

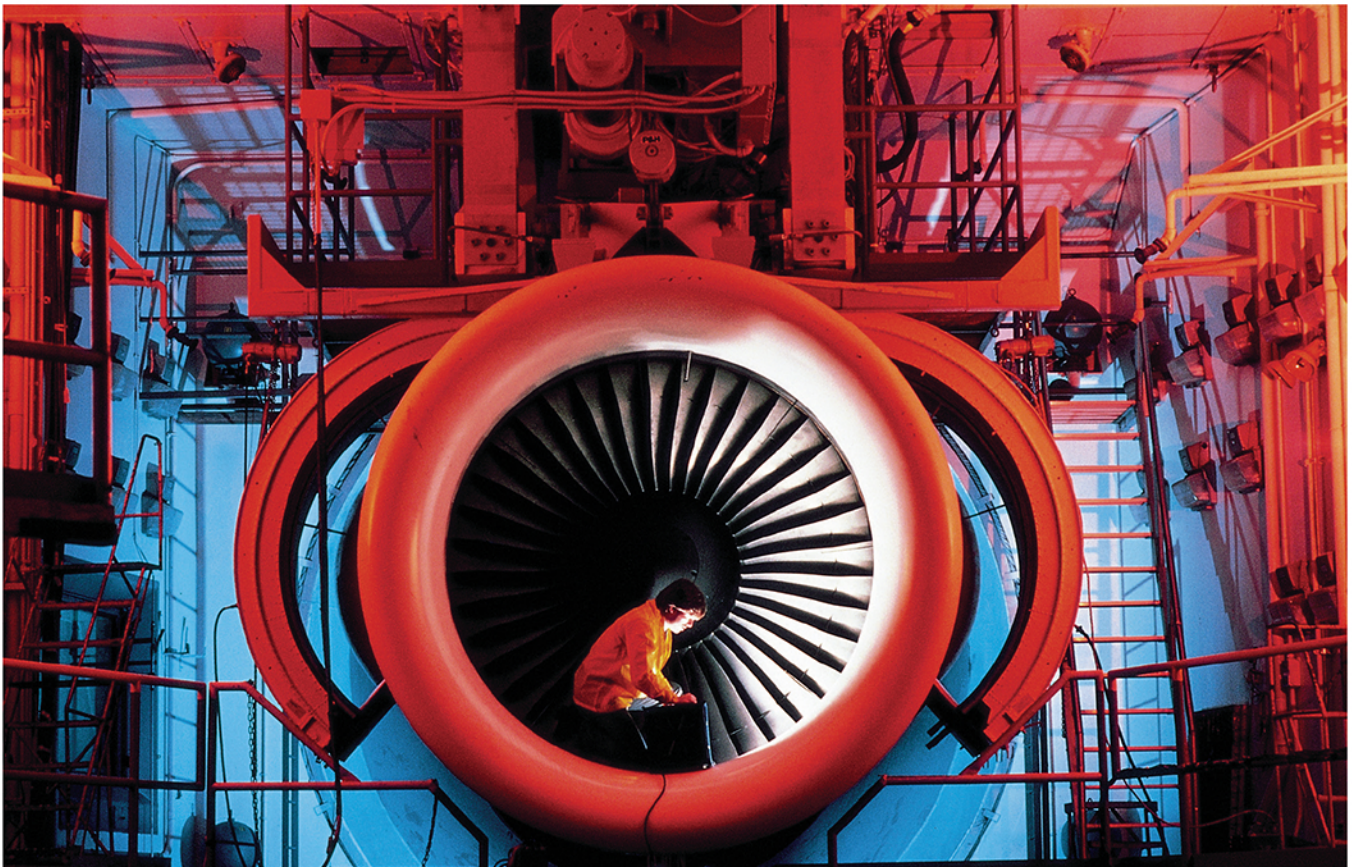


Aviation Maintenance Technician Series

DALE CRANE

Powerplant

Fourth Edition



**Aviation Maintenance
Technician Series**

**Powerplant
Fourth Edition**

DALE CRANE

T. DAVID SCROGGINS
Technical Editor

PROFESSOR OF APPLIED AVIATION SCIENCES
COLLEGE OF AVIATION
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Aviation Supplies & Academics, Inc.
NEWCASTLE, WASHINGTON

Aviation Maintenance Technician Series: Powerplant
Fourth Edition

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Newcastle, Washington 98059-3153
Email: asa@asa2fly.com
Website: www.asa2fly.com

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ASA-AMT-P4-PD

ISBN 978-1-61954-648-6

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PREFACE

TO THE FOURTH EDITION

Aviation maintenance is a profession requiring a broad spectrum of skills and knowledge that is constantly evolving as new technologies are introduced. Technicians today need a solid foundation of mechanics, physics, electricity, electronics and logic, in addition to the information unique to aircraft maintenance and construction. The training material in the *Aviation Maintenance Technician Series* is chosen to reflect today's required knowledge for the aviation maintenance technician. This material comes from a combination of both personal experience and research. Like previous editions, this *Powerplant* textbook, along with the other ASA maintenance volumes, endeavors to meet the needs of today's technicians.

