt and other foreign matter does not get through the system. If these elements were able to go through the fuel system, dire consequences could result.

Water is heavier than gasoline and settles to the bottom of the tank. When the aircraft is in flight, the water may get into the fuel lines, freeze at high altitudes and block off the flow of gasoline to the engine. A tiny particle of dirt may block off the metering jet in the carburetor and wholly or partially block the gasoline's flow to the engine. In either case, the engine fails either partly or completely. To be sure that these impurities are not present in the fuel system, the ground crew usually checks the strainers, screens and traps for accumulated water and dirt immediately after refueling the aircraft. After passing through these strainers and filters, the clean gasoline is fed through a most important part of the fuel system, the carburetor.

The Carburetor

Gasoline in its liquid form burns too slowly for good engine performance. But mixed with air, gasoline is the most satisfactory aircraft fuel yet found for use in reciprocating engines. The carburetor is a device built into the engine to atomize the gasoline, measure it to proper quantities, and mix it with air. The proper air-gasoline mixture is one that will burn slowly, evenly, and completely.

The word "carburetor" comes from the same root word as does carbon. The dictionary describes "carburetor" as a device which effects the chemical mixing of an element with carbon. In this case, the carbon is found in the hydrocarbons of the gasoline. The element with which it is to be combined is the oxygen in the air. The result of this combination is the explosive mixture that drives the engine.

The carburetor must be capable of measuring the gasoline and air mixture to the right proportions for the best operation of the engine. The ideal mixture is considered at about 15 parts of air to one part of gasoline. These proportions are decided by weight, not by volume, because of differences which might occur as a result of tem-

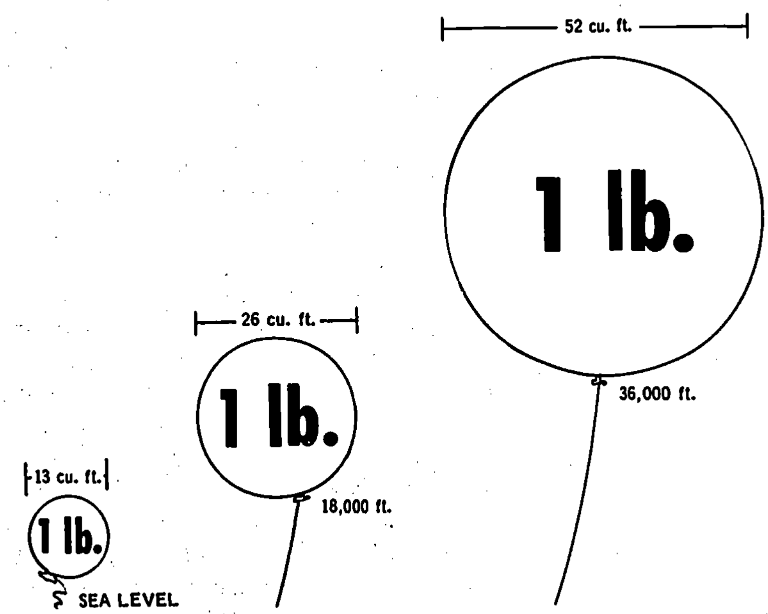


Figure 11. A Pound of Air Expands with Altitude.

perature and altitude effects on the density of air. (Fig. 11) Thus, the ideal fuel mixture would be about 15 pounds of air to one pound of gasoline. A mixture with a higher ratio of air is called a "lean" mixture, while a mixture with a lower ratio of air is said to be "rich."

Gasoline will burn in a cylinder when it is mixed with air in a ratio of between 8:1 and 18:1, that is, when the mixture contains between 8 and 18 parts of air, by weight, to 1 part of gasoline. Generally speaking, the 15:1 ratio is nearly ideal for the best power production. One interesting difference in the aircraft engine's carburetor and the carburetor in an automobile engine is this: the pilot may change the mixture control settings of his carburetor while the aircraft is in flight, while the automobile driver has no such controls available on his dashboard. A rich fuel-air mixture is used at high and low aircraft speeds, while a slightly lean mixture is more efficient at medium, or cruising, speeds.

An overly rich mixture may result in engine stoppage or detonation. An overly lean mixture causes loss of power and may result in overheating in the engine. This overheating may also cause detonation in the cylinder. It also can cause backfiring through the carburetor.

A backfire may occur if the fuel mixture in the cylinder is still burning when the intake valve opens to begin the next power cycle. The burning fuel ignites the fuel in the intake manifold. Chain reaction feeds the fire back through the carburetor barrel into the carburetor. Severe damage can result from this occurrence.

The carburetor must be designed and controlled so that it mixes the proper amount of gasoline with a given amount of air. Moreover, the carburetor of a modern airplane must operate well in a variety of situations. It must be capable of changing automatically to accommodate different speeds and weight loads.

These requirements have brought about increasing sophistication so that modern, high-performance carburetors have become quite complex. In this section, we will explore the basic workings of the carburetor and look at some of the devices developed to insure its constant, efficient operation.

The carburetor makes use of Bernoulli's principle, which states that as the velocity of a fluid at a given point increases, the atmospheric pressure at that point decreases; and of the Venturi tube, which puts Bernoulli's principle to work. (Fig. 12)

Float Carburetors

The simplest kind of carburetor is the float type. This carburetor, used on small planes, consists essentially of (1) a float chamber,

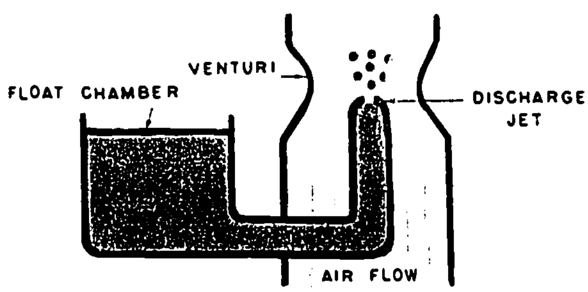


Figure 12. The Venturi in the Carburetor.

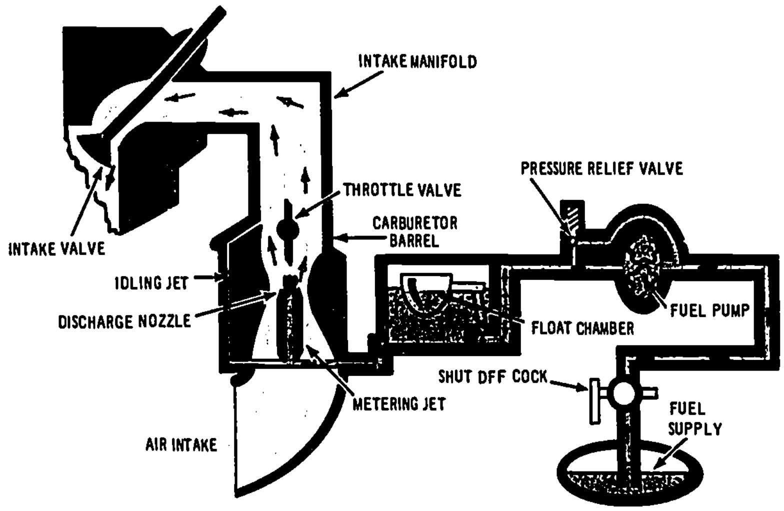


Figure 13. The Simple Float Carburetor.

(2) a main metering jet, (3) a discharge tube and nozzle, (4) a carburetor barrel, and (5) a throttle valve. (Fig. 13)

The fuel is fed from the fuel system into the float chamber. This chamber is a reservoir used to insure a constant level of fuel within the carburetor. The float is connected to a needle valve and operates similarly to the float system in the tank of modern bathroom plumbing. As the fuel level in the chamber drops, the float drops with it. As the float drops, it opens the needle valve. When that valve opens, more fuel enters the chamber, the float rises again and the valve closes.

The fuel travels out of the float chamber through the metering jet. This jet, or nozzle, measures the gasoline into the discharge tube. The level of the fuel in the discharge tube is the same as the level of the fuel in the float chamber when the engine is not operating. The discharge tube and nozzle is set up into the carburetor barrel.

The carburetor barrel is an air chamber built in the shape of a venturi. That is, it is constricted to increase the velocity of the air flowing through it. As the velocity increases, the air pressure drops. The throttle valve, usually of the butterfly type, is set in the carburetor barrel above the constriction and above the discharge nozzle. (Fig. 14)

The throttle valve is connected to the throttle control, which is operated by the pilot. When the engine is started and the throttle valve opened, the carburetor goes into action. The piston goes downward in the cylinder on its intake stroke, creating a vacuum above it. The intake valve, located above the piston, opens into the intake manifold, which is in turn connected to the carburetor barrel. When the intake valve opens, air is pulled through the carburetor toward the cylinder. The intake manifold is a pipe that supplies all the cylinders with the fuel mixture from the carburetor. As the air rushes past the discharge nozzle, Bernoulli's principle goes to work and the pressure around the nozzle drops.

The downward pressure on the top of the nozzle, then, becomes less than the downward pressure on the gasoline in the float chamber, where the pressure is atmospheric. This combination of suction and pressure differential opens the discharge nozzle and draws the

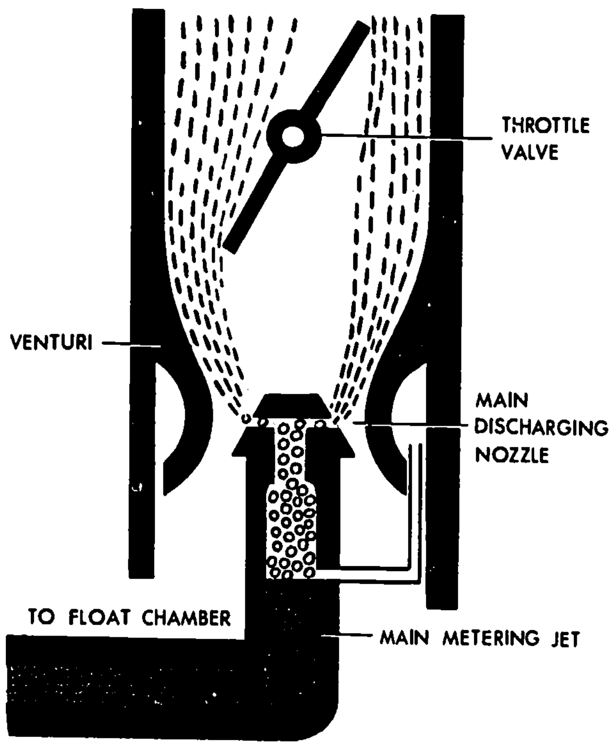


Figure 14. Carburetor Barrel and Throttle Valve.

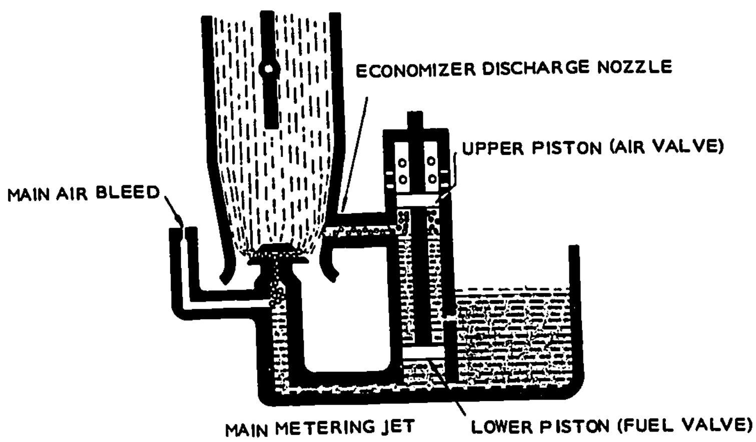


Figure 15. The Economizer System.

gasoline into the airstream, through the intake manifold, past the intake valve and into the cylinder. As the intake valve closes in the next step of the cylinder's operation, compression, the air-gasoline mixture continues to come through the intake manifold and goes into the other cylinders.

As the throttle is opened, the throttle valve responds by opening. When that valve opens, more air is allowed through the venturi, the pressure on the discharge nozzle drops more, and more gasoline is pulled into the carburetor barrel. As the throttle is closed, the reverse takes place. The air stream is partially blocked by the throttle valve, the pressure rises on the discharge nozzle, the nozzle partially closes, the gasoline flow is blocked and the engine slows.

When the throttle is in the idle position, the throttle valve is closed as far as it will go. But the valve does not quite close off all of the air traveling through the air duct, that is, the carburetor barrel. A small amount of air is able to pass the throttle valve along the walls of the carburetor barrel. When the engine is at idle, the fuel supply does not come out through the discharge nozzle, but through a smaller opening above the nozzle, called an idling jet.

Carburetor Accessories

There are a number of devices in operation which are considered a part of the carburetor system. These devices, while not actually essential to the theoretical operation of the carburetor, do improve performance to such an extent that they are considered vital in modern aircraft. Some of the most important of these devices are the economizer, the accelerating system, the carburetor heater, and the supercharger.

The economizer.—This device is designed to provide additional fuel to the fuel-air mixture for high-speed operation. The economizer is a valve which is closed at cruising speeds but open at high speeds. Its controls are connected to the throttle controls (Fig. 15). The economizer is so named because it allows the pilot to use the leanest mixture which will maintain the maximum power output at any desired rpm (revolutions per minute of the crankshaft).

Accelerating systems.—Most modern carburetors are equipped with an accelerating system. The accelerating system is designed to overcome the problem of temporary lean mixtures which occur when the throttle is suddenly thrown open. Normally, the fuel supply would require a short time to catch up with the increased amount of air flowing through the carburetor on sudden acceleration. The accelerating system overcomes that problem. It works either from a well or a pump. When the throttle valve suddenly opens, the accelerating system responds immediately by pushing more fuel through the discharge nozzle (Fig. 16).

Heater.—As we have seen, carburetor icing can be a serious problem. Icing can occur even on a warm day, because the tem-

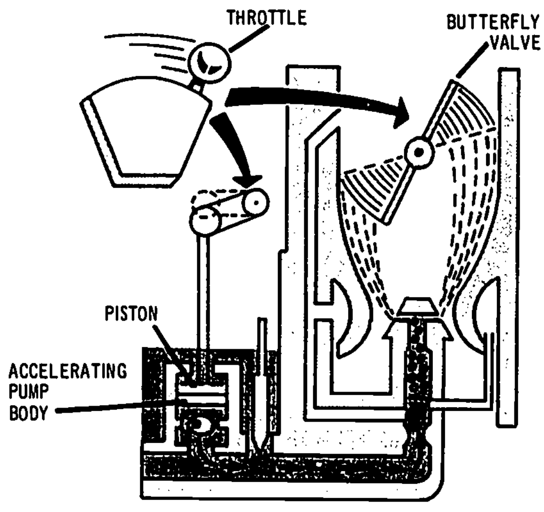


Figure 16. The Accelerating System.

perature inside the carburetor drops dramatically during the vaporization process. To prevent this icing, most carburetors are outfitted with heating devices. These heaters usually transmit heat from the cylinders in the engine to the air in the carburetor. The heaters must be controlled, however, because too much heat will cause the fuel-air charge to expand and lose some of its power.

Superchargers.—On larger aircraft, power demands are great. To increase the power output of the engine, the charge is compressed. This compression is accomplished through the use of the supercharger.

The function of the supercharger is to increase the amount of fuel-air mixture in each charge fed into the cylinder. The superchargers are small, high-speed fans which increase the amount of air drawn into the engine; compress the charge, so that a charge of a given size, or volume, will have more air and more fuel in it; and force the compressed charge into the intake manifold.

The supercharger forces more air through the carburetor, and the carburetor reacts by pouring in enough gasoline to keep the charge in its proper ratio. Since more air and fuel are therefore available for burning in each combustion stroke of the piston, more power is obtained. The action of the supercharger also increases the pressure in the intake manifold, which then supplies all the cylinders with equal charges under equal pressure. High pressure in the intake manifold means smoother operation and more power from the engine as a whole.

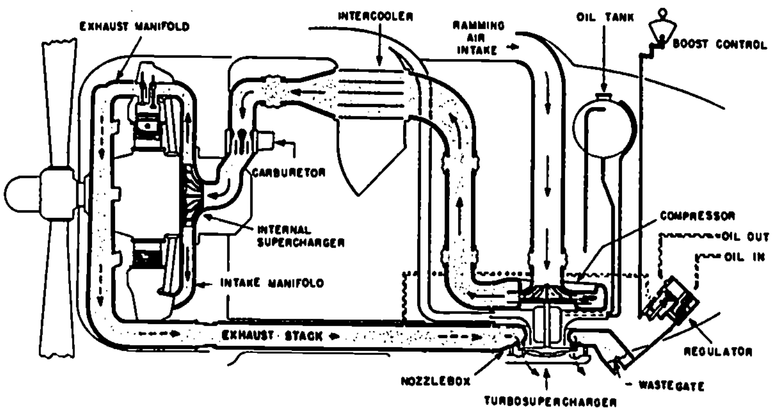


Figure 17. The Supercharger System.

The supercharger may be "external" or "internal" (Fig. 17). The internal fan, or impeller, is located between the carburetor and the intake manifold. It operates through a gear connection with the crankshaft. The external fan is located between the carburetor and the free air outside, and makes use of the exhaust gases for its operation. The gases escaping the engine's cylinders on the exhaust strokes are directed through buckets of a turbine wheel, connected to the supercharger fan. Since the turbine principle is used in operating the external fan, it is called the turbosupercharger. Supercharger systems with the external fan usually are also equipped with the internal fan.

The supercharger system is not only helpful, but actually essential for the operation of aircraft at very high altitudes. This is true because the air at high altitudes is thinner—it has less weight in the same volume—than air at sea level. And the carburetor, remember, is metered to considerations of weight, not of volume. The supercharger pulls in great volumes of air in order to force through the carburetor enough air poundage to operate the engine.

The external fan, then—the turbosupercharger—pulls in air from outside and pushes it through the carburetor. The internal fan pulls air and gasoline out of the carburetor and pushes it into the intake manifold. Thus, the supercharger system delivers literally a "super" charge of fuel-air mixture to the cylinders.

Other Carburetor Types

The float carburetor we have discussed is of the updraft type. That is, the air is drawn in from the outside and upwards through the carburetor venturi. There are carburetors which reverse this arrangement and pull the air downward through the venturi. They are called, appropriately, downdraft carburetors. Included in the downdraft group are the float type; the pressure injection type; and the variable venturi, or diaphragm type.

Downdraft float carburetor.—The downdraft float type carburetor operates on much the same principle as does its updraft brother, but the arrangement of the parts is a little different (Fig. 18). The main discharge nozzle is in the venturi, but it protrudes from the side instead of being in the middle. The idling jet is below the discharge nozzle. Air is vented into the float chamber, providing enough pressure to force the fuel up through the nozzle and into the carburetor barrel.

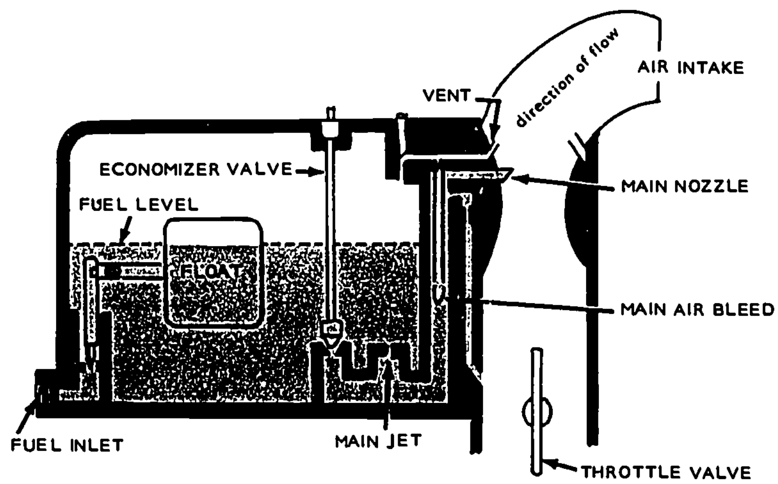


Figure 18. The Downdraft Float Carburetor.

Pressure injection carburetors.—As we have pointed out, the float type carburetor is used on small aircraft. The larger craft employ the pressure injection type carburetor. (Fig. 19)

This carburetor makes use of a pump to deliver fuel under pressure to nozzles in the carburetor barrel just before the entrance of the internal fan, or impeller. The fuel is atomized into the rushing air under pressure. This results in smooth, economical operation, the elimination of icing in the throttle valve, and protection against vapor lock due to the fuel's "boiling" in the lines.

The pressure injection carburetor is entirely closed, which means that it will operate normally during all types of aircraft maneuvers. An automatic mixture control meters the fuel correctly at all operating altitudes and at all operating load levels. The metering is done in response to venturi air suction.