ASA is dedicated to providing easy to understand training materials for the AMT certificate applicant. The chapters are carefully chosen to reflect FAA requirements, while the arrangement of information is intended to lend itself to a Part 147 curriculum. This arrangement also provides a logical flow of information that enhances individual learning. Therefore, the AMT Series textbooks contribute to the knowledge necessary for the building of well-rounded aircraft technicians, who will not only be equipped to understand the workings of aircraft systems, but will have the skills to repair, service, inspect, and troubleshoot them.

Additional recommended study materials would include such material as the FAA's *Aviation Maintenance Technician Handbook—General* (FAA-H-8083-30), —*Airframe* (FAA-H-8083-31), and —*Powerplant* (FAA-H-8083-32), also available from ASA. ASA provides the best collection of AMT-related federal aviation regulation reprints in *FAR for Aviation Maintenance Technicians*, printed yearly and provided with periodic updates on the ASA website (www.asa2fly.com). For those who are preparing to take their FAA exams, ASA's Test Guides are an invaluable tool to test your knowledge of aircraft maintenance.

Finally, we in aviation build on the legacy of the people who came before us as pioneers. That was true for the early experimenters trying to get off the ground for the first time just as it is true for today's mechanics, engineers, and pilots who are building and operating jumbo jets. The principle of building on the legacy of others is certainly true with this textbook—Dale Crane was the author of many of the ASA texts. Many students over the years came to trust Dale's authorship to not only inform, but to do so in an accurate, concise, and straight-forward manner.

Continued

Later, technical editors carried on that tradition by updating the book as aviation technology continued to evolve. The current technical editor never had the opportunity to study directly under Mr. Crane but many of his mentors and friends began their careers in aviation as Mr. Crane's students. Therefore, the current technical editor benefits heavily from Mr. Crane's knowledge and ability. It is the goal of this editor to carry on in the tradition of quality and clarity that Dale Crane established.

T. David Scroggins
Technical Editor for the Fourth Edition

ABOUT THE AUTHOR AND EDITORS

Dale Crane (1923 – 2010) was involved in aviation for more than 50 years. He began his career in the U.S. Navy as a mechanic and flight engineer in PBYS. After World War II, he attended Parks Air College. After college, he worked as an instrument overhaul mechanic, instrument shop manager, and flight test instrumentation engineer. Later he became an instructor and then director of an aviation maintenance school. Dale was active as a writer of aviation technical materials, and as a consultant in developing aviation training programs. ATEC presented to Dale Crane their special recognition award for “his contribution to the development of aviation technicians as a prolific author of specialized maintenance publications.” He also received the FAA’s Charles Taylor “Master Mechanic” award for his years of service in and contributions to the aviation maintenance industry, and the recognition of his peers for excellence as a leader and educator in aircraft maintenance, and aviation safety advocate.

T. David Scroggins, technical editor for the Fourth Edition, is a Professor of Applied Aviation Science in the College of Aviation at LeTourneau University. He studied in Moody Bible Institute’s Aviation program obtaining his Bachelor of Science in Missionary Aviation Technology; after earning his Mechanic’s certificate in 1981, David worked in several general aviation maintenance jobs in the U.S. and overseas. He started teaching at LeTourneau University in 1992; in 1996 he earned his Master of Science Degree in Technology from the University of Texas at Tyler. At LeTourneau David teaches courses in Reciprocating Engines, Turbine Engines, Propellers and Instrument Systems. He currently holds an Airframe and Powerplant Mechanic certificate, a Commercial Pilot Certificate and a Mechanic Examiner’s Designation.

Technical editors for the previous editions were Pat Benton, Western Michigan University, and Terry Michmerhuizen, Cornerstone College (First and Second Editions); Jerry Lee Foulk, LeTourneau University (Second and Third Editions).

ACKNOWLEDGEMENTS

A series of texts such as this *Aviation Maintenance Technician Series* could never be compiled without the assistance of modern industry. Many individuals have been personally helpful, and many companies have been generous with their information. We want to acknowledge this and say thank you to them all.

ACES Systems—TEC Aviation
Division, *Knoxville, TN*

Aero Quality International,
Stamford, CT

Aero-Mach Labs, Inc., *Wichita, KS*

Aeroquip Corporation, *Jackson, MI*

Airborne Division, Parker Hanniflin
Corporation, *Elyria, OH*

Allied Signal Aerospace, *Phoenix, AZ*

Allison Engine Company,
Indianapolis, IN

ASCO Aeronautical, *Columbus, OH*

Aviation Laboratories, Inc.,
Houston, TX

Barfield, Inc., *Atlanta, GA*

Beech Aircraft Corporation,
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Bendix Electrical Components
Division, *Sidney, NY*

Cessna Aircraft Company,
Wichita, KS

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Superior Air Parts, Inc., *Addison, TX*

Textron Lycoming, *Williamsport, PA*

TRW Hartzell Propeller Products
Division, *Piqua, OH*

T.W. Smith Engine Company, Inc.,
Cincinnati, OH

UE Systems, Inc., *Elmsford, NY*

United Technologies, Pratt & Whitney,
East Hartford, CT

Welch Allyn Imaging Products Division,
Skaneateles Falls, NY

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DEVELOPMENT OF AIRCRAFT POWERPLANTS

1

The first man-carrying flights were made in hot air balloons swept along by air currents and without means for the pilot to control the direction of flight. Aircraft had little practical utility until the development of engine-driven propellers. This development of the powerplant has made aviation the vital factor that it is today in the economic world.

The Principle of Heat Engines

All powered aircraft are driven by some form of heat engine. Chemical energy stored in the fuel is released as heat energy that causes air to expand. The expansion of this air is what performs useful work, driving either a piston or a turbine.

There are two basic types of heat engines: external-combustion and internal-combustion.

External-Combustion Engines

External-combustion engines are most familiar to us as steam engines. Energy released in coal- or gas-fired furnaces or in nuclear reactors is transferred into water, changing it into steam that expands and drives either a piston or a turbine.

Steam engines were used to power experiments in flight made during the late 1800s. Dr. Samuel Langley of the Smithsonian Institution in Washington, D.C. used small steam engines to power a successful series of unmanned machines he called Aerodromes. In 1896, Dr. Langley made a number of powered flights with these models. The most successful had tandem wings with a span of 14 feet, weighed 26 pounds, and was powered by a one-horsepower steam engine. It was launched from a catapult atop a houseboat on the Potomac river, and flew for 90 seconds, traveling more than half a mile.

There was one successful but impractical aircraft steam engine developed in America in 1933 by the Besler brothers, manufacturers of logging locomotives. This 150-horsepower engine, using an oil-fired boiler and having a total installed weight of approximately 500 pounds, was used to power a Travel Air 2000 biplane.

powerplant. The complete installation of an aircraft engine, propeller, and all accessories needed for its proper function.

heat engine. A mechanical device that converts chemical energy in a fuel into heat energy, and then into mechanical energy.

internal-combustion engine. A form of heat engine in which the fuel and air mixture is burned inside the engine.

external-combustion engine. A form of heat engine in which the fuel releases its energy outside of the engine.

piston. The movable plug inside the cylinder of a reciprocating engine.

turbine. A wheel fitted with vanes or airfoils radiating out from a central disk. Used to extract energy from a stream of moving fluid.

Aerodrome. The name given by Dr. Samuel Langley to the flying machines built under his supervision between the years of 1891 and 1903.

Otto cycle of energy transformation. The four-stroke, five-event, constant-volume cycle of energy transformation used in a reciprocating engine.

gas turbine engine. An internal combustion engine that burns its fuel in a constant-pressure cycle and uses the expansion of the air to drive a turbine which, in turn, rotates a compressor. Energy beyond that needed to rotate the compressor is used to produce torque or thrust.

turbojet engine. A gas turbine engine that produces thrust by accelerating the mass of air flowing through it.

turbofan engine. A type of gas turbine engine in which lengthened compressor or turbine blades accelerate air around the outside of the core engine.

turboprop engine. A turbine engine in which energy extracted from the accelerated gases is used to drive a propeller.

turboshaft engine. A turbine engine in which energy extracted from the accelerated gases is used to drive helicopter rotors, generators, or pumps.

reciprocating engine. A type of heat engine that changes the reciprocating (back-and-forth) motion of pistons inside the cylinders into rotary motion of a crankshaft.

brake horsepower. The actual horsepower delivered to the propeller shaft of an aircraft engine.

cylinder. The component of a reciprocating engine which houses the piston, valves, and spark plugs and forms the combustion chamber.

Internal-Combustion Engines

The concept of releasing energy from fuel directly inside an engine to heat and expand the air has challenged engineers since the late 1700s. The expanding air can drive reciprocating pistons or spin turbines.

Coal dust, gunpowder, and even turpentine vapors have been exploded inside cylinders, but it was not until 1860 that the French engineer Etienne Lenoir actually built a practical engine that could use illuminating gas as its fuel.

In 1876, Dr. Nikolaus Otto of Germany made practical engines using the four-stroke cycle that bears his name, and it is the principal cycle upon which almost all aircraft reciprocating engines operate. This cycle of energy transformation is discussed in detail in Chapter 2.

Gas turbine engines in the form of turbojet, turbofan, turboprop, and turboshaft engines have revolutionized aviation, and their principle of operation is discussed in Chapter 10.