The pressure regulator unit of this carburetor is located behind the throttle section. It consists of an air section and a fuel section, each of which is divided into two chambers with a diaphragm between.

A poppet valve, operated by the movement of the diaphragms, connects the two sections. The head of the poppet valve opens and closes an orifice through which fuel is pumped from the aircraft's fuel system into the fuel chamber of the carburetor. Thus, all parts of the carburetor move as one unit.

The operation of the pressure injection carburetor is as follows: Air is fed through the automatic mixture control in proportion to the air flowing through the carburetor venturi. The mixture control passes the air to the air chambers in the regulator unit. A pressure differential is formed between the two chambers of the air section. The diaphragm moves, activating the poppet valve in the fuel section. As the valve opens, fuel is pumped, under pressure, through the opening and into the fuel chamber of the regulator. This causes a pressure differential between the two chambers of the fuel section and activates the second diaphragm. The action of the diaphragm pushes the poppet valve back the other way, closing off the opening to the fuel supply. The fuel, still under pressure, passes from the fuel section of the regulator unit down to the fuel nozzle, through which it is sprayed into the carburetor barrel.

As you can see, the rate at which the fuel is delivered into the airflow is controlled jointly by the position of the throttle valve and by the temperature and pressure acting through the automatic mixture control.

In the pressure injection carburetor, the economizer, idling system, and accelerator system are controlled by pressure in the fuel chamber section, in concert with the venturi air pressure.

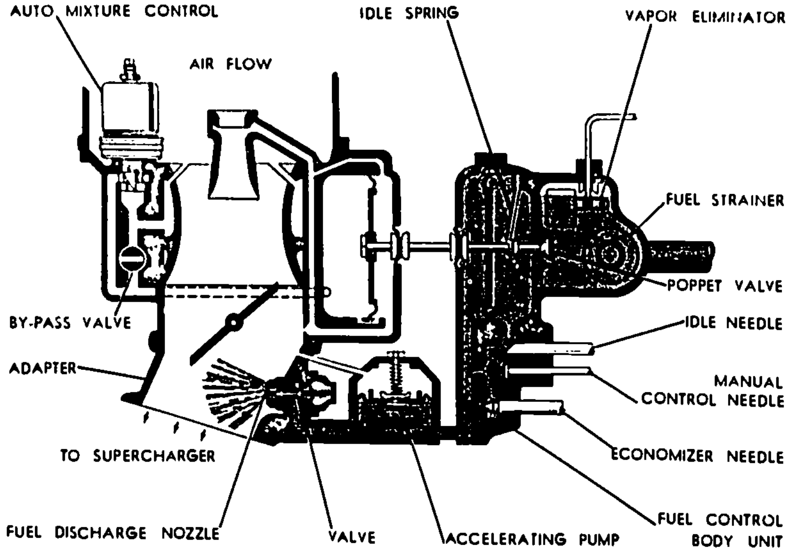


Figure 19. The Pressure Injection Carburetor.

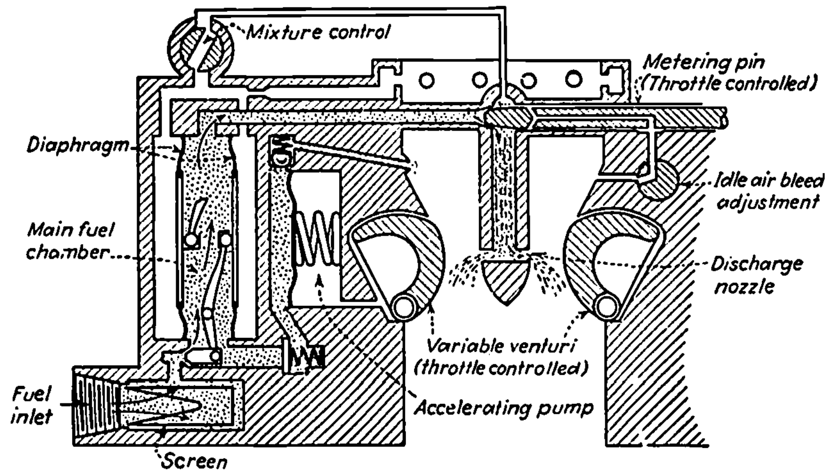


Figure 20. The Diaphragm Carburetor.

Diaphragm carburetor.—In the variable venturi, or diaphragm, type of carburetor, the throttle valve is replaced by two moveable knobs located at the entrance to the venturi (Fig. 20). The knobs are rotated by action of the throttle control and regulate the flow of air by opening or closing the venturi. As the air flow is changed, a variable fuel metering jet supplies fuel in the proper amounts to maintain the best air-fuel ratio.

The fuel supply chamber in this carburetor remains full at all times through the action of a pair of diaphragms set into the chamber. The diaphragms are connected by a spring whose action tends to pull them together. Levers connected to the diaphragms control the opening of the inlet valve between the fuel supply and the fuel chamber of the carburetor.

As the fuel enters the chamber through this inlet valve, its force pushes the diaphragms apart. As the diaphragms move apart, the lever connection moves to close the fuel inlet valve. As the fuel is forced out the top of the fuel chamber into the carburetor, the remaining force on the diaphragms lessens, the spring pulls them back together, and the lever connection opens the fuel inlet valve. The cycle then starts anew.

Diaphragm carburetors are practically non-icing, since they have no throttle valve. They are unaffected by airplane maneuvers, since the pressure of the diaphragms is sufficient to force fuel into the carburetor at any aircraft attitude.

FUEL INJECTION SYSTEMS

Some aircraft use a fuel injection system to perform the functions of the carburetor. This system replaces the carburetor by having the fuel sprayed, under pressure, directly into the intake manifold above the intake valve of the cylinder. The fuel is pumped into the manifold by a plunger-cylinder arrangement, operating through a gear and cam connection with the main camshaft.

The fuel injection system completely eliminates icing hazards, since the temperature in the intake manifold, where vaporization takes place, is normally quite high. It also reduces fire hazards, functions well at any aircraft attitude, and is said to deliver more power from each unit of fuel.

The fuel injection system becomes quite complicated, however, when used in reciprocating engines with many cylinders. A major problem is the design and the synchronization of the spraying action with the intake cycle of the cylinder.

The fuel injection system is well fitted to jet engine operation, as we presently will see.

IGNITION SYSTEM

We have seen how the fuel travels from the tanks, through the carburetor and into the manifold and into the combustion chamber. But before the fuel-air mixture in the combustion chamber (the cylinder) can supply the aircraft with power, it must be ignited. As we have seen, the force of an engine comes from the expansion of gases after the fuel mixture is set on fire.

This ignition of the fuel in the cylinder is brought about through the use of electricity. The fuel is set off by a spark from the spark plug. The origin of that spark is the magneto.

The magneto is a kind of generator. It produces the electricity by whirling a set of magnets around between two conductor poles. To help to understand how this works, let us review some essential facts about electricity.

1. A magnetic field, composed of magnetic lines of force, surrounds any magnet.

2. An electric current flowing through a conductor sets up a magnetic field around that conductor.

3. Magnetic lines of force, or lines of flux, take the path of least resistance through a conductor.

4. When a conductor of electricity is moved through a magnetic field, an electric current will flow through the conductor.

5. When a magnetic field is moved around a conductor, the effect is the same as when a conductor is moved through the magnetic field.

A magneto is an electric generator which makes use of these principles. It produces electrical current by rotating a set of magnets between two metal pole shoes. The pole shoes are joined together by a core, which is wound with two sets of wire coils to increase the voltage of the current.

An important point to remember is that no electric current is induced in the coils unless the magnets, or the coils, are moving. The most commonly used magneto in today's aircraft is the type in which the magnets move.

The rotating magnet part of the magneto may consist of four, six, or eight magnets, arranged in a circular pattern on the end of a bar. The other end of the bar connects to the engine's crankshaft through a gear arrangement. The turning of the crankshaft turns the magnets. The purpose of the pole shoes and the core which connects them is to collect and direct the magnetic lines of flux of the

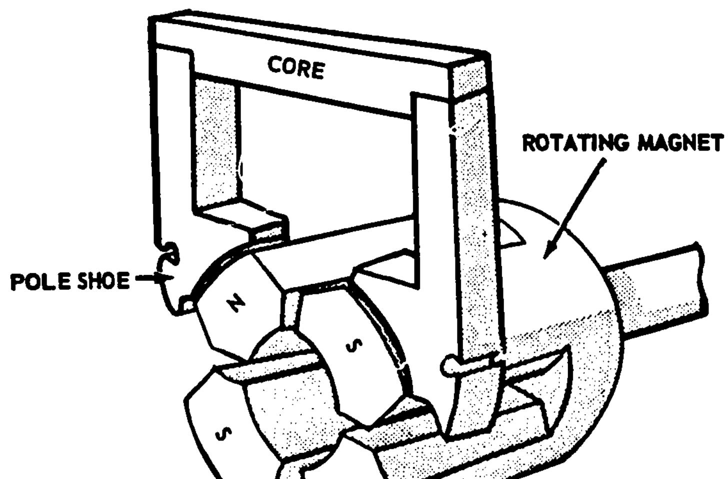


Figure 21. Magneto's Movable Magnets, with Pole Shoes and Core.

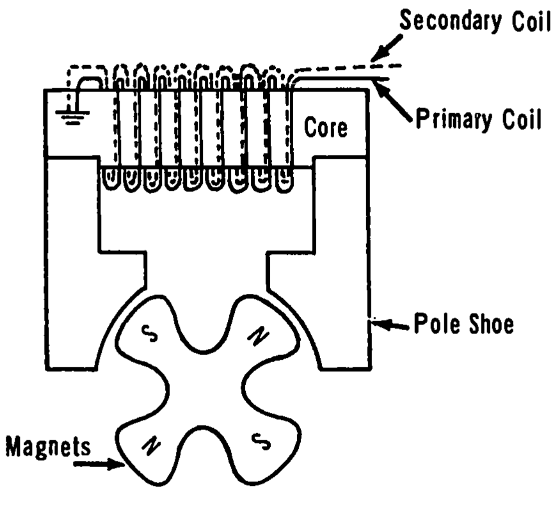


Figure 22. Primary and Secondary Coils Increase Electrical Current.

whirling magnets (Fig. 21). The shoes and core are made of soft metal, which is a better conductor than is air. So, since the lines of flux always flow along the path of least resistance, they flow through the shoes and core instead of through the air.

As the magnets turn between the shoes, the electric current runs through the shoes and core. Around the core are wound two sets of coils, the primary and the secondary coils. The coils are made of a material which is an even better conductor than the metal of the core. Because of this, the current drains off the core and through the primary coil, which is directly attached to the core.

The primary coil transfers the current through breaker points to the secondary coil, which multiplies the current's voltage (Fig. 22). The amount of voltage induced in the coils depends in great part on the number of turns of wire in the coil. For instance, a primary coil of 50 turns of wire may produce 12 volts. The secondary coil of 500 turns of wire will then produce 120 volts. (The primary coil always has comparatively few turns while the secondary coil has many.) Since the magneto produces about 22,000 volts—the voltage necessary to fire the spark plugs at the proper time—you can see that the secondary coil will consist of many thousands of turns of wire.

The current in the secondary coil cannot build up unless the current in the primary coil is either increasing or decreasing. The faster this increase or decrease takes place, the stronger the voltage will be in the secondary coil. For this reason, an instantaneous collapse of the current in the primary coil is desirable. An automatic switch device, called breaker points, brings this collapse about. At the moment when the current in the primary coil is greatest, the breaker points open and the current collapses.

But every electrical current resists any change in its intensity—whether increase or decrease. This resistance, called self-induction, is similar to the inertia effect in a solid object.

Self-induction prevents the current from building up quickly and from collapsing instantly. When the breaker points open, self-induction will cause an electrical arc to jump between the points. If left unchecked, this arcing could cause burning and pitting of the points. To correct this situation, a condenser is used.

A *condenser* is an electrical device which can store electrical energy for later discharge. It is connected in a parallel circuit with the breaker points and it intercepts the electrical arc (Fig. 23). The instant collapse is accomplished, the condenser stores the intercepted charge momentarily, then discharges it back into the primary coil. This reverses the flow of current and helps with rapid buildup of the current in the primary coil.

From the secondary coil, the current goes into the distributor; from there to a harness of cables; and from the cables to the spark plugs (Fig. 24).

The distributor is the device which passes out the electrical current to the spark plugs in the proper firing sequence. This is done

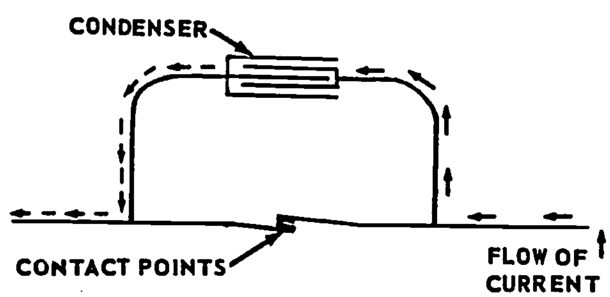


Figure 23. The Condenser Collapses the Current.

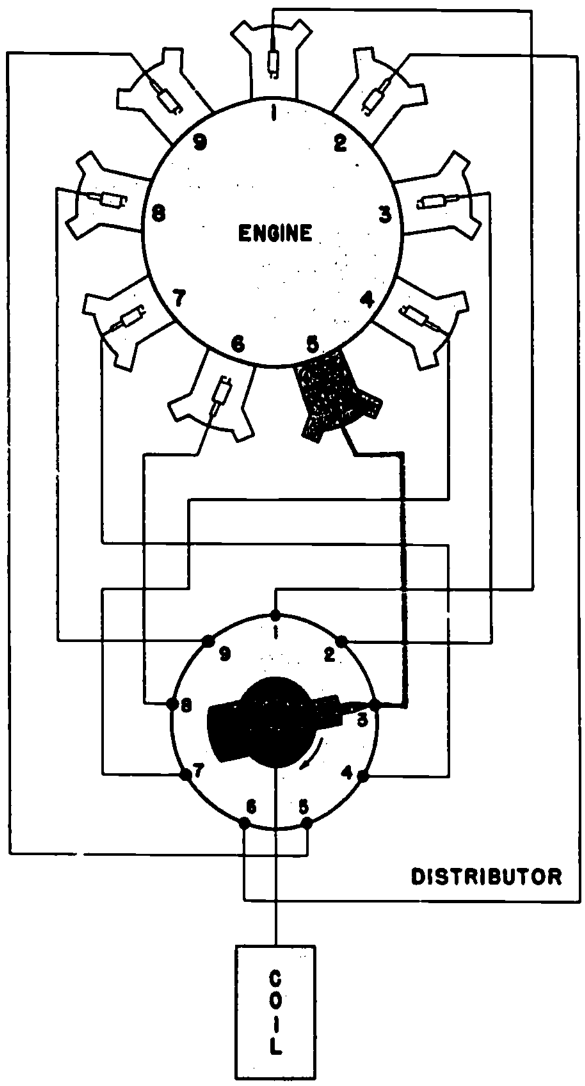


Figure 24. The Current's Route to the Spark Plugs.

through a revolving contact point in the distributor, which passes over a circle of stationary contact points. There is one stationary contact point for each engine cylinder. As the revolving point passes over the stationary point, the electrical current feeds into the spark plug.

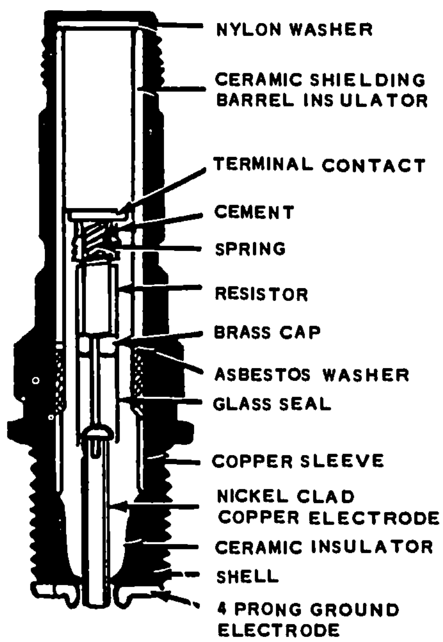


Figure 25. Cut-away of Spark Plug.

The spark plug is a high tension conductor which feeds the electrical current into the cylinder (Fig. 25). On its bottom end, the plug has two electrodes separated by a gap. The electrical impulse jumps the gap between the two points when the voltage mounts high enough to break down the resistance of the gases in the air in the gap. When the spark jumps, the fuel mixture ignites.

Most of the heavy aircraft in use today have double ignition systems. In some of the big double-row radial engines, one ignition system serves the front row of cylinders and the other the back row. In some cases, both ignition systems connect to all the cylinders to produce faster and more efficient burning of the fuel. The double ignition system also is a safety factor.

Starting Systems

We have seen that the magneto furnishes the spark; the spark ignites the fuel; the fuel explosion pushes down the piston; the piston drives the crankshaft; and the crankshaft turns the magneto (in addition to its other duties) to keep the electrical current flowing.

But we must have some way to start the whole process before the engine can take over its own operation.

Most modern aircraft are equipped with small electric motors which operate the starting mechanism. The electric motors take their power from batteries or from gasoline-powered generators called *starting units*. The mechanical energy of the electric motor can be applied either directly or indirectly.

In the indirect application—called inertia starting—the electric motor turns a flywheel, which builds up speed enough to activate the clutch. The clutch engages the crankshaft and starts it turning, and the crankshaft then operates the magneto. This same system is used where the propeller must be turned by hand, or where a smaller hand crank is used, to start the engine.

Direct electrical starting is most widely used, however. This system makes use of an electromagnet, called a solenoid. Electric power from the battery activates the solenoid, which pours current through a booster coil. The booster coil provides a shower of sparks to the spark plugs until the magneto begins to operate. The solenoid-booster coil system is made of very tough material so that it can withstand, for the brief periods of time necessary, the strong current required to start the engine.

The pilot can stop the engine by means of the ignition switch. The switch is connected across the breaker points in the two coils, or it may be parallel to them in the same manner as the condenser. When the switch is turned to the "off" position, it connects the breaker points, stops the current variations in the primary and secondary coils, and thus stops the magneto.

THE LUBRICATION SYSTEM

The engine systems we have discussed so far are all directly concerned with supplying power. The fuel system delivers fuel to the carburetor; the carburetor mixes it with air and passes it to the cylinder; there, the ignition system sparks the fuel, releasing its energy; the mechanical system converts that energy into motion, to turn the propeller.

But one essential system is not directly concerned with producing power, and that is the lubrication system. The lubrication system's job is to control heat so that the engine parts are allowed to move freely. In a way, the lubrication system and the cooling system are complementary—they are both concerned with heat control—but the emphasis of the systems is different. Whereas the cooling system is concerned with the overabundance of heat energy produced by the burning fuel in the cylinder, the lubrication system is most concerned with another kind of heat, that produced by friction.

The main purpose of the lubricating system is to prevent metal-to-metal contact between the moving parts of the engine. If this contact were permitted, the result would be excessive heat, produced by friction. The friction heat would cause the parts to expand, bringing about loss of power, rapid wear on the metal surfaces, and perhaps even temperatures high enough to melt the parts. Speaking in medical terms, if the engine were a person and the friction heat a disease, oil from the lubricating system would be preventive medicine—medicine which stops the disease before it develops.

The oil also has other functions. It provides a seal between the piston and the wall of the cylinder, which halts any gases that might otherwise escape past the piston and into the crankcase. It prevents corrosion. It helps to cool the engine. And it is the fluid that operates the many hydraulic devices in the modern aircraft.

But the prevention of excessive friction heat is the most important job of the lubrication system. This is done simply by putting a thin layer of oil between the moving metal parts. When this layer is in place, the high friction that would result from metal-to-metal contact is replaced by low friction in the oil film.

Oil Properties

The oil must be heavy enough that it will not be squeezed out from between the metal parts and light enough that it will not give too much resistance to the movement of the metal parts.

Lubricating oil, like gasoline, is composed of hydrocarbons and is refined from petroleum. In fact, the oil is taken from the part of the petroleum that is left over after the gasoline and kerosene are distilled out.

Engine manufacturers list certain specifications for the oil to be used to lubricate their engines. These specifications include information on viscosity, flash point, pour point, and other factors.

Viscosity is the relative heaviness of the oil and is used as the measure of the oil's ability to be pumped through the engine at certain temperatures. A heavy-bodied oil is said to have high viscosity, while a light-weight oil is said to have low viscosity.

The flash point is the temperature at which the oil will give off flammable vapors that will catch fire. The pour point is the lowest temperature at which an oil will flow. Now that we are familiar with the properties of the lubricating oil, let us see how it is put to work in the aircraft.

Aircraft lubrication systems use pressure pumps to force the oil through passages and into the many parts of the engine which need lubrication. Some parts of the engine, such as the cylinder walls, the piston pins, and some of the ball bearings and roller bearings, get their oil by splash or spray.

The oil system consists of an oil storage tank, an oil pump, oil lines, a sump (collection place), a scavenger pump, filters, and a radiator. The oil is pumped out of the storage tank and into the engine parts through the lines. Leaving the engine parts, the oil goes into the sump.

The scavenger pump forces the oil out of the sump and through the filter, which screens out any dirt, sludge (a gummy residue deposited by burning oil), and metal particles the oil may have picked up on its trip through the engine.

From the filter, the oil passes through a radiator for cooling. This radiator operates in the same way as does the radiator to the cooling system in liquid-cooled engines. Passing air carries off excess heat collected by the oil on its trip through the engine. From the radiator, the oil is pumped back to the storage tank.

In some small in-line engines, the engine crankcase itself may carry the oil supply. This is called the wet sump system. In the wet sump engine, no scavenger pump is needed because the oil drains to the bottom of the engine crankcase by gravity after it goes through the engine. The crankcase thus acts as both storage tank and sump.

On the larger, more powerful in-line engines and on all radial engines, the oil storage tank is located outside the engine. This is called the dry sump system.

If the oil storage tank is very large, as on some of the big aircraft powered by radial engines, the oil coming back from the scavenger pump flows into a small hopper tank. The hopper tank is located inside the storage tank.

Oil is pumped directly from the hopper tank back into the engine. When the oil level in the hopper tank falls below the level of the oil in the main tank, more oil pours into the hopper tank from the main supply. The chief advantage of the hopper tank is that it provides a quicker engine warm-up.

Most of the big multi-engine planes have a separate oil system for each engine.

PROPELLERS

We have now learned something about all of the different divisions of the engine, and how all of these systems work together to produce power efficiently. But remember, the whole purpose of the engine is to provide power to turn the aircraft's propeller or propellers.

Without the propeller, an aircraft with the world's greatest reciprocating engine would just sit on the runway and burn fuel. On

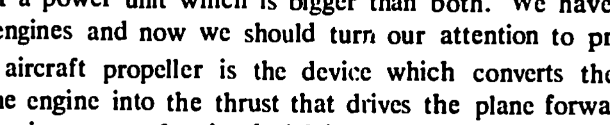


Figure 26. Propeller Sections show Airfoil Shape.

the other hand, the world's greatest propeller could not run for very long on rubber bands: the point is that engine and propeller are parts of a power unit which is bigger than both. We have learned about engines and now we should turn our attention to propellers.

The aircraft propeller is the device which converts the energy from the engine into the thrust that drives the plane forward. The propeller is a type of twisted airfoil, similar in shape and function to the wing of the airplane.

We can see this similarity in shape by examining the propeller in small sections of the whole blade (Fig. 26). Each section has the shape of a section of wing; but the camber and chord of each individual propeller blade section will be different from the camber and chord of every other section. Moreover, while the wing of an aircraft has only one motion—forward—the propeller blade has two motions—forward and rotary.

The propeller produces the thrust to drive the aircraft forward; and this forward motion sets up the reaction between air and wing to produce lift on the wing.

The principle used in propeller operation is Newton's Third Law of Motion, which states that for every action, there is an equal and opposite reaction. In the case of the propeller, the "action" is the forcing of large quantities of air to the rear. The "reaction" is the forward motion, the thrust, of the plane. Additionally, when the propeller starts rotating, air flows around its blades, just as air flows around the wing of a plane in flight. But where the wing is lifted upward by the force of the air (Bernoulli's Principle), the propeller is "lifted" forward, and pulls the aircraft with it.

The engine furnishes the propeller with power. In small engines, the propeller may be attached directly to the crankshaft. In the larger engines, however, the crankshaft turns too fast for good propeller efficiency. In this case, the propeller is attached to the crankshaft indirectly, through a set of gears. The gears reduce the propeller's rotation rate below that of the crankshaft but allow the propeller to turn fast enough to make good use of the available engine power. (Generally speaking, propellers lose efficiency very quickly if they rotate at more than 2,000 revolutions per minute.)

Propeller parts.—The propeller blade has a leading edge and a trailing edge, just as a wing does (Fig. 27). The leading edge is the

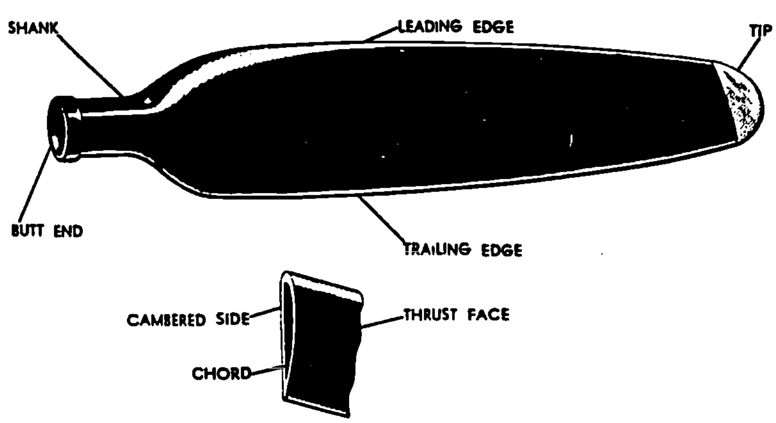


Figure 27. The Propeller Blade's Elements.

fatter edge, and heads into the air. The trailing edge is the thinner edge. The blade back is the curved portion of the propeller blade, and corresponds to the top of the wing. The blade face is comparatively flat and corresponds to the bottom of the wing.

The hub is the metal unit used to attach the propeller to the crankshaft (directly or indirectly). The part of the propeller which joins the hub is called the blade butt, or shank. The butt is thick for strength, is usually cylindrical in shape, and contributes very little to the propeller's thrust. The outermost end of the blade is called the blade tip.

Motion and angles.—The propeller turns in an arc perpendicular to the crankshaft. This arc is called the plane of rotation. The blade angle is the angle between the face of a particular section of

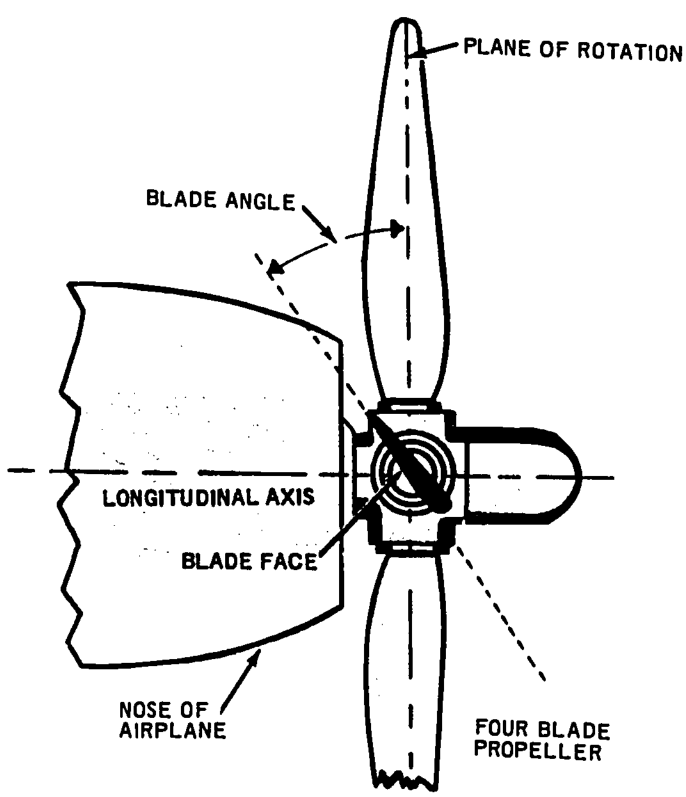


Figure 28. Plane of Rotation and Blade Angle, or "Pitch."

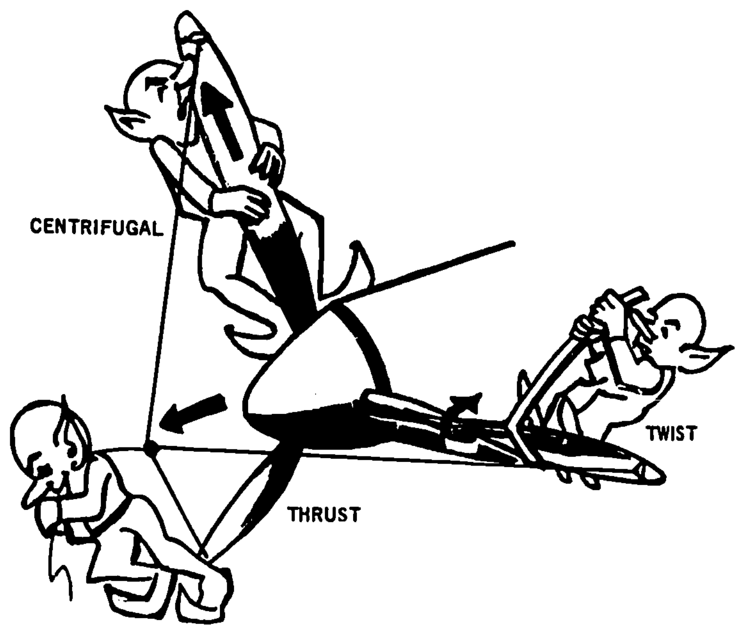


Figure 29. Forces Acting on the Propeller.

the blade and the plane of rotation. The blade's angle of attack is the angle between the face of the blade section and the direction of the relative air stream. This corresponds to the angle of attack in the wing. The actual distance that the propeller moves forward in one revolution is called the effective pitch (Fig. 28).

The terms "pitch" and "blade angle" do not strictly mean the same thing. But the terms are closely related, so much so that they are often used interchangeably. Thus, a propeller with a small blade angle would be said to have "low pitch," while a propeller with a large blade angle would be called a "high pitch" propeller. A high pitch propeller will move an aircraft farther forward during one revolution than will a low pitch propeller.

Propeller force.—Three forces act on a propeller in flight. They are thrust, centrifugal force, and torsion (Fig. 29).

The propeller produces thrust by moving volumes of air toward the back of the plane. This thrust compares with the lift force exerted on the wing by the movement of air. But in the case of the propeller, the lifting force acts forward instead of upward. As the propeller is "lifted" forward, the thrust force pulling on the blades tends to bend the blades forward. Forces tending to bend the blades backward, caused by air drag, are small enough to be ignored.

Centrifugal force is created by the rotation of the propeller. Centrifugal force (the force which tends to throw a rotating body outward from the center of rotation) exerts a constant pull on the blades of the propeller. This force causes tensile stresses (strain on the material of which the blades are made). The hub of the propeller resists the tendency of centrifugal force by holding the blades in at the center. These conflicting forces may stretch the blades slightly during flight.

The torsional force is the force tending to twist the propeller blade along its axis and straighten it out. Torsion is caused in part by the action of the air on the blades and in part by the action of centrifugal force, which tends to turn the blades to a lower angle. The action of the air on the blade is called the "aerodynamic twisting moment" and the torsional action of centrifugal force is called the "centrifugal twisting moment."

Propeller types.—There are four types of propellers, the fixed pitch, the adjustable pitch, the controllable pitch, and the constant speed propeller.

The *fixed pitch* propeller is the simplest of the lot. It is made in one piece, and the blade angle cannot be changed without bending or reworking the blades. This propeller is used on small, single-engine planes.

The *adjustable pitch* propeller usually has a split hub. This makes it possible for the ground crew to adjust the blade while the aircraft is on the ground and the engine is turned off. The propeller blades may be turned to such an angle that they will serve a particular purpose (either to provide more speed or more power). But the operation of the adjustable pitch propeller in flight is the same as that of the fixed pitch propeller.

The *controllable pitch* propeller is so constructed that the pilot may change the blade angle while the aircraft is in flight. This function may be compared to shifting gears in an automobile. For instance, the blades may be set at a low angle for power during take-off and climbing, then turned to a higher angle for speed at cruising altitudes. The changing mechanism may be operated mechanically, electrically, or hydraulically.

The *constant speed* propeller adjusts itself automatically according to the amount of power it gets from the engine. The engine controls are set to the desired rpm rate of the crankshaft, and to the desired manifold pressure rate. A flyweight arrangement (a governor) and a hydraulic control keep the propeller's blades at the angle needed to maintain the desired engine speed, whether the plane is climbing, diving, or in level flight. The governor is sensitive to changes in the crankshaft rpm rate. If the rpm rate increases (in a dive, for instance) the governor-hydraulic system changes the blade pitch to a higher angle. This acts as a brake on the crankshaft. If the rpm rate decreases (in a climb), the blade pitch is changed to a lower angle and the crankshaft rpm rate can increase. The constant speed propeller thus insures that the propeller blades are always set at their most efficient operating angle.

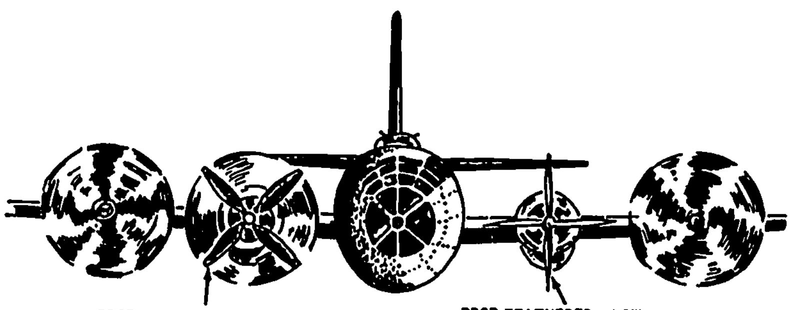


Figure 30. Feathered and Unfeathered Propellers.

Feathering.—The propellers on most modern planes with more than one engine also have a "feathering" capability. The term "feathering" refers to the operation in which the propeller's blades are turned to an angle in line with the line of flight. The propeller is feathered in case of engine failure. When the blades are turned to a position where they are streamlined with the line of flight, the pressure of the air on the face and the back of the blade is equal and the blade stops turning.

If the propeller is not being driven by the engine and is not feathered, it will "windmill," or rotate from the force of the air pressure. This windmilling can damage the engine. It also causes more drag on the wing by disturbing the smooth flow of air over the wing. For this reason, the aircraft's working engine-propeller units function more smoothly and efficiently when the propeller on a faulty engine is feathered (Fig. 30).

Reversible pitch.—Most controllable pitch and constant speed propellers also are capable of being reversed. In this process, the pilot rotates the propeller blades until he obtains a negative angle of pitch. This movement, coupled with increased engine power, reverses the propeller's thrust. The air is thus forced forward, away from the aircraft, instead of rearward, over the wings. The reversible thrust feature reduces the required landing run and saves considerably on brakes and tires.

Propeller efficiency.—Airmen have accepted the fact that no propeller will be 100 percent efficient. That is, no propeller can change to thrust all of the energy supplied by the engine through the crankshaft. This is true because some of the work done by the engine is lost to various other forces before it can be transformed into thrust by the propeller.

The maximum efficiency that can be obtained by a conventional propeller operating in ideal conditions and in connection with a conventional engine is about 92 percent. But in order to obtain an efficiency that high, the blades of the propeller at the tip must be very thin and the leading and trailing edges must be very sharp. These conditions have been found to be impractical for normal operation. The most efficient propellers in every day use provide something under 90 percent of full efficiency.

Two forces, thrust and torque, must be considered in rating the efficiency of the propeller. Thrust acts parallel to the axis of rotation of the propeller, while torque operates parallel to the propeller's plane of rotation. Thrust and torque operate perpendicular to each other.

Thrust horsepower (the actual amount of horsepower that a propeller transforms into thrust) is less than the full amount of useful horsepower developed by the engine. Torque horsepower, however, is about the same as the amount of useful horsepower the engine develops. Propeller efficiency is the ratio of thrust horsepower to torque horsepower.

Tip speed.—A major limitation on the use of the reciprocating engine in really high-speed flight is the fact that the speed of the tip of the propeller blade must be kept below the speed of sound.

Generally, the speed of sound is 1,120 feet per second at sea level, decreasing by about 5 feet per second for every 1,000 feet of altitude.

When the tip speed approaches the speed of sound, the propeller develops flutter, or vibration. Vibration causes strains to develop and seriously affects propeller efficiency. A propeller whose tip speed at sea level is 900 feet per second will deliver about 86 percent efficiency. But at 1,200 feet per second, the efficiency has dropped to around 72 percent.

In modern, high-powered engine-and-propeller units, it is necessary to gear down the propeller to keep its tip speed below the speed of sound. Were it not for this limitation, there is no reason why an aircraft powered by reciprocating engines could not surpass the speed of sound.

But science has not yet found a way to get around the propeller's tip speed limitation. To surpass the speed of sound, a different type of engine, loosely called the reaction engine, must be used. The term "reaction engine" includes both jet and rocket engines. Further, there are several different types of jet engines, and several different types of rocket engines.

Jet and rocket development lagged behind the development of reciprocating engines prior to World War II. But since that time, the reaction engine has come into its own, expanding the limits of speed and altitude at which man can move.

Despite the numerical predominance of propeller-driven aircraft today, no modern survey of propulsion systems would be more than half complete without considering the reaction engine.

REVIEW QUESTIONS

1. **Name the five systems that make up the complete reciprocating engine.**
2. **What are the advantages of the petroleum-based fuels used as aviation fuels?**
3. **What is the function of the carburetor?**
4. **Why does the carburetor measure fuel and air by weight instead of by volume?**
5. **What is the function of the supercharger?**
6. **What are the various types and functions of the lubricating system?**
7. **How does the propeller provide thrust and lift to the aircraft?**

8. **Name the parts of the propeller. What is the "plane of rotation?" The "effective pitch?"**

9. **What three forces act on a propeller in flight? Describe these forces.**

10. **Why are propeller-driven aircraft incapable of supersonic flight?**

THINGS TO DO

1. Recent incidents in the Middle East threatened America's supplies of oil from fields in that area. Find out and report on how much oil, gasoline, and other petroleum products are used in this country annually and where our sources of supply are located. Could the United States get along without Middle Eastern oil supplies?

2. Recently, some automobiles have introduced the use of fuel injection in their engine systems. Find out how these engines operate and report to the class. See if any reciprocating aircraft engines are now using the fuel injection system. What developments have made this use possible?

3. Helicopters are known in the military services as "rotary wing aircraft." Do some research on the helicopter and report on it, including comparisons of the helicopter rotors to wings and propellers of conventional aircraft (or "fixed wing" aircraft). Explain the theory behind helicopter flight and discuss its problems with torque, along with how these problems are resolved.

SUGGESTIONS FOR FURTHER READING

CHAPEL, CHARLES E., ed. *Aircraft Power Plants.* New York: McGraw-Hill Book Co., 1948.

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MCKINLEY, JAMES L. and RALPH D. BERT. *Powerplants for Aerospace Vehicles.* New York: McGraw-Hill Book Co., 1965.

VAN DEVENTER, C. N. *An Introduction to General Aeronautics.* Chicago: American Technical Society, 1965.

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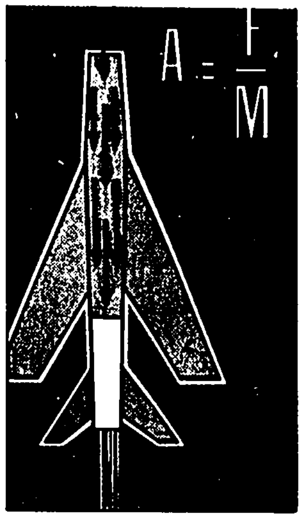
Chapter 4



Reaction Engines

THIS CHAPTER deals with reaction engines, with the emphasis on jet engines. It describes the operation of the jet in theory, gives examples of how the different types of jet engines operate, and exploins the relative advontages of these engines. Rocket engines are considered briefly, since they are the subject of fuller study elsewhere in the Aerospoce Education course. When you finish this chapter, you should be oble to: (1) compore the operation and performonce of the jet and the reciprocoting engine; (2) describe the operotional differences in the three moin types of jet engines; (3) exploin in some detail the operation of the turbojet engine; (4) describe such adaptations as the turbofan and the turboprop engines; ond (5) explain solid and liquid rocket engines and how rocket fuel is rated.

WITH THE ADVENT of jet propulsion as a practical means of powering aircraft, a whole new experience was opened to mankind. The key word in this experience was "speed." Jet-propelled aircraft were eyed with suspicion at first by a public which had become accustomed to seeing propellers on planes. But with exposure came acceptance, and the world was soon electrified to learn that a manned, jet aircraft had flown beyond the speed of sound.