Aircraft Reciprocating Engines

Throughout the history of aviation, progress has always been dependent upon the development of suitable powerplants.

Aviation as we know it today was born at the beginning of the 1900s with powered flights made by Wilbur and Orville Wright. The Wright brothers approached the problems of flight in a sensible and professional way. They first solved the problem of lift with kites, then the problem of control with gliders, and finally by 1902, they were ready for powered flight. First they painstakingly designed the propellers and then began their search for a suitable engine. Their requirements were for a gasoline engine that would develop 8 or 9 brake horsepower and weigh no more than 180 pounds. No manufacturer had such an engine available, and none were willing to develop one for them. Their only recourse was to design and build it on their own.

The engine, built to their design by Mr. Charles Taylor, had four cylinders in-line and lay on its side. It drove two 8½-foot-long wooden propellers through chain drives and developed between 12 and 16 horsepower when it turned at 1,090 RPM. It weighed 179 pounds.

On December 17, 1903, this engine powered the Wright *Flyer* on its historic flight of 59 seconds, covering a distance of 852 feet on the wind-swept sand at Kitty Hawk, North Carolina.

Because of Dr. Langley's success with his Aerodromes, the U.S. government gave him a contract to build a full-scale man-carrying machine. The steam engines used in the models could not be effectively scaled up to power this aircraft, so a better means of propulsion had to be found.

Charles Manly, Dr. Langley's assistant, searched without success, both in the United States and Europe, for a suitable powerplant. The best he found was a three-cylinder rotary radial automobile engine built by Stephen Balzer

in New York. This engine was not directly adaptable to the Aerodrome, but Manly, building upon Balzer's work, constructed a suitable engine for it. The Manly-Balzer engine was a five-cylinder, water-cooled static radial engine that produced 52.4 horsepower at 950 RPM and weighed 207.5 pounds complete with water.

On October 7, 1903, the full-scale Aerodrome with Manly as the pilot was launched from atop the houseboat. As the aircraft neared the end of the catapult, it snagged part of the launching mechanism and was dumped into the river. But Manly's engine, which was far ahead of its time, functioned properly and was in no way responsible for the failure of the Aerodrome to achieve powered flight.

Glenn Curtiss was a successful motorcycle builder and racer from western New York state. The use of one of his motorcycle engines in a dirigible in 1907 got Curtiss interested in aviation, and as a result, he became involved in furnishing the powerplants for Dr. Alexander Graham Bell's Aerial Experiment Association. A number of successful aircraft, including the first aircraft to fly in Canada, came from this group.

Curtiss's own company designed and built some of the most important engines in America in the periods before and during World War I and up until 1929, when the Curtiss Aeroplane and Motor Corporation merged with the Wright Aeronautical Corporation to form the giant Curtiss-Wright Corporation.

World War I, between 1914 and 1918, was a time of rapid growth in aviation. The British, French, Germans, and Americans all developed aero engines.

One of the most popular configuration of engines built in this era was the rotary radial engine. With this engine, the crankshaft was attached rigidly to the airframe, and the propeller, crankcase, and cylinders all spun around. Clerget, Gnome, and Rhone in France, Bentley in Britain, Thulin in Sweden, and Oberursel, BMW, Goebel, and Siemens-Halske in Germany all built rotary radial engines. These engines had 5, 7, 9, 11, or 14 cylinders and produced between 80 and 230 horsepower.

The Germans used some very efficient 6-cylinder in-line water-cooled engines built by the Mercedes, Maybach, BMW, Benz, and Austro-Daimler companies. Some of these engines developed up to 300 hp.

Some of the most popular V-8 engines of this time were the French-built 150- to 300-horsepower Hispano-Suizas. These engines were also built under license agreements in Great Britain and the United States.

There were only two aircraft engines designed and built in quantities in the United States during this time, and both were V-engines. Glenn Curtiss's Company built the 90-horsepower, water-cooled V-8 Curtiss OX-5 engine in great numbers, and various automobile manufacturers built the 400-horsepower water-cooled V-12 Liberty engine.

dirigible. A large, cigar-shaped, lighter-than-air flying machine. Dirigibles differ from balloons in that they are powered and can be steered.

rotary radial engine. A form of reciprocating engine in which the crankshaft is rigidly attached to the airframe and the cylinders revolve with propeller.

crankshaft. The central component of a reciprocating engine. This high-strength alloy steel shaft has hardened and polished bearing surfaces that ride in bearings in the crankcase. Offset throws, formed on the crankshaft, have ground and polished surfaces on which the connecting rods ride. The connecting rods change the in-and-out motion of the pistons into rotation of the crankshaft.

crankcase. The housing that encloses the crankshaft, camshaft, and many of the accessory drive gears of a reciprocating engine.

The cylinders are mounted on the crankcase, and the engine attaches to the airframe by the crankcase.

V-engine. A form of reciprocating engine in which the cylinders are arranged in two banks. The banks are separated by an angle of between 45° and 90°.

Pistons in two cylinders, one in each bank, are connected to each throw of the crankshaft.

Curtiss Jenny (Curtiss JN4-D). A World War I training airplane powered by a Curtiss OX-5 engine. It was widely available after the war and helped introduce aviation to the general public.

Standard J-1. A World War I training airplane powered by a Curtiss OX-5 engine.

DeHaviland DH-4. An English designed observation airplane built in large quantities in America during World War I. After the war, surplus DH-4s were used for carrying the U.S. mail.

radial engine (static radial). A form of reciprocating engine in which the cylinders radiate out from a small central crankcase. The pistons in the cylinders drive a central crankshaft which in turn drives the propeller.

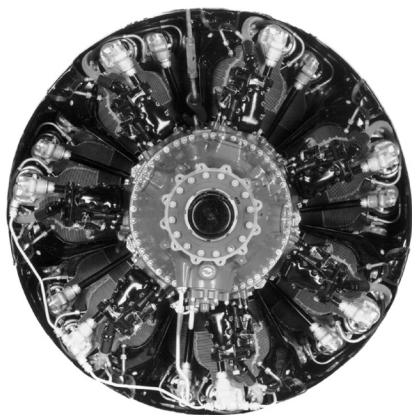


Figure 1-1. The Pratt & Whitney R-4360 Wasp Major, with 28 air-cooled cylinders weighed 3,670 pounds and produced 3,800 horsepower. This engine, with four rows of seven cylinders, was the largest practical aircraft reciprocating engine.

The years between World Wars I and II are called the golden years of aviation because of the tremendous strides made during this era. Powerplant development was largely responsible for this progress.

At the end of hostilities in 1918, the aviation market was flooded with surplus Curtiss Jennies and Standard J-1s, with their Curtiss OX-5 engines and DeHaviland DH-4 airplanes with Liberty V-12 engines. These airplanes and engines, while limited in utility, were so abundant and cheap that manufacturers were discouraged from developing new engines until these were used up.

Aviation did not become a viable form of transportation until a dependable engine was developed. Beginning in about 1923, Charles Lawrance built a 9-cylinder radial engine that was developed by the Wright Aeronautical Corporation into their famous Whirlwind series of engines, the most famous of which was the 220-horsepower Wright J-5. This is the engine that powered Charles Lindbergh's *Spirit of St. Louis* on its successful 33-hour nonstop flight from New York to Paris in May of 1927. About two weeks later, Clarence Chamberlain, flying a Bellanca, also powered by a Wright J-5 engine, flew nonstop from New York to Germany in 43 hours.

Small 3-, 5-, and 7-cylinder radial engines powered the light airplanes of the 1930s and 1940s, and 7-, 9-, and 14-cylinder radial engines powered the faster private and business airplanes, as well as military and airline aircraft.

During World War II the radial engine was the most popular configuration in the United States. Some fighter airplanes used liquid-cooled V-12 engines, but most aircraft were powered by 9-, 14-, and 18-cylinder radial engines, and by the end of the war, by a popular 28-cylinder engine.

The point of diminishing returns in reciprocating engine development was reached during World War II by the Lycoming XR-7755, a 5,000-horsepower 36-cylinder liquid-cooled radial engine. Fortunately the gas-turbine engine became functional at about this time.

Horizontally opposed engines first became popular as powerplants for very light aircraft in 2- and 4-cylinder models of less than 40 horsepower. This configuration has the advantage of smooth operation, small frontal area, light weight, and dependability. Because of these characteristics, they have been widely produced with 4-, 6-, and even 8-cylinders, with power output of up to 520 horsepower or more.

After World War II, horizontally opposed engines replaced radial engines for almost all reciprocating engine-powered private airplanes. Recently, however, there have been a several in-line and V-configured diesel engines marketed.

Private aviation in the United States has undergone drastic changes since the 1960s. The cost of private aircraft ownership skyrocketed because of the proliferation of product liability lawsuits, and commercial manufacturers virtually stopped producing reciprocating-engine-powered private aircraft in the 1980s. By the mid 1990s, changes in tort reform laws encouraged some manufacturers to re-enter the private aircraft field.

The amateur-built or homebuilt aircraft movement originally began because people wanted to build and fly ultra-simple aircraft without complex tooling, at minimum of cost. Today there are still some very basic designs yet there are also a number of homebuilt aircraft on the cutting edge of technology, costing hundreds of thousands of dollars. Freedom from some of the FAA constraints under which production aircraft are built and the accompanying reduction of the threat of product liability lawsuits allow private builders to exploit the limitless advantages of composite construction.

Amateur-built aircraft do not require FAA-certificated engines, and as a result, there is a strong movement in the conversion of automobile engines for aircraft use. Some converted automobile engines are truly state-of-the-art powerplants, with electronic ignition and fuel injection. The safety record for these engines is excellent, and it is quite possible that this will continue to be a viable means of developing engines for private aircraft in the future.