JET ENGINES

Compared to the reciprocating engine and propeller combination, the workings of the jet engine are simple. In broad terms, the jet

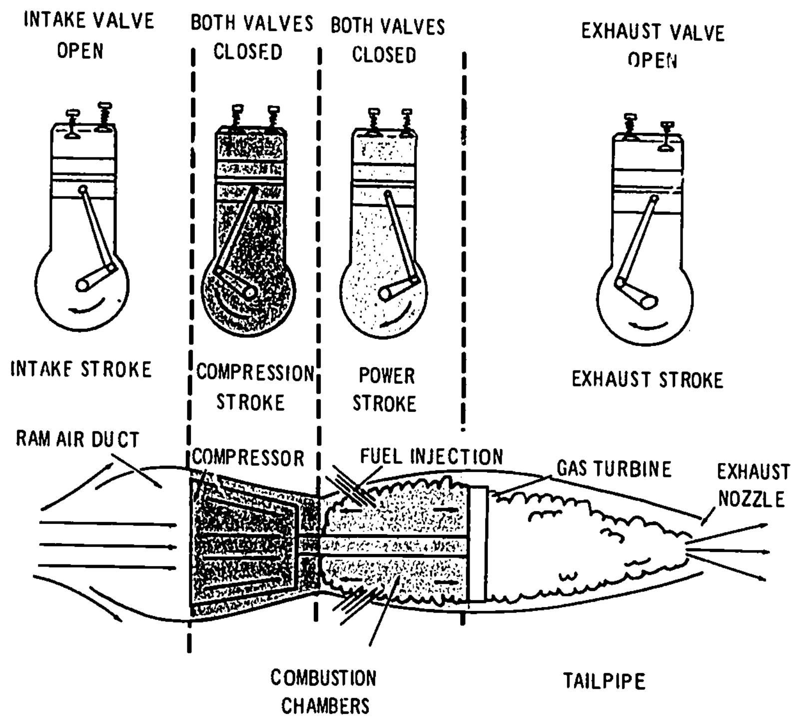


Figure 31. The Jet Engine and the Four-Stroke Cycle.

engine is essentially a tube in which the four-stage combustion cycle takes place. It is composed of an air intake section, a compression section, a combustion section, and an exhaust section (Fig. 31).

Although the two different propulsion systems have much in common when it comes to working principles, they are quite different mechanically. Both the jet and the reciprocating engine have their places in today's aviation, and they are well suited to their different uses.

The chief advantages of the jet-propelled aircraft are speed and the ability to fly at high altitudes. The chief advantage of the reciprocating engine-propeller powered craft is economy at low speeds and at low altitudes.

Both systems get their power from the gases formed by burning fuel. Both depend on the air outside the engine for the oxygen needed to burn the fuel. Both utilize the same basic laws of motion for their "push." Finally both use the four-stage cycle of intake, compression, combustion and exhaust.

But despite these similarities in the two engines, there are two major differences. While the exhaust in the reciprocating engine is mainly wasted, the jet engine's exhaust is the force that makes the aircraft go. And the jet engine has no propeller.

Principles of Operation

The jet engine depends on Newton's second and third laws of motion for its operation. As we noted earlier, Newton's third law states that for every action, a reaction of equal force occurs in the opposite direction; Newton's second law says that force is equal to mass times acceleration.

Probably the most often-used illustration of Newton's third law is the action of a balloon released with its neck open. The balloon zips around the room as air escapes from the open neck. The flight of the balloon is not caused by escaping air pushing against the air outside the balloon, but by the reaction to that escaping air inside the balloon.

The air rushing out of the balloon may be called the action. But inside the balloon, there is a reaction, just as strong, and in an opposite direction to the outrushing air. If our balloon had two necks directly opposite each other, the air would rush out of both openings and the balloon would merely drop to the floor. But since there is only one neck, the balloon moves. This motion is caused by the reacting air pushing against the inside surface of the balloon, in accordance with Newton's Third Law of Motion.

Newton's second law, applied to the jet engine, would mean that the force moving the aircraft (thrust) is equal to the mass (quantity) of air taken in through the front of the engine, multiplied by the acceleration (increase in speed) of that air before it leaves the exhaust nozzle at the back end of the engine.

You can see, then, that the jet engine and the propeller both provide thrust by throwing quantities of air backward. In the jet, the air is channeled through a tube (the engine) of smaller diameter than the unconfined air in the propeller-type aircraft. This means that a smaller mass of air is being moved by the jet engine. But in the jet, the acceleration of the moving air is much higher than the acceleration of air being moved by a propeller. And since

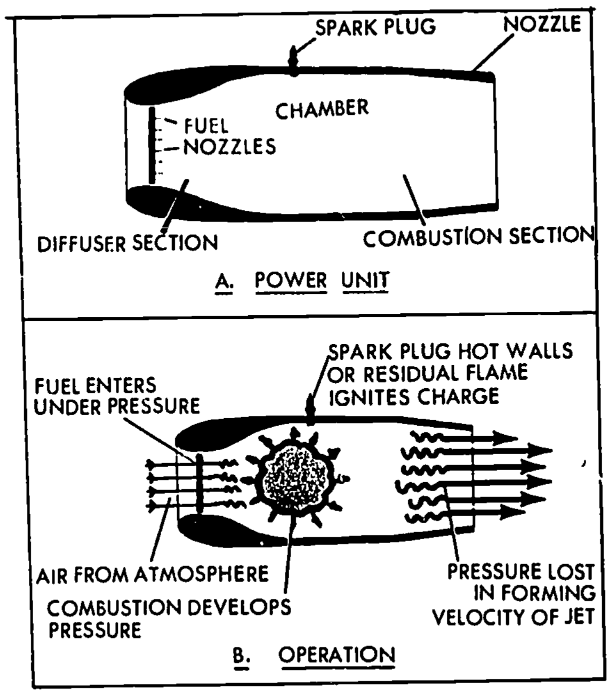


Figure 32. The Ramjet, or "Flying Smokestack."

the velocity (the "action") of the air leaving the jet engine is very strong, so is the thrust (the "reaction"). In this booklet, we will consider past and present jet engine types, including the ramjet, pulsejet, turbojet, turboprop, and turbofan engines.

Ramjet

The simplest type of jet engine is the ramjet. With no moving parts, the ramjet is little more than a tube fitted with fuel nozzles, and spark plugs to get it started. In fact, the ramjet has been described as a "flying smokestack" (Fig. 32).

The air is taken into the ramjet through the diffuser in the air intake section at the front of the tube. The diffuser is designed to decrease the velocity of the incoming air, thereby increasing its pressure. (The total amount of energy in a mass, remember, must remain the same.) This compressed air is channeled into the combustion section, where fuel is sprayed into it under pressure. The spark plugs ignite the mixture.

The resulting explosion hurls the air forcefully out the exhaust, and the reaction to that force moves the engine forward. There is equal force exerted in all directions when the explosion occurs, of course. But the high-pressure air in the diffuser blocks the expansion of the air forward; the walls of the engine and passing air block the expansion outward; and the hot gases are forced out the rear of the engine.

It should be pointed out that in jet engines, the spark plugs are used only to ignite the charge for the first time. The electric current to the plugs is then cut off. The flow of air and fuel into the combustion chamber is continuous, and so is the flame. Thus, the charge feeds itself fire. Instead of a series of fuel-air charges, as in the reciprocating engine, the jet engine has one continuous charge which burns until the flow of air and/or fuel is discontinued.

The fire is held in the combustion chamber by a blocking device called a flameholder. Otherwise, the fire would be blown out the rear of the engine with the exhaust gases and other air.

The ramjet cannot operate until it is moving at sufficient speed to bring about compression from the ramming air in the front of the engine (about 250 miles per hour). Aircraft using the ramjet must have another type of propulsion to get them moving at that speed before the ramjet can be turned on. In theory, the speed attainable by the ramjet is unlimited, since the faster it goes, the more air compression it gets; the more compression it gets, the more violent the explosion in the combustion chamber; and the more violent this explosion, the more thrust is developed and the faster it goes. In practice, however, the ramjet's speed is limited to about five times the speed of sound (mach 5),* which is still a pretty fast clip. This limitation is due to friction-caused heat on the outside of the engine and the aircraft to which it is attached (called skin temperatures). Beyond mach 5, this friction heat would cause the metals now in common use to melt.

* The word "mach" is used to describe the speed of an object in relation to the speed of sound in the same medium. The number accompanying the word "mach" indicates the multiples of the speed of sound at which the object—in our case, the aircraft—is traveling. At speeds below, but approaching, the speed of sound, numerals less than 1 may be used. Thus, an aircraft moving at mach .7 would be traveling at seven-tenths the speed of sound. At mach 1, the aircraft would be moving at exactly the speed of sound. At mach 2.5, the aircraft would be moving at two-and-a-half times the speed of sound. The speed of sound at sea level, in dry air at 32 degrees F, is about 1,087 feet per second (741 miles an hour).

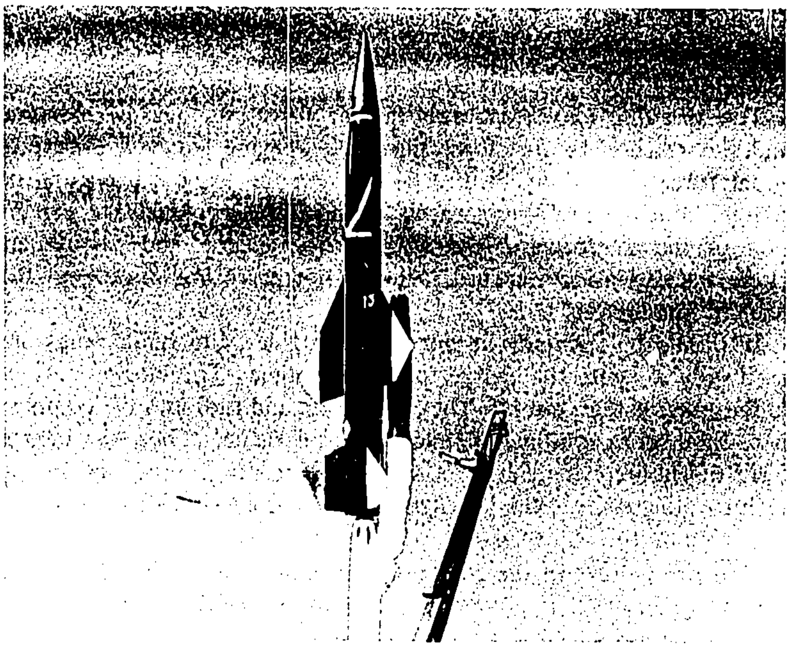


Figure 33. Bomarc Missile Takes Off with Rocket Power, Shifts to Ramjet.

The ramjet engine is used in missiles, which are lifted off the ground by another engine system—usually, a rocket engine. Just before the rocket engine burns out, the ramjet "kicks in" and takes over the job of powering the missile. Some examples of ramjet-powered missiles in use today are the Bomarc surface-to-air interceptor missile and the Redhead/Roadrunner guided target missile (Fig. 33).

A late development in ramjet engines is capable of hypersonic flight; that is, flight at speeds above mach 5. This engine is called the "scramjet," and may be used in the future on aircraft designed to cruise at hypersonic speeds, on recoverable launch vehicles, and on defense missiles.

Pulse Jet

The pulsejet is only slightly more complex than the ramjet, but it is much less useful in modern aviation. It has a diffuser, a grill assembly, a combustion chamber, and a tailpipe. Air feeds through the diffuser, just as in the ramjet, and through the grill to the combustion chamber.

The grill is a honeycomb of air valves which allow the air to flow through if the pressure in the diffuser chamber (intake) is greater than the pressure in the combustion chamber. These air valves are spring-loaded in the closed position and open inward, toward the combustion chamber.

When the air is allowed into the combustion chamber, a fuel charge is injected and the fuel-air charge is ignited. The force of the resulting explosion closes the air valves in the grill and forces the exhaust out the tailpipe. When the pressure of that charge lessens

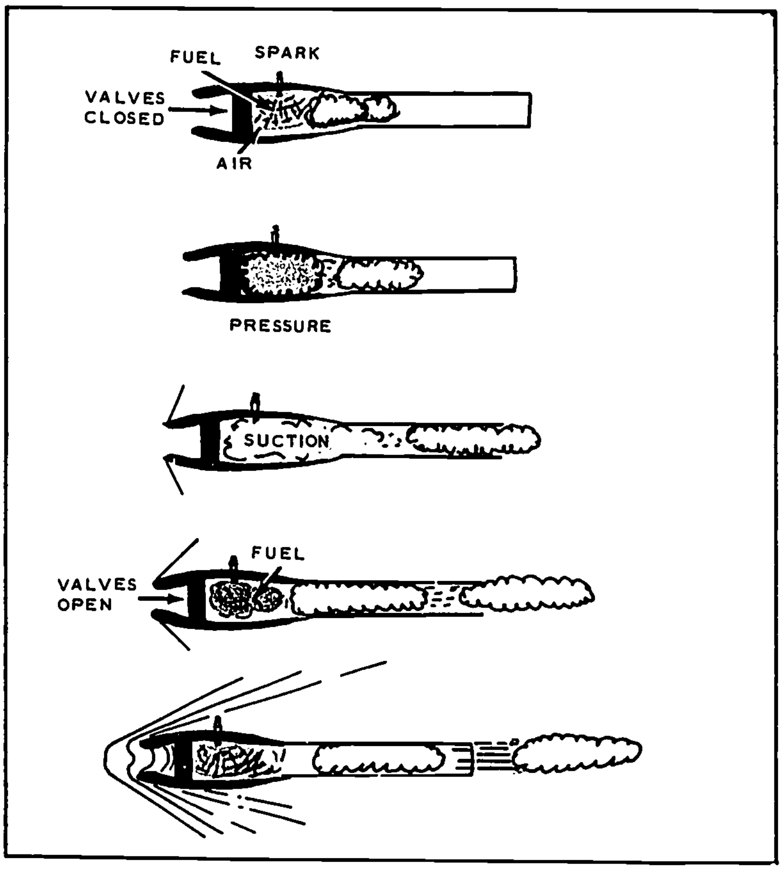


Figure 34. Operating Cycle of the Pulsejet Engine.

in the combustion chamber, the valves open again and more air moves into the combustion chamber. The cycle repeats, with the ignition of the second charge coming from the flame of the first charge, feeding back (Fig. 34).

Pulsejets powered the German V–1 missile in World War II. The characteristic noise produced by the pulse jet was responsible for the V–1's nickname of "buzz bomb."

Although the pulsejet is simple and inexpensive to build, its speed is limited. At air speeds above mach 0.6 (slightly over half the speed of sound), the pressure in the diffuser section holds the air valves open too long for efficient operation. Because it cannot compete effectively against the reciprocating engine on the one hand and more advanced jet engines on the other, the pulsejet has nearly vanished from the aviation scene.

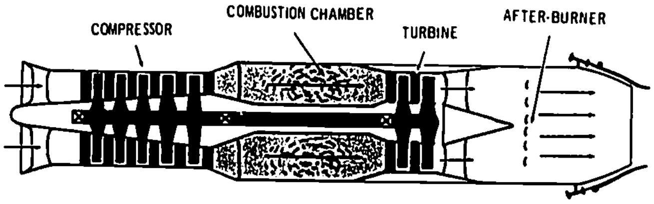


Figure 35. Turbojet Engine, with Afterburner in Exhaust Section.

The Turbojet

The turbojet engine, the most widely used engine in the jet world today, uses the same principles used by the ramjet and the pulse-jet, but is a much more refined and practical machine.

Employing the combination of gas turbine and air compressor, the turbojet is its own master. It can start from a dead stop and can power aircraft to more than twice the speed of sound.

There are many models and several modifications of the turbojet engine, but they all share the same basic operational sequence: air enters through the air intake section (diffuser); goes through the mechanical compressor, where its pressure is greatly increased; is forced into the combustion chambers, mixed with fuel, and burned; and escapes as high-velocity gases out the exhaust nozzle, producing thrust (Fig. 35).

Between the combustion chambers and the exhaust nozzle, there is a turbine. The exhaust gases turn the turbine wheel just as wind turns the wheel of a windmill. The turbine is connected by a direct shaft to the compressor. The rotation of the turbine operates the compressor, which sends more air through the engine to turn the turbine.

The compressor section of the turbojet is the area where the air is compacted in preparation for burning. It corresponds to the reciprocating engine's cylinder in the compression stage. Turbojet engines are generally classified as centrifugal flow or axial flow engines. These terms refer to the design of the air compressor in the engine, and the way the air flows through it.

Centrifugal flow engines.—The centrifugal flow compressor is composed of a rotor, a stator, and a casing. The rotor is mounted within the stator, and that whole assembly is enclosed in the casing.

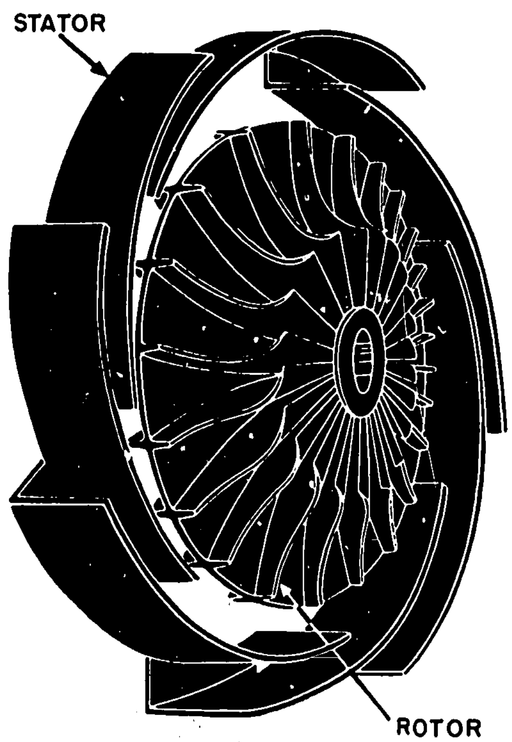


Figure 36. Centrifugal Compressor, Without Casing.

The casing has an opening near the center for the air to enter (Fig. 36).

The rotor is made up of a series of flat blades. The blades revolve, take the air in, and whirl it around, increasing its velocity. Centrifugal force causes the air to move outward from the center to the rim of the rotor blades, where it is thrown out of the wheel and into the stator with considerable velocity.

The stator consists of diffuser vanes, or blades, which curl out from the central axis of the rotor. The stator does not rotate. The moving air acquires energy, in the form of velocity, in the rotor. This energy is converted to pressure energy by the stator. As the air moves through the stator's diffuser vanes, it loses velocity and acquires pressure (since the total energy of velocity and pressure must remain the same).

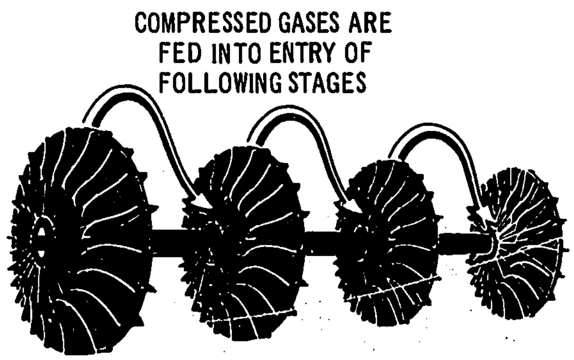


Figure 37. Multi-stage Compressor gets more Air Compression.

From the stators, the compressed air is fed into the combustion chambers.

Each set of rotors and stators is called a stage. A single stage centrifugal flow compressor will produce a compression ratio of about four to one. That is, it will reduce a given mass of air to about one-fourth the volume it had in its free state.

Additional stages will improve the compression ratio somewhat (Fig. 37). But much of the potential energy of the air mass in the centrifugal flow compressor is lost through drastic changes in direction caused by centrifugal force. For this reason, most jet engines made today employ the more efficient axial flow compressor.

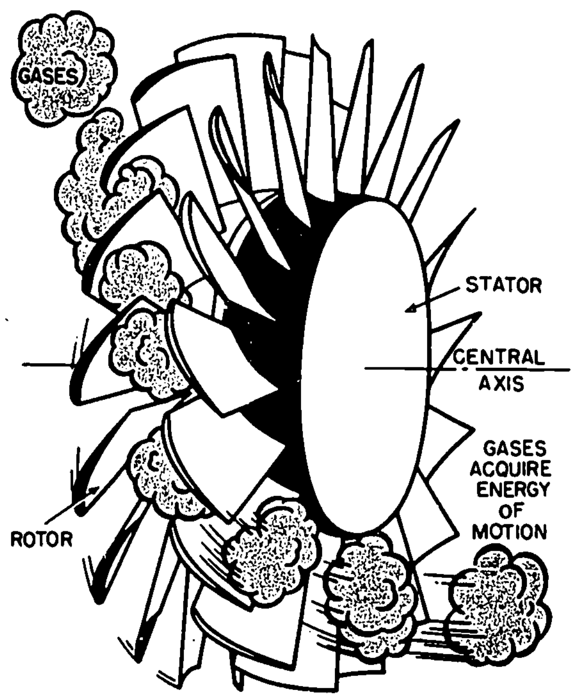


Figure 38. Single Stage Operation of the Axial Compressor.