As aviation begins its second century, the gasoline reciprocating engine, in spite of its inefficiency, continues to be used, but not without competition. Practically all airline and military aircraft are turbine powered and will continue to be.

Air-cooled, horizontally-opposed gasoline engines will continue to dominate the piston-powered aircraft market for the foreseeable future. There have been, and continue to be, inroads made to develop more fuel-efficient powerplants, but none have risen to the forefront in any significant way to unseat the gasoline-fired mainstay. Some of the ongoing innovations include liquid-cooled gasoline engines, compression-ignition (CI) engines, rotating combustion (RC) engines developed from the Wankel engine, and cam (as opposed to crankshaft) engines.

The most significant of these improved engines has been the compression-ignition engine, better known as the diesel engine. The diesel or CI engine is about 10% to 15% more fuel efficient than the gasoline engine. This could be a significant savings if that were the only consideration, but the CI engine is considerably heavier than the gasoline-fired engine. This aspect in itself produces considerable inefficiencies when cost per mile is concerned; the search for ideas for more efficient piston engine power therefore continues.

amateur-built aircraft. Aircraft built by individuals as a hobby rather than by factories as commercial products. Amateur-built or homebuilt aircraft do not fall under the stringent requirements imposed by the FAA on commercially built aircraft.

rotating combustion (RC) engine. A form of internal combustion engine in which a rounded, triangular-shaped rotor with sliding seals at the apexes forms the combustion space inside an hourglass-shaped chamber. Expanding gases from the burning fuel-air mixture push the rotor around and turn a geared drive shaft in its center. The RC engine was conceived in Germany by Felix Wankel in 1955.

Figure 1-2 highlights the progress made in aircraft reciprocating engines. In only 40 years, engines progressed from almost 15 pounds per horsepower to slightly less than one pound per horsepower.

Manufacturer and Name	Year	Configuration	H.P.	Weight
Wright <i>Flyer</i>	1903	4 I L	12-16	179
Manly-Balzer	1903	5 R L	52.4	207
Curtiss OX-5	1910	8V L	90	400
Le Rhone J	1916	9 Ro A	120	323
Liberty V-12	1918	12 V L	400	900
Wright J-5	1925	9 R A	220	510
Pratt & Whitney R-1830	1932	14 R A	1,200	1,467
Wright Turbocompound	1940	18 R A	3,700	2,779
Pratt & Whitney R-4360	1943	28 R A	4,300	3,600
Engines for Private Aircraft				
Continental A-65	1938	4 O A	65	170
Lycoming TIGO-541	1959	6 O A	450	396
I = Inline, R = Radial, V = V, Ro = Rotary, O = Horizontally opposed, L = Liquid cooled, A = Aircooled				

Figure 1-2. Progress made in aircraft reciprocating engines

Aircraft Turbine Engines

The principle of using a turbine as a source of power has been known for more than 400 years, since the days of Leonardo da Vinci. Wind-driven turbines in the form of windmills have converted much of the arid wasteland in the western United States into profitable farms and ranches.

Water-driven turbines are used to generate electricity in the huge hydroelectric powerplants, and steam turbines are used to drive electrical generators and propel ocean-going ships.

The first practical use of turbines in aviation was the turbosupercharger developed by Dr. Sanford Moss during World War I. A turbine spun by exhaust gases leaving the engine drove a centrifugal compressor that increased the pressure of the air entering the cylinders. Turbosuperchargers allow reciprocating engines to maintain their sea-level power to a high altitude.

The gas-turbine engine is a logical progression from a turbosupercharger. A combustion chamber is placed between the turbine wheel and the compressor. Air from the compressor flows through the combustion chamber where fuel is added and burned. The expanding gases drive the turbine, which in turn drives the compressor. Though the compressor requires a tremendous amount of power, the turbine produces enough, with some left over for torque or thrust.

turbosupercharger. A centrifugal air compressor driven by exhaust gases flowing through a turbine. The compressed air is used to increase the power produced by a reciprocating engine at altitude.

centrifugal compressor. An air compressor that uses a scroll-type impeller. Air is taken into the center of the impeller and slung outward by centrifugal force into a diffuser where its velocity is decreased and its pressure is increased.

In 1929, Frank Whittle, a brilliant young pilot-officer in the British Royal Air Force, filed a patent for a turbojet airplane engine. Unfortunately, Whittle's genius was not appreciated, and it was not until 1937 that his first jet engine actually ran.

Some scientists in the British Air Ministry were interested in gas-turbine engines, but thought of them only as a source of power to drive propellers.

A propeller produces thrust by delivering a small change in momentum to a large mass of air, but Whittle's concept was that thrust could be produced by a jet engine delivering a far larger change in momentum to a much smaller mass of air. The thrust produced by a turbojet would increase as the aircraft flew faster and would be efficient at high altitude.

Whittle's engine used a turbine-driven centrifugal compressor to move a large mass of air through the engine. Fuel was sprayed into the fast moving air and burned, expanding it and accelerating it enough to produce useful thrust.

The turbojet engine came about at exactly the correct time. In spite of the lack of interest by the British government, Frank Whittle and his small but devoted crew at Power Jets, Ltd., proved the feasibility of the turbojet engine. In October of 1941, The General Electric Company was licensed to build the Whittle engine in the United States. GE was chosen for two reasons: because of their experience with turbosuperchargers, and because the two primary aircraft engine manufacturers, Pratt & Whitney and Wright Aeronautical, had more than they could handle in the continued development of reciprocating engines that were so desperately needed for the war which, at that time, appeared imminent.

The technology of turbojet engines was so new and the world was so deeply involved in the war, that no great strides in turbine engine development were made until the war was over.

At the end of the war, many reciprocating engines were declared surplus and sold for such low prices that there was little incentive for manufacturers to design and build new reciprocating engines. The gas turbine engine showed so much promise that neither Pratt & Whitney nor Wright Aeronautical felt it wise to continue developing reciprocating engines. Pratt & Whitney transitioned heavily into turbine engines, but Wright Aeronautical did not develop any of their own. They did produce some British engines under license but soon departed entirely from aviation engines.

Turbine engines have a far greater versatility than reciprocating engines because they can be operated either as a thrust or torque producer. Turbojet and turbofan engines produce thrust by accelerating a mass of air. Turboprop and turboshaft engines produce torque to drive propellers or helicopter rotors, or generators and air compressors for auxiliary power units.

torque. A force that produces or tries to produce rotation.

thrust. The aerodynamic force produced by a propeller or turbojet engine as it forces a mass of air to the rear, behind the aircraft.

A propeller produces its thrust by accelerating a large mass of air by a relatively small amount. A turbojet engine produces its thrust by accelerating a smaller mass of air by a much larger amount.

power. The time rate of doing work. Power is found by dividing the amount of work done, measured in foot-pounds, by the time in seconds or minutes used to do the work.

Power may be expressed in foot-pounds of work per minute or in horsepower. One horsepower is 33,000 foot-pounds of work done in one minute, or 550 foot-pounds of work done in one second.

thrust horsepower. The horsepower equivalent of the thrust produced by a turbojet engine. Thrust horsepower is found by multiplying the net thrust of the engine, measured in pounds, by the speed of the aircraft, measured in miles per hour, and then dividing this by 375.

There is no direct comparison between turbine engines and reciprocating engines that allows us to visualize the tremendous strides that have been made in aircraft propulsion systems, but we can convert thrust into thrust horsepower and make a power-to-weight comparison.

Power requires movement, so thrust horsepower must take into consideration the speed of the aircraft. Thrust horsepower is found by multiplying the net thrust of the engine measured in pounds, by the speed of the aircraft measured in miles per hour, then dividing this by 375.

$$\text{Thrust horsepower} = \frac{\text{Net thrust (pounds)} \cdot \text{Aircraft speed (miles per hour)}}{375 \text{ mile-pound / hour}}$$

The Pratt & Whitney R-1830 engine used in the ubiquitous Douglas DC-3 weighed approximately 1,500 pounds and produced 1,200 brake horsepower for takeoff. This is a power-to-weight ratio of 0.8 horsepower per pound, which is still an acceptable ratio for reciprocating engines.

The Pratt & Whitney JT9D that powers the Boeing 747 weighs approximately 9,000 pounds and produces up to 56,000 pounds of thrust, which at a cruise speed of 550 miles per hour, gives a little over 82,000 thrust horsepower. This is a power-to-weight ratio of a little more than 9 horsepower per pound!

	R-1830 Reciprocating	PT-6 Turboprop
Takeoff horsepower	1,200	1,377
Weight	1,500	486
Horsepower/ weight ratio	0.8	2.8

Figure 1-3. Horsepower to weight ratio comparison between a reciprocating engine and a turboprop engine of comparable power

It is easy to see the advantage that turbine engines have over reciprocating engines by comparing two popular torque-producing engines of the same basic power and used in the same types of aircraft. The Pratt & Whitney R-1830 reciprocating engine powers the 21-passenger Douglas DC-3, and the Pratt & Whitney of Canada PT-6 turboprop engine powers the 19-passenger Beech 1900D airliner. The power-to-weight ratio of the turboprop engine is 3.5 times as high as that of the reciprocating engine. *See* Figure 1-3.

Thrust-producing turbine engines have made tremendous progress since their first flight in 1939. Figure 1-4 shows the progress made in a little over fifty years.