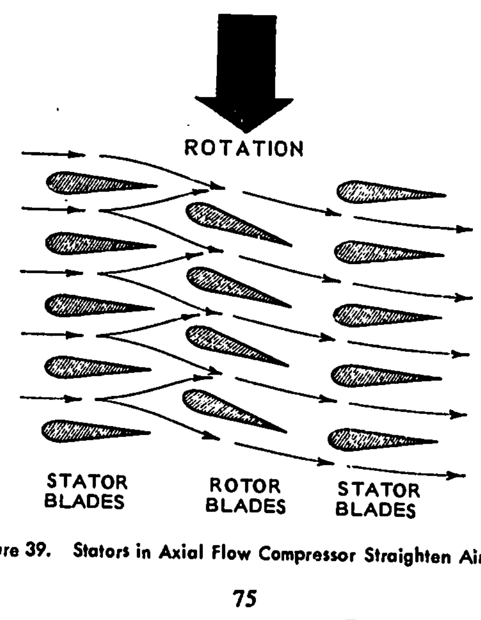


Figure 39. Stators in Axial Flow Compressor Straighten Airflow.

Axial flow engines.—The axial flow compressor is also made up of rotors and stators. But the blades are shaped like airfoils instead of being flat. The rotor may be likened to a many-bladed propeller. Because of the airfoil shape of the rotor blades, the air mass moves toward the rear of the engine, and only slightly outward (Fig. 38).

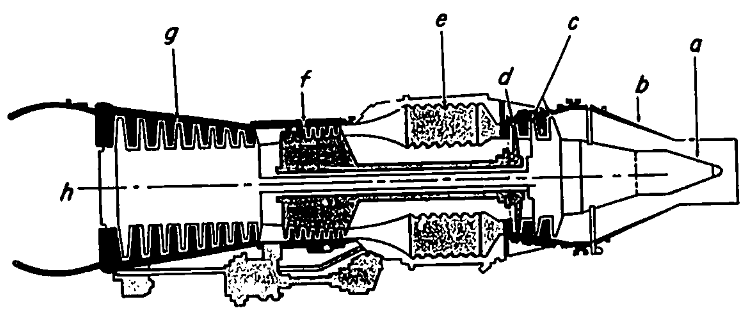
The stators, also of the airfoil design, are mounted behind the rotors. The stators may be likened to many small wings. They do not rotate, but receive the air from the rotors and direct it either toward the combustion chambers or onto the next set of rotors.

One row of rotors and one row of stators constitutes a stage in the axial flow compressor. The motion of the rotors creates pressure in a manner similar to the ram effect, and the stators serve to straighten out the flow (Fig. 39).

The axial flow compressor may be composed of many stages. Each stage is smaller than the one before it, which increases the compression of the air. Axial flow compressors give compression ratios of more than 5 to 1.

Split compressors.—Some turbojet engines have dual compressor and turbine arrangements, called split compressors. The split compressor provides greater engine flexibility and maintains high compression ratios at high altitudes, where the ram air pressure is less.

This dual arrangement consists of a high-pressure compressor driven by a turbine that is controlled by the throttle; and a low-pressure compressor driven by a free-turning turbine (Fig. 40). Split compressors can develop compression ratios of up to 14 to 1.



A. EXHAUST CONE
B. TAILPIPE
C. SECOND AND THIRD-STAGE TURBINES
D. FIRST-STAGE TURBINE
E. BURNER CAN
F. HIGH-PRESSURE (N_2) COMPRESSOR
G. LOW-PRESSURE (N_1) COMPRESSOR
H. INLET DUCT

Figure 40. Turbojet Engine with Split Compressor.

At high altitudes, the air is thin and the ram pressure in the front of the engine is therefore reduced. But a free-turning compressor takes advantage of the thin air's lesser resistance on its rotor blades, and turns faster, bringing in greater volumes of air. This arrangement enables the free compressor to keep the high-pressure compressor supplied with air.

The split compressor illustrates how theory and practice do not always agree. In theory, a single axial flow compressor with many stages could develop an unlimited amount of compression. But in practice, this is true only at a certain engine speed. At other speeds, the smaller stages toward the rear of the compressor lose efficiency because they cannot handle the large volumes of air being supplied by the larger stages toward the front. As a result, the front sections become overloaded and turbulence results. This turbulence interferes with the effective angle of attack of the airfoil-shaped rotors and stators, and the result is compressor stall.

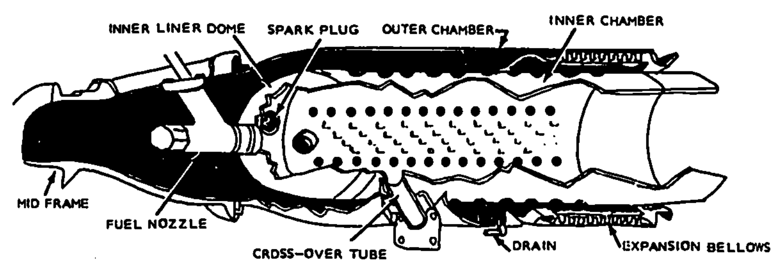


Figure 41. Jet Engine Combustion Chamber.

With the split compressor, the rearmost stages are large enough to handle the larger volumes of air without loss of efficiency.

Combustion chambers.—On leaving the compressor, the air is forced into the combustion chambers, mixed with the fuel, and burned in the continuous combustion process. Jet engines can operate on a wide variety of fuels, but refined kerosene has been found to be the most satisfactory fuel available so far.

Only about one-fourth of the air from the compressors is used for combustion. The rest of the air is channeled around the outside of the combustion chambers, or around the fire inside the combustion chambers, for cooling purposes.

Ordinary turbojet engines may have 14 separate combustion chambers in their combustion section, divided so that the cooling air can be more effective.

The combustion chamber includes an inner chamber, where the actual burning takes place; an outer chamber; a fuel nozzle; and crossover tubes (Fig. 41).

Temperatures in the inner chamber get above 3,000 degrees Fahrenheit. But these temperatures never reach the wall of the inner chamber. The burning is centered in the chamber through careful design, and is surrounded by a blanket of air that is, of course, heated, but does not burn. All of the burning must be completed before the exhaust leaves the inner chamber, because the intense heat of the burning charge could severely damage the turbine wheel.

Air flows through the liner between the inner and outer chambers. The outer chamber keeps a supply of high-pressure air available to the inner chamber for cooling.

The fuel nozzle sprays the proper amount of fuel into the inner chamber, using the fuel injection system. The fuel spray is under pressure at about 700 pounds per square inch, and the fuel flow is regulated to achieve an air-fuel ratio of about 14 to 1.

Usually, only two spark plugs serve the entire combustion system, and then only for the initial ignition. After the engine is started and the spark plugs have ignited the fuel-air mixture, the plugs are turned off.

The crossover tubes connecting the combustion chambers feed the initial flame into those chambers without spark plugs. After the flame is introduced into all the chambers, the burning process feeds itself. The high-pressure air blanket then blocks off the openings in the crossover tubes before temperatures mount very high.

Turbine section.—The hot exhaust gases and unburned air leave the combustion section through a nozzle diaphragm, which increases their velocity to about 2,000 feet per second and directs them onto the turbine wheel blades.

The turbine wheel is the toughest part of the jet engine. It has to be, to withstand the tremendous temperatures and other stresses on it.

The temperature of the gases striking the turbine wheel blades may reach 1,500° F., and the wheel rotates at about 1,200 revolutions per minute. These stresses were a serious problem to early

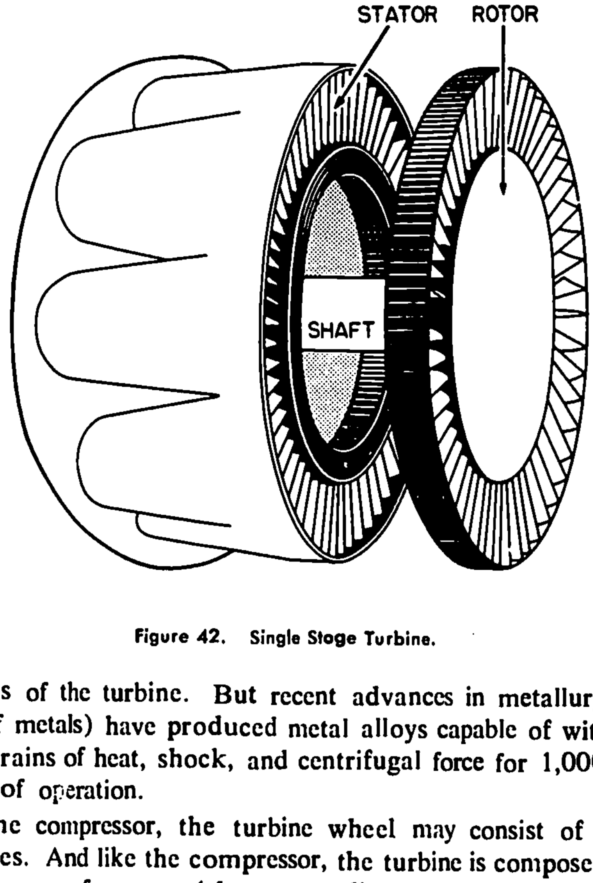


Figure 42. Single Stage Turbine.

developers of the turbine. But recent advances in metallurgy (the science of metals) have produced metal alloys capable of withstanding the strains of heat, shock, and centrifugal force for 1,000 hours or more of operation.

Like the compressor, the turbine wheel may consist of one or more stages. And like the compressor, the turbine is composed of alternating rows of stators (the nozzle diaphragm) and rotors (the turbine wheel blades).

The shaft attached to the center of the turbine is connected at the other end to the compressor, which it drives (Fig. 42).

Exhaust Section.—The gases exit the turbine at temperatures of about 1,200° F. and speeds of about 1,200 feet per second and enter the exhaust nozzle. This nozzle has an inner cone, supported by struts. Together, the nozzle, cone, and struts straighten out the flow of the gases leaving the revolving turbine wheel, and send these gases through the tailpipe (Fig. 43).

The tailpipe is designed to increase the velocity of the gases to a point where they furnish maximum thrust without causing the engine to overheat. As the gases leave the tailpipe, their temperature has

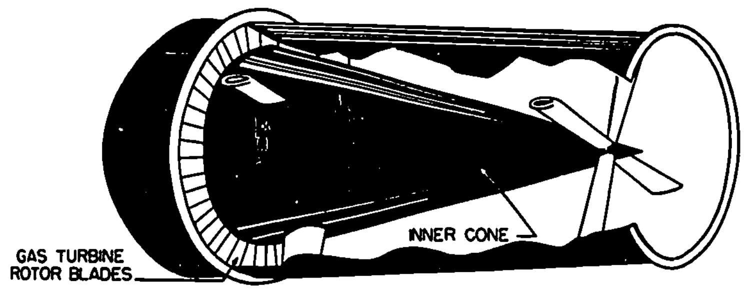


Figure 43. Exhoust Section ond Toilpipe.

dropped to about 1,000° F. and their velocity has increased to 1,800 feet per second or more.

Remember, the velocity of the gases leaving the tailpipe is an important factor in the thrust-determining equation, Force = Mass times Velocity.

The afterburner.—Some turbojet engines, principally on military aircraft, are equipped with devices which increase the velocity of the exhaust gases—and thereby, increase thrust—when maximum performance is required.

This device, aptly called the afterburner, acts in the manner of a small ramjet engine when it is in use and as a tailpipe when not in operation (Fig. 44).

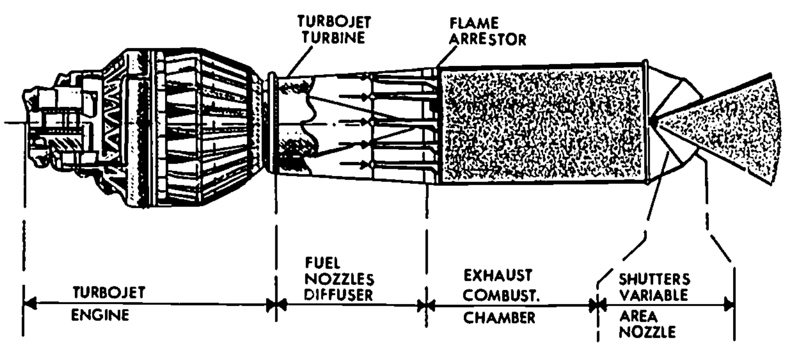


Figure 44. Turbojet Engine Equipped with Afterburner.

Since a large amount of the air that enters a turbojet engine is used for cooling and not for burning, there is ample oxygen in the exhaust air to operate the afterburner. As in the ramjet, fuel is injected into the afterburner under pressure. The exhaust gases from the main engine are of high enough temperature to ignite the fuel on contact, and the resulting burning greatly increases the exhaust velocity from the afterburner.

The afterburner is fitted with flameholders to keep the high-speed exhaust gases from blowing the burning gases out of the chamber.

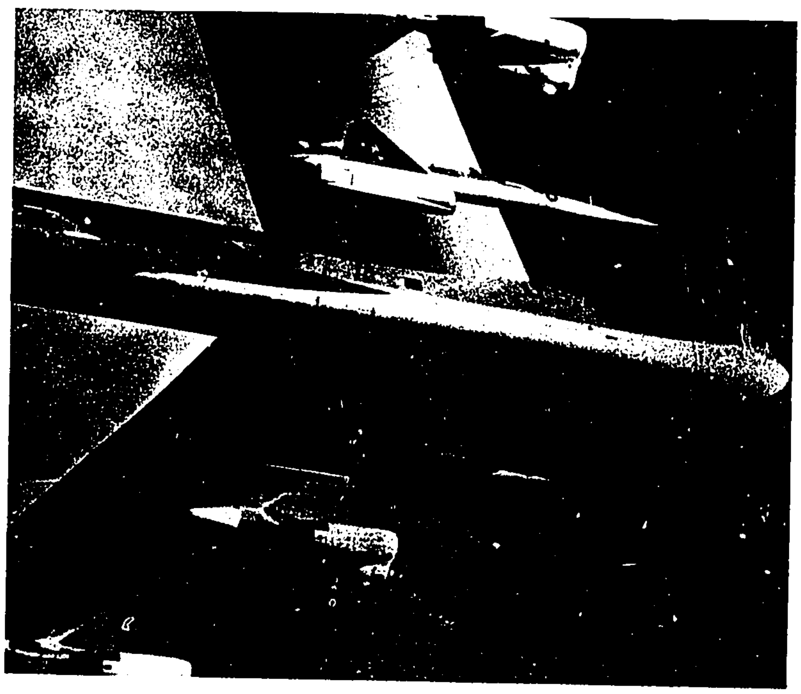


Figure 45. B–52 Bomber and Hound Dog Missiles are Powered by Turbojet Engines.

The turbojet—with or without the afterburner—has become the most widely-used type of jet engine. It is found supplying the power for many different types of aircraft, from fighters to bombers and passenger planes to guided missiles. Some examples of the aircraft using the turbojet engine for power are the F–105 Thunderchief, a workhorse for the United States in Vietnam; the F–5 Freedom Fighter, used by a number of nations as a primary defensive air-

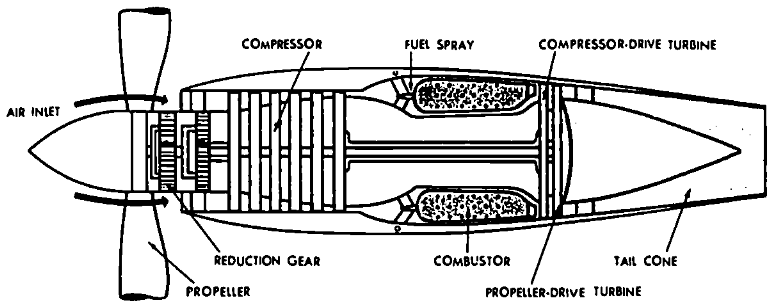


Figure 46. The Turboprop Engine.

craft; the B–52 bomber; some versions of the Boeing 707 and 720 and the Douglas DC–8 passenger aircraft, used by commercial airlines; the Hound Dog air-to-ground missile; and the mach 3-plus SR–71 strategic reconnaissance plane (Fig. 45).

The Turboprop Engine

Experience has shown that jet-powered aircraft are superior to propeller-driven aircraft at high speeds and high altitudes, while the propeller-driven planes excel at comparatively low speeds and low altitudes. In fact, the turbojet engine does not equal the reciprocating engine-propeller system in efficiency until speeds of nearly 400 miles per hour are reached.

In an effort to combine the best features of both systems, engine designers developed the turboprop engine. As the name implies, this engine uses a gas turbine-powered propeller for its drive.

In the turbojet engine, most of the gases passing through the combustion chamber are forced out the tailpipe to produce thrust. Only a small amount of the energy of these gases is used to turn the turbine and compressor.

But in the turboprop engine, the reverse is true. The turbine in this engine is designed to absorb almost all the energy from the exhaust gases. Part of this energy turns the compressor, allowing the engine to function in essentially the same manner as the pure turbojet.

But the bulk of the energy is passed from the turbine to the propeller, which is mounted at the front of the engine (Fig. 46). The turboprop has a weak exhaust from its tailpipe. Turboprop-powered aircraft obtain their thrust from the propeller, which moves a larger mass of air than would the turbojet, but at a lower velocity.

Strictly speaking, the turboprop system is not a jet engine (its thrust is not produced by high-velocity exhaust gases), but a propeller driven by a gas turbine engine.

The gas turbine engine can supply the propeller with double the horsepower of the conventional reciprocating engine. But reduction gearing must be used to slow the rpm rate of the propeller and keep its tip speed below the speed of sound. All the limitations of the propeller still apply to the turboprop engine.

A number of engine manufacturers and aircraft users have accepted the limitations of the turboprop engine—along with its benefits—and the engine is seeing extensive use today.

Among the aircraft using the turboprop system are the C–130 Hercules and the C–133 Cargomaster, both cargo planes built by Douglas Aircraft; the Lockheed Electra; and the Convair 580, now being used by at least three airlines, more than a dozen corporations, and the Federal Aviation Administration.

But engine manufacturers have not stopped with that compromise between the propeller craft's superiority at low speeds and the jet engine's class at high speeds. Continuing experimentation and design changes have produced a much better "compromise" than the turboprop engine. This newest development is an improved turbojet called the turbofan engine, and may become the dominant engine before long.

Turbofan Engine

The turbofan engine, also called the ducted fan or bypass engine, is of more recent development than the turboprop engine. It shares the turboprop's principle of moving larger volumes of air at lower velocities, but is still strictly a jet engine.

In the turbofan engine, one or more rows of the compressor blades are extended beyond the length of the rest of the compressor blades. These elongated blades pull large volumes of air through ducts outside the power section of the engine (Fig. 47).

A normal amount of air is fed through the combustion chambers, the turbine, and the exhaust section. But the air pulled by the extended blades (the fan) is ducted outside the engine so that it by-passes the combustion chamber, is forced backward, and is discharged without burning. It is discharged with the exhaust gases.

In one respect, the turbofan's extended compressor blades (its fan) resemble the action of the propeller in the turboprop engine. But the fan is run directly by the turbine, without the necessity of reduction gearing, and it is not subject to the propeller's speed limitations.

The turbofan engine moves up to four times as much air as the simple turbojet. It is capable of driving an aircraft at supersonic speeds without the benefit of an afterburner.

An innovation in the turbofan engine allows burning of the air in the fan stream. This type of engine, called the fan burner, is essentially a turbofan engine with an afterburner capability. Economical operation can be obtained from this engine at low altitudes

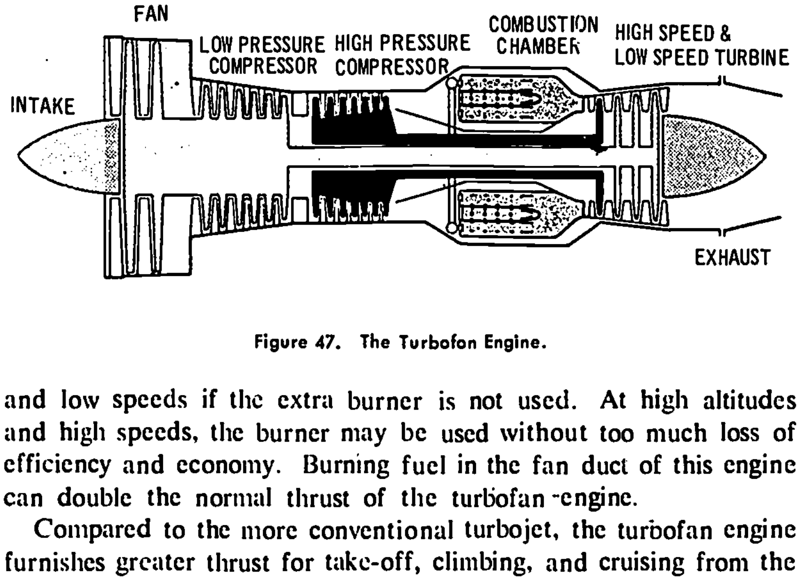


Figure 47. The Turbofan Engine.

and low speeds if the extra burner is not used. At high altitudes and high speeds, the burner may be used without too much loss of efficiency and economy. Burning fuel in the fan duct of this engine can double the normal thrust of the turbofan engine.

Compared to the more conventional turbojet, the turbofan engine furnishes greater thrust for take-off, climbing, and cruising from the same amount of fuel, mainly due to its larger air movement. The addition of the afterburner capacity has boosted the popularity of the turbofan. Some of the outstanding aircraft now using this kind of engine are the famed F–4 Phantom, used by the Air Force, the Navy, and the Marines; some versions of the B–52 bomber; the KC–135B tanker aircraft; the commercial airlines' Boeing 727 and Douglas DC–9, plus some versions of the Boeing 707; the C–141 Starlifter cargo plane; and the new A–7 Corsair II attack aircraft.

A look at that list will show the variety of uses of these aircraft. and the versatility of the turbofan engine. Very powerful turbofan engines also will drive America's supersonic transport (SST), now in development.

Noise Suppressors

Since they first came into use, jet-powered aircraft have been noted for the loud, objectionable noises they make. These noises in the conventional turbojet are caused by the movement of the high-velocity jet stream (exhaust) moving through the relatively quiet, still air around it. The sound of the high-speed air is of low frequency, and travels farther than would a higher-pitched sound of the same initial intensity. These loud noises are more of a nuisance than a real threat; they annoy passengers in the aircraft and people on the ground, particularly people who live near airports. But sustained, loud exhaust noises also can have a bad effect on the efficiency of the crew.

To curb these noises as much as possible, exhaust silencers have been put into use on some turbojet engines. These noise suppressors break up the large exhaust stream into smaller streams. This division raises the sound frequency of the smaller streams so that part of the noise is thrown outside the range of human hearing. The rest of the noise dissipates quickly, so that the sound does not "carry" as far.

Thrust Reversers

One big problem in the use of jet aircraft is the need for long runways for landing. The thrust force of the jet cannot be reversed in the same manner as the thrust of the propeller.

Early attempts at braking the jet aircraft made use of a parachute, which would, when released by the pilot, flare out behind the aircraft. The drag caused by the parachute slowed the plane down and reduced the required length of the landing strip.

But the parabrake, as it was called, was not entirely satisfactory. For one thing, its braking power could not be controlled by the pilot—it was all or nothing, since the parabrake would open fully when released. For another thing, the parachute had to be repacked after each use.

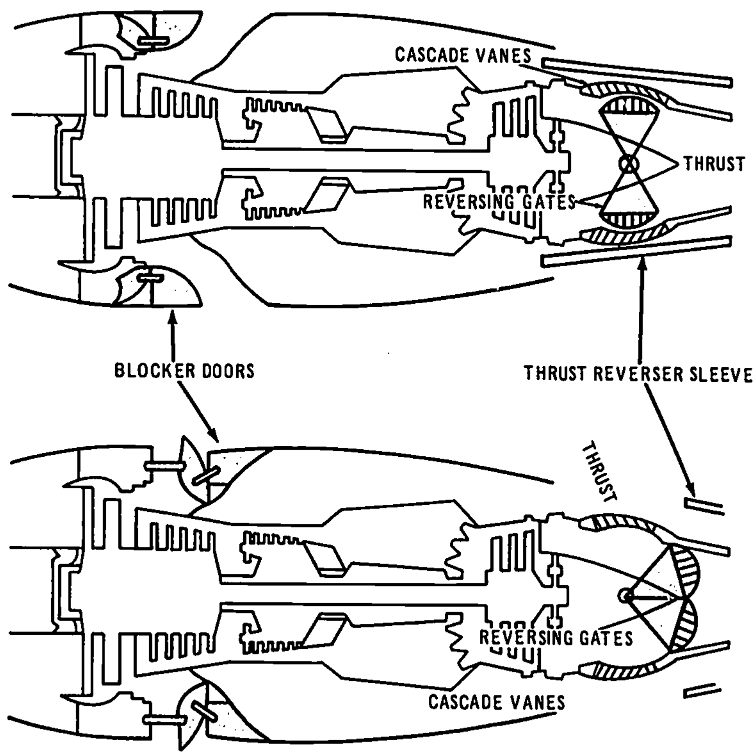


Figure 48. Turbofan Engine During Normal Flight (top) and with Fan and Aft Thrust Reverser in Operation (bottom).

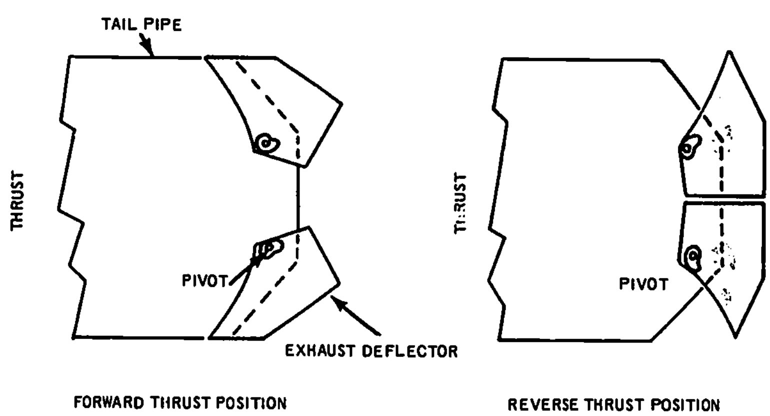


Figure 49. Simple Tailpipe Thrust Reverser, Showing Forward and Reversing Positions.

Two types of mechanical thrust reversers have been devised and are in use on some jet aircraft today. These reversers are used on aircraft equipped with turbofan engines and in some turbojet-powered aircraft. One of these reversers affects the airstream in the bypass duct in front of the engine and at the exhaust nozzle in the rear. The other reverser affects only the exhaust gases.

The "aft" part of the fan and aft reverser is connected to the exhaust nozzle in the tailpipe section of the engine. Its three principal parts are a set of clamshell-type doors, called reversing gates, inside the tailpipe; a set of vaned openings, called cascade vanes, in the side of the engine; and a sliding sleeve which covers the cascade vanes until the thrust reverser is activated (Fig. 48).

When the fan and aft thrust reverser is activated, the sleeve slides rearward, opening the cascade vanes on the side of the engine. The reversing gates swing shut, blocking the straight rearward thrust of the exhaust gases and forcing them out the cascade vanes, at an angle slightly forward of perpendicular to the straight rearward flow.

At the same time, blocker doors in the front of the fan section move into the duct, forcing the bypass air to reverse at about the same angle (see Fig. 48).

Another type of thrust reverser, operating only at the rear of the engine, has exhaust deflectors mounted on the outside frame of the tailpipe section. It can be used on turbojet as well as on turbofan engines. When this reverser is activated, the doors swing shut and the exhaust gases are diverted slightly forward. On this type of reverser, the doors are mounted externally; there are no cascade vanes; and there is no sliding sleeve. When this reverser is not operating, the deflectors form an extension of the tailpipe (Fig. 49).

Use of the mechanical thrust reverser allows the pilot to maintain full engine power while landing. Maximum thrust can be obtained immediately, in case the pilot has to pull out of his planned landing, by retracting the thrust reverser.

Accessory Section

The accessory section of the turbojet houses the engine's electric starter, generator, oil and fuel pumps, hydraulic pumps, and other accessories important to the engine.

The accessory section is housed in the front center of the engine, between the air intake section and the compression section. It is covered by the diffuser cone.

Water Injection

Many jet engines are fitted with water injection systems which can spray water into the combustion chambers as a means of increasing mass airflow through the engine. The water not only adds its own mass to the flowing matter, but cools the engine temperatures so that more fuel is burned in an attempt to bring the engine back to normal operating temperatures. The extra fuel increases the intensity of the explosion in the combustion chamber, and increases the velocity of the exhaust gases.

The tailpipe section also is affected by the cooling effects of water injection on the exhaust gases. Many tailpipes have automatically regulated orifices, or openings, through which the exhaust gases escape. As the temperatures of the gases drop, the tailpipe orifice closes somewhat as a means of bringing the temperature of the gases back to their most efficient heat. When the tailpipe opening is thus constricted, the velocity of the exhaust gases increases, and thrust increases with it.

Metals

Despite dramatic advances in metallurgy, the chief limiting factor in the further development of jet engines is the lack of materials capable of standing up under the jet's high temperatures and wind velocities.

Currently, more than 25 different alloys, or blends of metals, are being used in jet construction. These metals, exposed to the heat in the jet engine, are called "refractory metals."

The alloys usually have as bases either chromium, nickel, cobalt, or tungsten, or combinations of those elements. Titanium is used where temperatures do not get above 700 degrees F.

Comparisons

Some of the disadvantages of the turbojet engine today, as compared to the reciprocating engine-propeller combination, are: high fuel consumption at low speeds; high materials costs, both in manufacture and in maintenance; exterior noise; length requirements for air strips used; and the possibility of damage to the engine from objects sucked into the air intake.

Continuing research and development, however, promises to ease all or at least some of these problems. The jet engine, remember, is still a relative infant.

The turbojet's advantages over the "conventional" engine include: freedom from vibration, since all the moving parts rotate instead of reciprocate; simplicity of design and operation; less interior noise; higher thrust-per-pound ratios; higher speeds; and reduced fire hazards, since the fuels used in jet engines are less volatile.

ROCKETS

The rocket is another type of reaction engine, sharing with the jet engine an operating principle based on Newton's Third Law of Motion—equal and opposite reaction. But an important difference in the jet and the rocket systems is that the jet is an air-breathing machine, dependent on atmospheric air for the oxygen that enables its fuel to burn. The rocket carries its oxidizer along with it. This means that the rocket is not dependent on atmospheric oxygen, and can operate where there is no oxygen in the air—in outer space, for instance.

In some cases of everyday use, the words "rocket" and "missile" are used to mean the same thing. For the purposes of this study, however, "rocket" will be used in reference to the propulsion system only, and "missile" will mean the complete vehicle.

Missiles, while usually powered by rockets, may be powered by other means. An example is the previously mentioned V–1 missile (the "buzz bomb"), which was powered by a pulse jet. A number of military missiles developed since World War II also are powered by air-breathing jet engines.

The principle parts of the rocket-powered missile are the rocket engine, the propellants (including fuels and oxidizers), the airframe, or body of the missile, and the payload, or cargo. The payload may be nearly anything, including scientific instruments, explosives, or men.

The rocket engine provides thrust by ejecting hot, gaseous materials from the missile's exhaust nozzle at high velocities. The source of these gases is the propellant, which may be either liquid or solid. The propellant may be changed to the gaseous state through any of a number of processes, but the most common method in use today is chemical combustion.

Rocket Classification

Rocket engines are generally classified by the type of fuel they use, liquid or solid. There are advantages to both types. Generally speaking, the liquid propellants are capable of producing more thrust per pound than are the solid propellants, while the solid fuel rockets use simpler engine systems.

Solid rocket.—In the solid propellant rocket, the fuel and oxidizer chemicals usually are mixed together and cast in a solid mass. This mass is called a grain.

The grain is cemented to the inside walls of the metal or plastic combustion chamber. It is cast with a hole down its center. The hole may be of any of a variety of shapes, but star, circle, and gear shapes are most commonly used.

The size and shape of the hole in the grain affects the burning rate of the fuel, and thus the rate at which the gases are expelled.

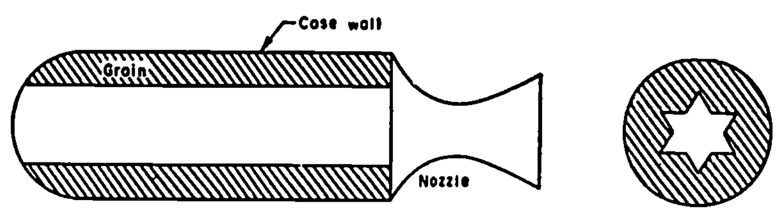


Figure 50. Diagram of a Solid Fuel Rocket.

The grain is ignited, usually with an electrical device, and burns on the entire inside surface. The gases produced by this burning rush down the hole to the exhaust nozzle, where they are discharged at tremendous velocities to produce thrust (Fig. 50).

The propellant grain usually consists of one of two types of chemical. One type is the double-base chemical, consisting largely of nitroglycerine and nitrocellulose. This propellant resembles smokeless gunpowder.

The other type of solid chemical in use is the composite propellant. The composite propellant is more widely used today than the double-base. It consists of an oxidizing agent, such as ammonium nitrate or ammonium chlorate, mixed with an organic or a metallic fuel. Many of the fuels are plastics.

Thrust from the solid propellant rocket may be stopped on command through two methods: blowing off the exhaust nozzle or opening vents in the combustion chamber walls. Both methods cause the pressure in the chamber to drop, and extinguish the flame.

Solid fuel rockets power a number of America's guided missiles, such as the Polaris and Poseidon submarine-launched missiles, Honest John, Little John, Minuteman, and a number of larger and smaller missiles. Solid rockets also are used as boosters in some space-probing missiles.

In some instances where the large missiles are concerned, solid rockets are used in combination with liquid rockets. This practice will be explored later in this chapter. But generally speaking, the liquid rockets are more powerful, pound for pound, and are easier to control. Both factors must be considered when real live human beings are riding the nose of these missiles.

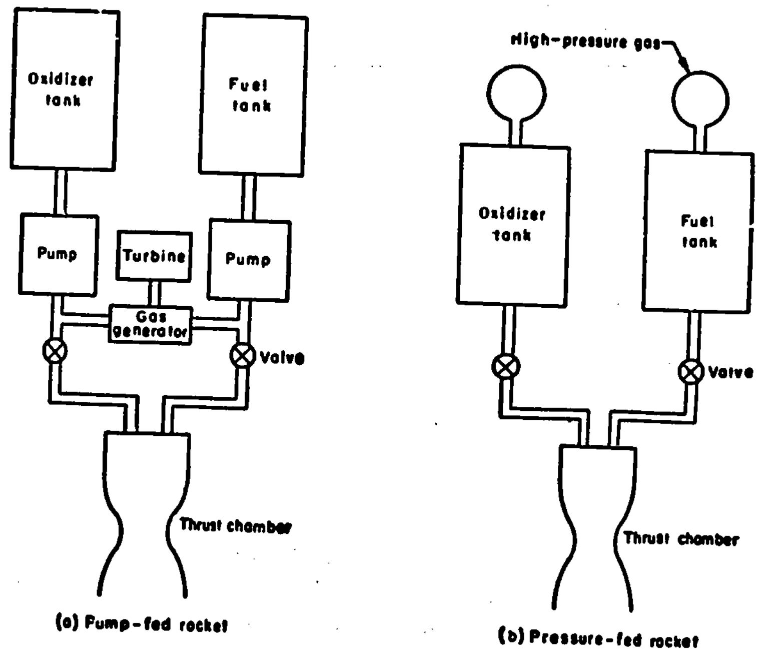


Figure 51. Pump-fed and Pressure-fed Liquid Fuel Rocket Diagram.

Liquid rocket.—Liquid-burning rocket engines are composed of tanks for fuel and oxidizer, lines from both tanks, pumps, a thrust (combustion) chamber, and an exhaust nozzle.

The common liquid rocket uses a liquid fuel and a liquid oxidizer, and is thus termed bipropellant. The fuel and the oxidizer (usually liquid oxygen) are contained in separate tanks and are mixed only upon injection into the thrust chamber. If the flow of either the fuel or the oxidizer is interrupted, combustion will stop.

The fuel and the oxidizer may be fed into the combustion chamber by pumps or by pressure within their tanks (Fig. 51).

In high-thrust engines, hundreds of gallons of propellant must flow into the combustion chamber every second. In these engines, the propellant is delivered by pumps, and the pumps are usually powered by a gas turbine (see Fig. 51).

The turbine is driven by a gas generator, which is actually a small combustion chamber whose exhaust gases are directed into the turbine wheel. Shafts from the turbine wheel drive the fuel and oxidizer pumps. The gas generator that drives the turbine uses the same propellants as the main rocket engine.

In the pressure feed system, the pumps are removed and the propellants are forced out of their tanks and into the combustion chamber by gas pressure of up to 500 pounds per square inch.

The pressure feed system is simpler and, perhaps, more reliable than the pump system, but it has its disadvantages. To withstand the high pressures, the tanks must be built of very heavy materials, which add additional dead weight to the missile. In many cases, this dead weight more than offsets the advantages obtained by removal of the pump system.

As in the solid propellant rocket, the exhaust nozzle of the liquid rocket is subjected to very high gas temperatures and velocities. The nozzle of the liquid fuel rocket is cooled by the propellant itself. Prior to injection into the thrust chamber, the propellant feeds through a system of passageways in the walls of the nozzle. This is called regenerative cooling.

In the liquid fuel rocket, the amount of thrust can be governed by means of valves which control the amount of propellant flow. Thrust can be stopped by closing the valves and blocking the propellant flow.

Some liquid fuel rockets use hypergolic propellants. A hypergolic propellant is a fuel that will ignite spontaneously when it comes into contact with an oxidizer. The word hypergolic is derived from "hypergol," a World War II German code name for these fuels.

Some of the most famous of American missiles have been powered by liquid rockets. These missiles include those used in the manned Mercury project, in which single men were sent into space by way of Atlas launch vehicles; the manned Gemini project, where two-man teams were sent up on Titan missiles; and in part of the giant Saturn missile, used in the three-man Apollo project. Also in the liquid rocket category is the Delta missile, used to put up a number of communications satellites including Early Bird, Telstar, Relay, and Syncom.

Propellants and Thrust

Now that we have an idea of how the liquid and solid fuel rockets operate, let us look at the methods scientists use to evaluate the power of these fuels.

Specific impulse.—The performance measurement of a rocket propellant is called the propellant's specific impulse. The unit of specific impulse is the measure of the number of pounds of thrust produced by each pound of propellant burned in one second (pounds of thrust/pound of fuel/second).

For simplicity, specific impulse is stated in "seconds." Thus, in the case of a chemical propellant with a specific impulse of 300 seconds, every pound of the chemical burned in one second would deliver 300 pounds of thrust through the exhaust nozzle.

Chemical propellants in use today have specific impulse ratings ranging from 175 to about 300 seconds. Theoretically, the most energetic chemical propellant would be capable of specific impulses up to 400 seconds.

The velocity that a rocket can attain is proportional to the specific impulse of its propellants. For example, if a given rocket can reach a speed of 10,000 feet per second with propellants delivering a specific impulse of 250 seconds, the same rocket would reach a speed of 11,000 feet per second (a 10 percent increase in speed) if the propellant's specific impulse were 275 seconds (a 10 percent increase in specific impulse).

Thrust requirements.—Vertical takeoff from the Earth requires a thrust that exceeds the total weight of the rocket-powered missile and its propellants by 30 to 50 percent. For example, a missile weighing 1,000 pounds would have to develop between 1,300 and 1,500 pounds of thrust before it could take off straight upward.

Rocket engines usually burn their propellants at a constant rate, and thus develop a constant rate of thrust, during their entire burning time. But as the fuel burns, the total weight of the missile decreases by the amount of weight of the fuel that has burned. This means that although the amount of thrust is the same, the engine has less weight to move. So the speed of the missile increases constantly, up to the time the last bit of fuel burns. At this point, the missile will either fall back to earth; go into orbit around the earth; or continue in a straight line into space, depending on the final speed of the missile and the angle at which it is traveling.

Escape velocity.—The amount of speed required to get beyond the gravitational pull of a planet or other cellestial body is called the escape velocity. Escape velocity varies for the different planets, and is dependent on the mass of the planet and the distance from the center of the planet to the space vehicle (Fig. 52).

The speed required to escape into space from the surface of the Earth is about 36,700 feet per second, or just under 7 miles per second. For example, if you had a gun with a muzzle velocity of 7 miles per second, and if you fired that gun straight up into the air, the bullet would escape into space. But the farther you go from the center of the Earth, the lower the escape velocity. At an altitude of 300 miles, for instance, the escape velocity is about 35,400 feet per second. Thus, if you were standing on a platform 300 miles high, the muzzle velocity of your gun would have to be only 6.7 miles per second before your bullet would fly on out into space.

Even if we had a rocket capable of providing an initial thrust of 7 miles per second at the instant of launch, this sudden thrust would put unbearable strains on any people riding inside the missile.

	Feet per second		*Feet per second*
Mercury	13,600	Mars	16,700
Venus	33,600	Asteroid Eros	~50
Earth	36,700	Jupiter	197,000
Moon	7,800		

Figure 52. Surface Escape Velocities of some Heavenly Bodies.