Manufacturer Name	Type	Mass Airflow pounds/second	Thrust pounds	Weight pounds	Application
Whittle W1	TJ	22	850	623	E. 28/29
Allison J-33	TJ	90	4,600	1,820	F-80
P&W JT4	TJ	256	17,500	5,100	B-707
P&W JT8D	TF	331	17,400	3,500	B-727
G.E. CF6	TF	1,465	51,000	8,731	DC-10
RR RB.211	TF	1,658	63,000	9,874	B-747
TJ = Turbojet		TF = Turbofan			

Figure 1-4. Progress in thrust-producing turbine engines

Turbofan engines have almost completely replaced turbojet engines, and a new generation of ultra-high-bypass engines shows promise of opening a new niche between the turboprop and the turbofan. UHB engines, such as that in Figure 1-5, drive short, multiblade, contrarotating propellers and have high propulsive efficiency, low noise, low thrust specific fuel consumption, and a high power-to-weight ratio.

TSFC (thrust specific fuel consumption). A measure of the efficiency of a turbojet or turbofan engine. TSFC is the number of pounds of fuel burned per hour for each pound of thrust produced.



Figure 1-5. The Unducted Fan™ engine is an ultra-high-bypass turbine engine that promises quiet operation with low fuel consumption at a speed higher than that used by turboprop-powered aircraft.

Electrically Powered Engines

While this book deals primarily with heat engines, in today's changing world of technology a short discussion of electrically powered flight is appropriate. The idea of using an electric motor as a source of power for flight has been around for quite a few years but was held back by technical challenges. Both the motor and the power source have prevented making electric power a viable alternative in the past.

In recent decades improved motor technology has become available. Several manufacturers have developed electric motors marketed for aviation propulsion. Most of these are limited to Experimental, Ultralight and LSA aircraft. However, this is changing as environmental concerns motivate aircraft manufacturers to find cleaner, quieter ways to fly. Siemens currently

has developed a 260kw (348 hp) electric motor that weighs only about 50 kilograms (110 lbs). This motor, installed in an Extra 300 aerobatic aircraft, has set several electric-powered records.

While motor efficiency has been improving, the greatest challenge is developing a suitable power supply. Yet battery technology has improved immensely; with the introduction of lithium-based batteries, the weight of batteries for a given amount of energy has gone down substantially. For example, one battery manufacturer compares their 100Ah 12V lithium-iron-phosphate technology battery to a lead-acid battery with similar capacity. The lead acid weighs in at 40 kg (88 lbs), while the lithium-iron-phosphate battery weighs only 13.6 kg (30 lbs). Additionally, its life expectancy is such that it can be charged and discharged 8 to 10 times more than a lead-acid battery before it must be retired from service.

While this is a significant improvement over previous power supplies, current battery power limits the flight to a relatively short duration of one to two hours maximum. To extend this time, some research aircraft have covered the upper surfaces of the aircraft with solar cells to charge the battery whenever there is sunlight available. This is, however, expensive and very dependent upon the weather.

One solution to the electricity supply problem is to build a hybrid system similar to what hybrid automobiles utilize. A hybrid system uses a liquid-fueled engine to drive a generator that charges batteries and powers the electric motor. There are a few light aircraft operating today as hybrid systems using piston engines. The batteries supply power to assist the generator during takeoff and climb. Once power is reduced to cruise setting, the generator can maintain the cruise speed and recharge the battery. This allows a smaller engine operating at an efficient speed to power the aircraft.

This idea is promising enough that Airbus, Siemens, and Rolls-Royce are working together in partnership to develop a hybrid regional airliner design. It will use an efficient gas-turbine engine driving a generator to power the propulsion motor. Their goal is to have a technology demonstrator flying by 2020 and a production aircraft operational around 2030. Several other manufacturers are working on similar plans.

STUDY QUESTIONS: DEVELOPMENT OF AIRCRAFT POWERPLANTS

Answers are found at the end of the chapter.

1. The basic name for an engine that produces mechanical energy by changing chemical energy in the fuel into heat is a/an _____ engine.
2. Two types of heat engines are:
 - a. _____
 - b. _____
3. Two types of internal combustion engines used to power modern aircraft are:
 - a. _____
 - b. _____
4. A reciprocating engine in which the crankshaft is rigidly attached to the airframe and the cylinders spin with the propeller is called a/an _____ radial engine.
5. The most popular configuration of reciprocating engine in the United States from the end of World War I through World War II was the _____ engine.
6. The most popular configuration of reciprocating engine for private aircraft built in the United States since World War II is the _____ engine.
7. The first practical use of a turbine in aircraft propulsion was the _____ .
8. Aircraft turbine engines are used to produce _____ or _____ .
9. Two types of thrust-producing aircraft turbine engines are:
 - a. _____
 - b. _____
10. Two types of torque-producing aircraft turbine engines are:
 - a. _____
 - b. _____
11. The problem that currently limits the use of completely battery-powered electric aircraft is _____ .
12. A hybrid propulsion system has an electric motor powered by a _____ and _____ .

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