The answer is a relatively gradual buildup of speed by the rocket to the point where the escape velocity is reached.

Multistage rockets.—At present, no single rocket can build up enough speed to get completely outside the gravitational pull of the Earth. This is due to limitations on fuel storage space, fuel weight, and the specific impulses obtainable from these fuels.

As a solution to these problems, space experts have devised the multistage rocket, such as Saturn V, in which one missile is carried aloft by another and launched when propulsion from the first rocket expires.

For instance, the first stage of this multiple stage missile may reach a terminal velocity (the speed at the end of propulsion) of 10,000 feet per second. At this point, the first stage will drop off and the second stage will ignite.

If the second stage also is capable of attaining a speed of 10,000 feet per second, then the terminal velocity of the second stage would be 20,000 feet per second. This would be true because the second stage would already be traveling at 10,000 feet per second at the time it fired, and would increase its speed by another 10,000 feet per second under its own power.

Many stages may be included in this multistage missile method, and the velocity of the last stage (which would carry the payload) would be the total of the velocities of all the stages.

Practical difficulties do impose limitations on the number of stages that can be included in this system, however, since the first stage must be powerful enough to lift to a high speed the total weight of all the stages.

In these multistage missiles, combinations of solid fuel rockets and liquid fuel rockets may be used.

An example of a "mixed" multistage missile is the Titan III, a modification of the missile used in the Gemini program. A further modification, the Titan III–C, has been designated to boost America's Manned Orbiting Laboratory into space. The Titan, as we have seen, is powered by liquid fuel rockets. But this modification employs two solid fuel engines, strapped onto the Titan's sides, to give additional boosting power (Fig. 53).

Advances

Continuing progress in all phases of rocketry is being made as the space programs continue. The biggest and best rockets we are

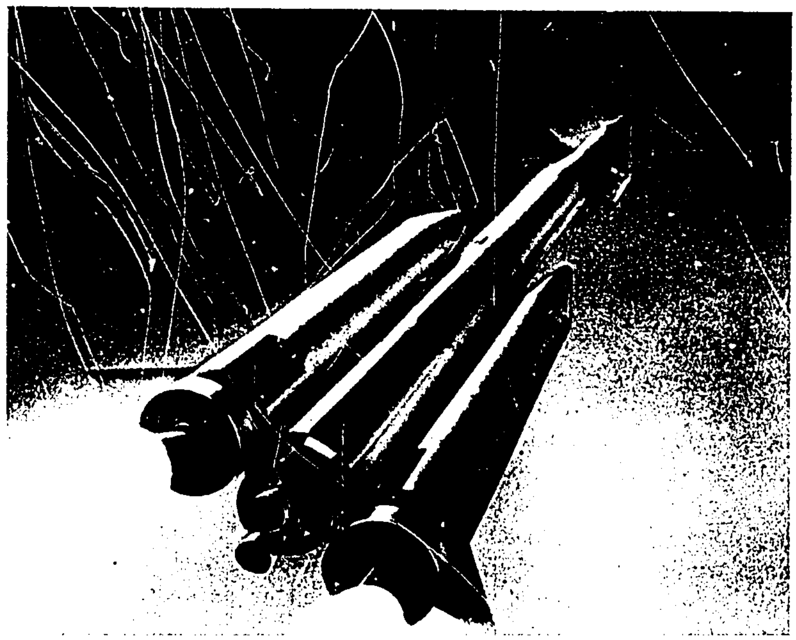


Figure 53. Titan III-C is Powered by Liquid and Solid Engines.

using today may one day be regarded as extremely primitive. This is more likely to be the case in the propulsion means than in the design of the missiles.

Better fuels, better metals, and better propulsion systems will no doubt be discovered as space investigation expands. Some ideas being seriously considered today, for instance, would have been regarded a very few years ago as the fantastic figments of some science fiction writer's imagination.

REVIEW QUESTIONS

1. **What are the four main sections of the jet engine?**
2. **Name some similarities in and differences between reciprocating and jet engines.**
3. **How does the ramjet differ from the pulsejet, both in construction and performance? How do these engines differ from the turbojet?**
4. **What is meant by the word, "mach"?**

5. What are some advantages of the turboprop engine over the conventional propeller-type engine?
6. Why is the turbofan engine the most satisfactory jet engine so far developed?
7. How does the water injection system increase thrust?
8. What is the chief difference between jet engines and rocket engines?
9. Describe the operation of solid and liquid rockets. Give advantages of each.
10. What is meant by "escape velocity"? What is the Earth's escape velocity?

THINGS TO DO

1. Turbine engines power many kinds of jet aircraft. Find out and report on some other uses for turbine propulsion systems. Include proposals and current developments in your report.

2. A major problem in the development of the supersonic transport (SST) is engine noise. Find out and report on the work being done to reduce jet engine noise in the SST and other aircraft engines. Enumerate the agencies and companies that are most active in this work.

3. During Christmas, 1968, a Saturn V carrier vehicle boosted 3 Americans to the moon in the flight of Apollo 8. Find out how the Apollo/Saturn V is put together: how many stages are included in the vehicle, which stages use solid and which use liquid propellants, and whether any hypergolic fuels are used. Compare the propulsion methods of Apollo 8 with those of the latest manned space flights, both American and Soviet.

SUGGESTIONS FOR FURTHER READING

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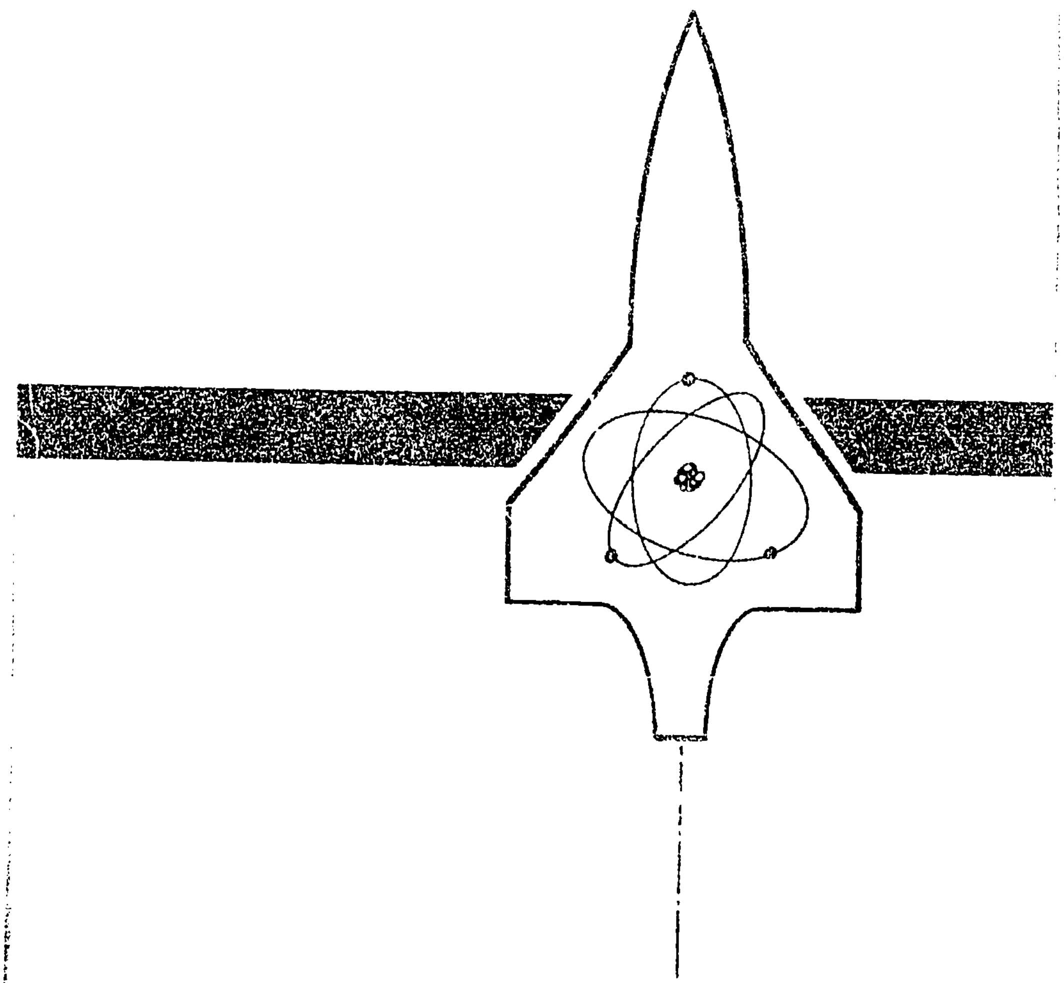
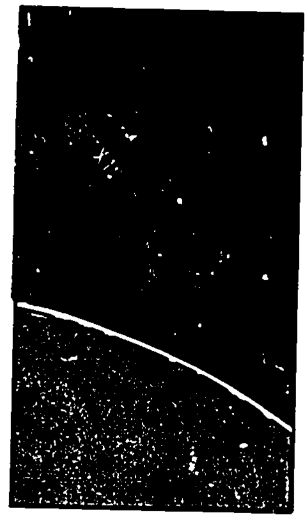


Chapter 5

Projections



THIS CHAPTER points out the rapid development of propulsion systems for aircraft and spacecraft and looks at what we expect in the near future. When you finish this chapter, you should be able to: (1) give some examples of the progress in jet engine performance; (2) discuss some of the new actual and theoretical methods of rocket propulsion, such as the nuclear, ion, and plasma engines; and (3) explain the theories behind the "solar sail" and the photon rocket.

SCIENTIFIC DEVELOPMENTS in the field of aerospace have come galloping out of the laboratory and into practical use at a terrific pace in the last few years. It is unreasonable to imagine that this trend will soon stop. With research and development continuing at such a pace, it is likely that what seems fantastic today will be ordinary 20 or even 10 years from now. Not only are new ideas being tested, but old ones are being refined. The result is that while marvelous new machines come into existence nearly every day, the "basic" machines we already have are better than ever.

JET DEVELOPMENT

Developments in the field of jet propulsion are an example. America's first operational jet fighter was the P–80 Shooting Star (Fig. 54). When news of this aircraft was announced in 1944, the P–80

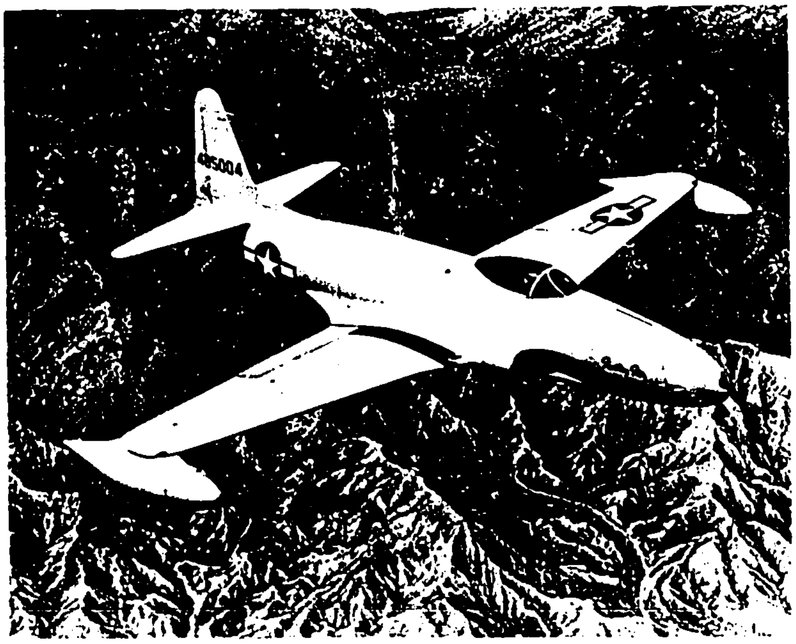


Figure 54. P–80 Shooting Star (now T–33) was First U.S. Operational Jet.

was said to be capable of speeds above 550 miles per hour, with a ceiling of 40,000 feet. By the mid-1960's the turbojet engine had been developed to such a degree that two of these engines could power one of the United States latest interceptor aircraft (the YF–12A) at more than 2,000 miles per hour and at altitudes up to 80,000 feet. Each engine on this missile-shaped aircraft develops 30,000 pounds of thrust (Fig. 55).

The F–4 Phantom fighter plane, in heavy use, is powered by two turbojet engines developing 17,000 pounds of thrust each, a meager amount compared to the YF–12A. But the Phantom can move at mach 2.5 plus (more than two and a half times the speed of sound) and can operate above 66,000 feet. It has climbed to an altitude of 98,000 feet (18.7 miles) in six minutes, 11 seconds.

Six turbojets, developing 33,000 pounds of thrust each (with afterburner), powered the now defunct XB–70 experimental bomber. This aircraft was designed to move at more than 2,000 miles an hour and to operate at altitudes of about 70,000 feet.

Continuing development of the turbojet engine has brought increased size and power. For example, turbojet engines designed to

Figure 55. YF–12A, Also Known as the A–11, is one of Latest Interceptors.

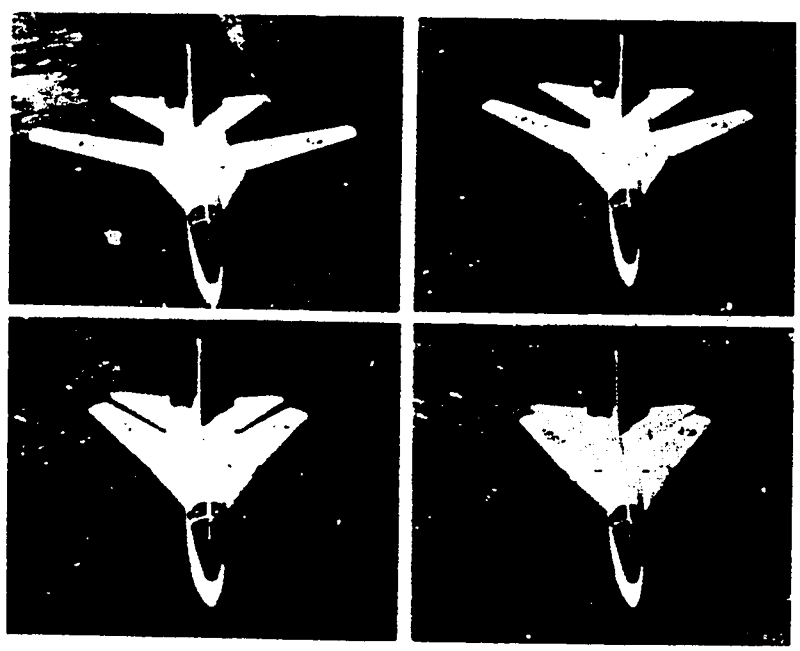


Figure 56. The F–111 has Variable Wings, two Turbofan Engines.

power an American supersonic transport plane (SST) develop more than 50,000 pounds of thrust each.

The F–111 all-purpose fighter has a number of unique features (Fig. 56). Its wings can extend straight out, allowing effective operation at speeds as low as 100 miles an hour; or they can be swept back in flight to allow faster speeds. Two turbofan engines power the F–111 to speeds approaching 2,000 miles an hour. Its operational ceiling is more than 60,000 feet.

The X–15

Although several different missiles are powered by jet engines instead of rocket engines, very few manned airplanes are powered by rockets. One of the most famous of these planes is the X–15. This small experimental aircraft is powered by a liquid-fuel rocket engine that develops 57,000 pounds of thrust at sea level and about 70,000 pounds of thrust at peak altitudes.

The X–15 has flown at speeds of more than 4,000 miles an hour and to altitudes of more than 354,000 feet (nearly 70 miles).

Figure 57. The X–15 Manned Rocket Plane Leaves its B–52 Mother Plane.

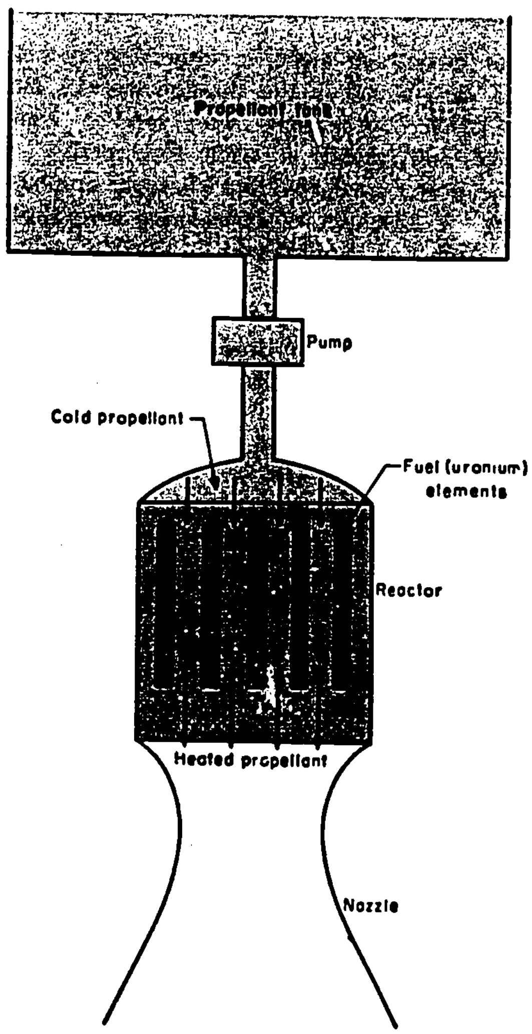


Figure 58. Nuclear Rocket may be Next Step in Rocket Propulsion.

Because of its design, the X–15 does not take off from the ground under its own power. It is carried to high altitudes by a B–52 jet bomber and released, then performs under power from its rocket engine (Fig. 57).

Testing in the X–15 program, which ended in 1968, led to many developments applied to use in jet aircraft and in space flight.

ROCKETS

Great strides have been made in improving rocket propulsion, both in engine design and in the development of more powerful propellants. Chemical propellants with specific impulses in the neighborhood of 300 seconds are well developed.

But since the power available from chemical combustion (oxidation) seems limited. scientists are considering several other methods of propulsion. Included on this list as a possible early development is the nuclear rocket (Fig. 58).

The nuclear rocket does not use any combustion process. It develops hot exhaust gases for propulsion (as does the chemical rocket). but it forms these gases by passing a fluid propellant through a fission reactor. The fission reactor produces heat by splitting the atoms of certain materials, thereby releasing great amounts of energy.

Liquid hydrogen is the propellant most mentioned for use in the nuclear engine. because of its light weight. The liquid hydrogen would pass through the reactor. The intense heat would transform the liquid into hot gases. and the gases would exhaust through the nozzle in the same manner as do the gases in the chemical rockets.

Another possible method of using the fission reactor in a rocket would avoid the severe strains of the heat on the materials of the reactor's walls. This method would employ a gaseous fissile material, instead of the hot reactor walls. to heat the propellant gas. The fissile gas would be held in the center of the rocket by magnetic means.

This system is still under investigation. as are most of the propulsion systems mentioned in this chapter. It has been estimated, though. that "conventional" nuclear rockets may provide specific impulses up to 1,200 seconds.

Electrical Propulsion

Scientists are looking into the possible use of electrically powered engines for rockets. The two electrical engines most commonly mentioned are ion and plasma propulsion rockets.

These electrical propulsion systems operate by thrusting electrified, or ionized, particles out of the rocket exhaust at very high velocities. But the energy density of these particles is small. For this reason, electrical propulsion as now envisioned could not provide enough thrust to get a missile off the ground.

Once a space ship is put into free orbit, however, very small amounts of thrust will increase the ship's flight velocity. A space ship fitted with ion, plasma, solar, or photon propulsion equipment would have to be put into space by another means, probably chemical or nuclear propulsion. In free space, conventional power could be turned off and small-thrust propulsion could take over.

Ionization

Both the ion and the plasma propulsion engines require large quantities of electricity for their operation. To understand how these systems work, we will review the physical makeup of molecules and atoms.

A molecule is the smallest particle of an element that retains all the qualities of the element. These qualities are as they are because of the particular way the smaller elements of the molecule are arranged.

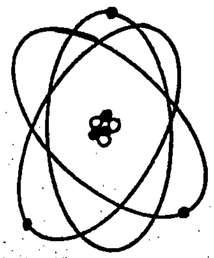


Figure 59. The Atom Includes Neutrons and Protons, Orbited by Electrons.

There are as many different kinds of molecules as there are elements. The only difference in the molecules is the number of smaller particles, called atoms, they contain and the way these atoms are made up.

So every molecule is composed of atoms. Every atom, in turn, is composed of smaller parts. These parts are the neutrons, protons, and electrons. They are arranged in the atom to form a nucleus, or center part, and orbits, or rings around the nucleus.

Neutrons are particles which have no electrical charge. Protons are particles with a positive electrical charge. Electrons are particles with a negative electrical charge.

The nucleus is composed of a given number of neutrons and the same number of protons. The orbits are rings where the electrons rotate around the nucleus (Fig. 59). Every stable atom has the same number of electrons in orbit as it has protons in the nucleus. This means positive and negative charges balance.

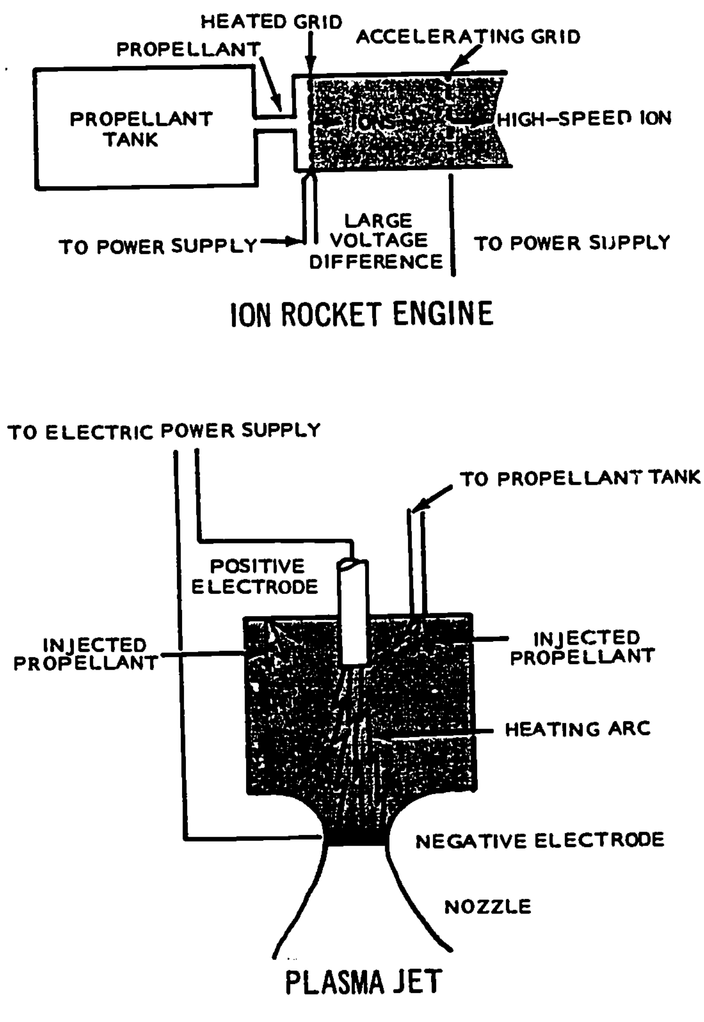


Figure 60. Examples of Ion and Plasma Rocket Engines.

In the process of ionization, an outside force knocks free of orbit one or more of the circling electrons. This leaves the atom with more protons than electrons, thus giving it a positive charge and making it unstable. Since the atom is charged, so is the molecule of which it is a part.

Ion Rockets

The ion engine probably will use the metal cesium as a propellant. Each molecule of the cesium will be given an electrical charge; that is, the cesium will be ionized.

This ionization can be accomplished by passing the cesium over heated metal grills. The heat acts as the outside force and knocks electrons loose. The charged molecules (or ions) can then be accelerated through the nozzle to very high velocities by means of an electrical magnetic field (Fig. 60).

The performance of such an ion engine is very good in the laboratory. Specific impulses can be obtained up to 20,000 seconds, but very heavy electrical equipment is required to provide enough power for good ionization.

Plasma Rockets

Another electrical rocket, called the plasma rocket, would work much the same as the ion rocket. But the heat would be supplied directly to a gaseous propellant through a powerful electrical arc instead of through a grill (See Fig. 60).

This method would provide high specific impulses, up in the thousands of seconds, without the heat problems involved in the ion engine. The heated propellant in the plasma rocket would be ionized as it passed through the electrical arc. The ionized gas, or plasma, as it is called, then could be directed out the exhaust nozzle at high velocities to produce thrust.

Plasma, in this sense, is a newly recognized fourth state of matter, taking its place along with the liquid, gaseous, and solid forms. Plasma is a wisp of gas that has been heated and compressed, so that it becomes electrically charged.

Future development of the ion and plasma rockets may include the development of nuclear reactors as suppliers of the large amounts of electricity required.

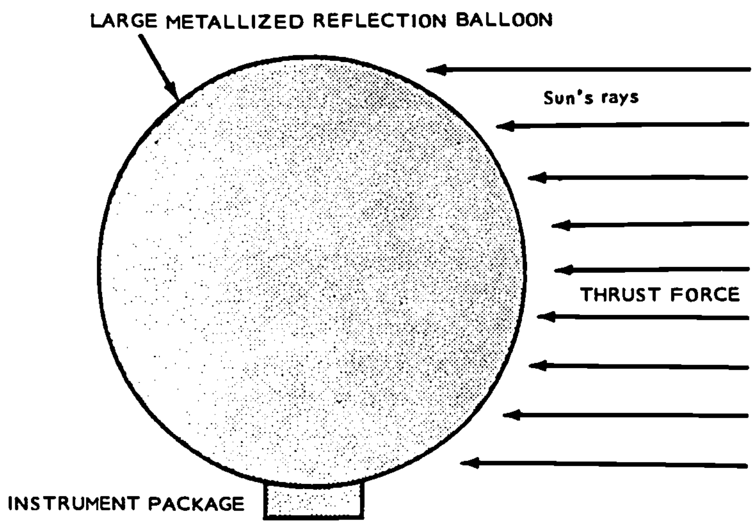


Figure 61. Solar Sail would be Pushed by Sun's Radiation.

Solar Propulsion

One proposed method of propulsion in outer space is to harness the radiation energy of the sun. The energy density of solar radiation is small as compared to the high density of chemical propellants; but solar radiation is sufficiently strong to move a space ship in "open" space. It is theorized that light rays have energy, and that this energy is made up of small bundles of power, called photons.

Two ways have been proposed as methods of harnessing sunlight for space propulsion. One of the ways is the "solar sail," a large balloon coated on one side with a metallic material (Fig. 61). The balloon would be attached to the space ship. The constant stream of pressure from the sun's radiation would push against the metallic side of the balloon, just as wind pushes against a sail in a sailing ship. The pressure would move the space ship along.

Another method of using the sun's rays for propulsion would be to trap the rays and use them to heat a gas inside the space ship. The expanding gas would then be expelled through the exhaust nozzle, as in the chemical propulsion rocket.

PROJECTIONS

Photon Rockets

Some researchers have proposed that a space ship may be propelled by internally-produced photons, the little bundles of energy mentioned above. In the photon rocket, light or other radiation generated within the rocket could be emitted from the exhaust in a focused beam. The action-reaction principle would make the space ship move.

A certain amount of momentum can be found in light beams, but so far, it is very small. A big military searchlight, for instance, may be considered as a version of the photon rocket. But such a searchlight yields less than one ten-thousandth of a pound of thrust from a power consumption of 100 kilowatts.

Unless a method could be found to completely convert matter into energy, the photon rocket system would be very inefficient.

REVIEW QUESTIONS

1. What was the first operational jet fighter plane developed by the United States? When was news of the aircraft announced?
2. Name one unique feature of the F-111.
3. How would a nuclear rocket be similar to the rockets in use today?
4. Why would electrically-driven missiles be satisfactory in outer space, but not for take-off from any planet?
5. Describe the operation of the ion rocket. The plasma rocket. The solar sail.
6. What are "photons"?

THINGS TO DO

1. Find out what kind of propulsion systems power the latest types of aircraft—for instance, the C-5, the proposed AMSA, and the developing V/STOL aircraft. Report on any significant powerplant developments used on these aircraft.

2. Designate someone to investigate and report on the progress of NERVA (nuclear engine for rocket vehicle application). Include in your report some of the major problems with the engine, how long it will be before NERVA is used operationally, how long the engine has been in study and development. Also speculate on the implications of NERVA in areas other than rocket flight.

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Summary

WE MAY SAFELY predict that for the foreseeable future, chemical propulsion will be the mainstay of rocket power.

Nuclear engines probably will be developed soon to the point that they will be used more and more often.

Serious study and experimentation with ion and plasma rockets is very promising, and could lead to practical use of these engines before long. Electrical and solar propulsion may prove effective in powering space ships over very long distances in open space. But within the gravitational pull of a celestial body, they are not powerful enough to function alone.

A combination of rocket and jet engines may be used to get future space ships off the ground, and to bring back for re-use the big booster sections of the first and second stages.

PERSPECTIVE ON PROPULSION

As man prepares to begin what probably will be his greatest adventure, travel into space, perhaps we should take a few seconds to get some perspective on the history of the engines which will power his ships. To get into space, man first had to get off the ground; to get off the ground, and stay off it for any length of time, he needed power. To see how long he worked to develop enough power to get off the ground, consider the following historic events. Note how, while America was engaged in winning its territory and its freedom, Europe was at work in the laboratory and in the field.

The origins of the first successful aircraft engine must be found in the piston-moving steam engine, invented by James Watt of Scotland. Watt invented his engine in 1769, the same year Napoleon Bonaparte was born, and four years before the Boston Tea Party. Changes in the steam engine were made gradually. In 1820, the Missouri Compromise Act passed the U.S. Congress and W. Cecil reported the development of an internal combustion engine in England. In 1860, Abraham Lincoln was elected President of the United States, and J. J. E. Lenoir of France designed the first practical internal combustion engine. Germany's Nikolaus Otto came up with a coal gas-burning engine in 1876, the same year U.S. Gen. George Custer and his troops were wiped out by Indians on the Little Big Horn and Wild Bill Hickok was shot down from behind while playing poker. Gottlieb Daimler, another German, invented a high-speed gasoline engine in 1883, three years before the Apache Indian Geronimo surrendered to the U.S. Army. Finally in 1903, the Wright brothers combined aerodynamics with an engine of sufficient power to get their "Flyer" off the ground. That was a year before the subway system opened in New York City.

Perhaps these historical parallels will demonstrate how long the search for powerful engines has been going on, and how recently it resulted in success. The lateness of this success will give you some idea of how rapidly the engine has been developed to its present state. No one can say what may be just around the corner, but one thing is sure: man has learned to take flight for granted; he has even had a taste of space, and has found it to his liking. He will not stop looking for better ways to power his flying machines. For this reason, research into propulsion systems for aircraft will continue—and it will turn up some startling results.

Glossary

A

accelerating system—carburetor device designed to prevent "lean" mixtures during sudden openings of the throttle.

acceleration—the action or process of velocity increase, or the rate of that increase.

aerodynamics—that field of dynamics concerned with the motion of air and other gaseous fluids, or of the forces acting on bodies in motion relative to such fluids.

afterburner—an auxiliary combustion chamber within the tailpipe section of some jet engines.

air baffle—wall designed to direct cooling air through engine parts.

airfoil—a surface or body, such as a wing or propeller, especially designed to obtain reaction, such as lift or thrust, from the air through which it moves.

airframe—the structural components of an airplane, including the framework and skin of the fuselage, empennage, wings, landing gear, and engine mounts.

augmenter tube—a venturi tube located behind some reciprocating engines, which increases airflow through the engine by creating a suction effect, aiding in engine cooling.

axial flow—in a jet aircraft, the flow of air along the longitudinal axis of the engine.

B

balloon—a nonrigid airship without a propelling system.

bank—a series of cylinders arranged in a circular row in a radial engine; also, in a different reference, to incline an airplane laterally.

Bernoulli's law—a law of physics stating that as the velocity of a fluid increases, its internal pressure decreases.

C

cam—a part mounted on a shaft and used to impart a reciprocating or alternating motion to another part by bearing against it as it rotates.

camshaft—the shaft on which the cams, or cam rings, are mounted.

carburetor—a device for mixing fuel and air in the proper proportions to form a combustible mixture and for conveying this mixture to the intake manifold, and ultimately, to the cylinders of an engine.

carburetor icing—icing formed in the carburetor as a result of rapid vaporization and cooling.

centrifugal flow—in a jet aircraft, the movement of air away from the center of rotation of the compressor.

compressor—a machine or apparatus for compressing air for delivery to the combustion chamber of an engine.

condenser—a device for storing electrical energy.
connecting rod—a rod connecting the piston to the crankshaft of an engine system.
cowling—a covering over an aircraft section for directing and regulating the flow of cooling air, for streamlining, or for protection of the section.
crankcase—the section encasing the crankshaft of an engine.
crankshaft—the shaft of an internal combustion reciprocating engine by which reciprocating motion is changed into rotational motion.
cylinder—the combustion chamber in a reciprocating engine.

D

detonation—the instantaneous and abnormal combustion of an unburned part of fuel mixture in the cylinder of an engine.
diesel—an internal combustion engine in which air is compressed to a temperature sufficiently high to ignite fuel injected into the cylinder, where combustion actuates a piston.
dirigible—a lighter-than-air aircraft with its own motive power, which may be steered in any desired direction by its crew.
distributor—an apparatus for directing the secondary current from the induction coil to the various spark plugs of an engine in their proper firing order.

E

economizer—a system associated with the carburetor that meters the fuel flow to economize on fuel at low speeds.
engine systems—the different sections of an engine that, working together, comprise the engine as a whole. These include the mechanical, cooling, electrical, lubrication, fuel, carburetor, and propeller systems of a reciprocating engine and the compressor, combustion, turbine, and exhaust systems of a jet engine.
escape velocity— in space flight, the speed at which an object is able to overcome the gravitational pull of the earth or other celestial bodies.
external combustion engine—a fuel-consuming engine in which fuel combustion takes place outside the cylinders or outside the reaction chamber.

F

feathering—changing the blade angle of a controllable-pitch propeller so that the propeller blade chords are parallel or almost parallel to the line of flight.
fission—of radioactive material splitting apart within the atomic nucleus.
force—in physics, an influence that if applied to a free body, results chiefly in an acceleration of that body.
four-cycle engine—an internal combustion, piston engine requiring four strokes of each piston to complete the cycle of intake, compression, combustion, and exhaust.
fuel injection—the forced spraying of fuel and air under pressure into the intake passages of an aircraft engine or into a combustion chamber.
fusion—of radioactive material: the act of process of fusing or uniting the atomic nuclei of an isotope to form other nuclei under the influence of intense heat.

H

horsepower—a unit of power in the United States equal to 746 watts and nearly equal to the English gravitational measure of 550 foot-pounds/minute.

hypergolic fuel—a rocket propellant that ignites spontaneously upon contact with an oxidizer.

hypersonic—of or pertaining to the speed of objects moving at mach 5 or greater.

I

inline engine—an internal combustion, reciprocating engine in which the cylinders are arranged in one or more straight rows, as distinguished from the radial engine.

intake manifold—a pipe which leads the fuel mixture from the carburetor to the cylinder or cylinders of an engine.

internal combustion engine—any engine in which the pressure of gases formed by combustion of fuel is directly used to give the engine motion; usually refers to piston-driven engines.

ion—an atom or group of atoms that carries a positive or negative electrical charge as a result of having lost or gained one or more electrons.

ionization—conversion of a substance (as air or liquid) into ions.

J

jet engine—a species of reaction engine, namely, an engine that takes in air from outside for use as a fuel oxidizer and projects a jet of hot gases backward to create thrust, the gases being derived from combustion within the engine.

K

knock—a sharp, metallic noise in a reciprocating engine, caused by abnormal ignition.

L

lean mixture—a fuel-air mixture containing a low percentage of fuel and a high percentage of air, as compared to a normal or rich mixture.

M

mach—a unit of speed measurement for a moving object equal to the speed of sound in the medium in which the object moves.

magneto—a generator using permanent magnets to generate an electric current, especially for the ignition of an internal combustion engine.

mass—a measure of the quantity of matter in a body, as distinguished from its weight.

O

octane rating—a number assigned to a liquid fuel to designate its relative antiknock value in a reciprocating engine.

oxidizer—in a rocket propellant, a substance that furnishes the oxygen for burning the fuel.

P

payload—that part of the load carried in a rocket vehicle, aircraft, or other vehicle so as to obtain the results for which the vehicle is launched or driven.

photon engine—a projected reaction engine in which thrust would be obtained from a stream of light rays.

piston—a sliding piece moved by or moving against fluid pressure that usually consists of a short cylinder fitting within a cylindrical vessel, along which it moves back and forth.

plasma—an electrically conductive mixture of positive ions, electrons, and neutral particles, differing from ordinary gas in its electrical conductivity, in its behavior as affected by a magnetic field, and in its internally stored energy.

propellant—a fuel, either liquid or solid, for powering a rocket engine; contains both fuel and oxidizer.

propeller—a device that consists of a central hub with radiating blades placed and twisted so that each forms part of a spiral plane, and used to propel or pull an aircraft forward through the air by the action of the blades eating into the air and thrusting it rearward.

pulsejet—a kind of jet engine having neither compressor nor turbine, but equipped with vanes in the front end which open and shut, taking in air to create power in rapid periodic bursts rather than continuously.

R

radial engine—an aircraft engine with one or more stationary rows of cylinders arranged radially around a common crankshaft.

ramjet—a kind of jet engine consisting essentially of tube open at both ends in which fuel is burned continuously to create a jet thrust, and having neither compressor nor turbine, the air for oxidizing the fuel being rammed into the engine as the engine moves forward.

reaction engine—an engine that derives thrust by expelling its gases of combustion to the rear.

reciprocating engine—an engine in which power is delivered by a back-and-forth movement of a piston or pistons; specifically, a piston-driven internal combustion engine.

regenerative cooling—the cooling of a rocket engine by circulating the fuel or oxidizer fluid in coils about the engine prior to use in the combustion chamber.

rich mixture—a fuel-air mixture containing a high percentage of fuel and a low percentage of air, as compared with a normal or lean mixture.

rocket engine—an engine or motor that moves forward by ejecting a stream of hot gases to the rear, and which, carrying its own oxidizer, is independent of the atmosphere for its operation.

rotor—a rotating part of an electrical or mechanical device or piece of equipment, as in the compressor of a jet engine.

RPM—revolutions per minute, applicable to any rotating mechanism. In a reciprocating engine, usually refers to crankshaft revolutions.

S

self-induction—induction within an electrical circuit induced by the circuit itself. Induction, or inductance, is the force in electricity that corresponds to inertia in matter.

shrinking—in engine construction, a method of securing the cylinder head to the cylinder barrel by heating the head, screwing it onto the barrel, and allowing it to set into place as it cools.

specific impulse—a performance measurement of a rocket propellant, expressed in seconds, and equal to the thrust in pounds divided by the weight flow rate in pounds per second.

stage—in a rocket vehicle powered by successive units, one of the separate propulsion units; a section of the vehicle housing a rocket engine or motor.

stator—in machinery, a part that remains fixed in relation to a rotating part, such as the stator section of a compressor.

supercharger—a pump or compressor for forcing more air or fuel-air mixture into a reciprocating engine than would normally induct at the prevailing atmospheric pressure.

supersonic—of or pertaining to the speed of an object moving at a speed greater than mach 1, or at a speed between mach 1 and mach 5.

T

throw—the eccentric bend in a crankshaft, onto which is joined the connecting rod.

thrust—the driving force exerted on any aircraft, rocket, or other object by its rotating propeller or rotor blades, jet or rocket engines, or other propulsive device; a unit for measuring the power of a reaction engine.

thrust horsepower—the thrust of a jet engine or rocket expressed in terms of horsepower.

thrust reverser—a device for redirecting a reaction engine's exhaust to an opposite direction.

turbine—a mechanical device or engine that spins in reaction to a fluid flow that passes through or over it.

turbofan—a turbojet engine with part of the compressor outside the inner engine case.

turbojet—a jet engine with a turbine-driven air compressor.

turboprop—a gas turbine engine designed to drive a propeller from a turbine shaft.

V

valve—any device, such as a swiveling plate, hinged lid, plug, or ball, through which the flow of gas, liquid or certain solid materials may be checked, stopped, started, or regulated.

vapor lock—a stoppage or diminution in the fuel flow of an engine caused by fuel vapor accumulating in the fuel lines.

venturi tube—a short tube with a constricted throat which, when placed in a fluid flow parallel to the flow, brings about an increase in flow velocity at the throat with a consequent diminished pressure within the fluid at the throat, in accordance with Bernoulli's Law.

viscosity—in a liquid, such as oil, the property of internal resistance, caused by molecular attraction, that makes the liquid resist flow.

W

windmill—of a propeller: to rotate by the force of air acting upon it, without power from the engine.

wind tunnel—a chamber through which air is forced at controlled velocities, up to several thousand miles an hour, and in which airfoils, airplanes, missiles, scale models of airplanes, or other objects are mounted in order to observe and study the airflow about such objects, as well as the aerodynamic effects upon them.

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