Aircraft Gas Turbine Engine Technology

……

IRWIN E. TREAGER

*Associate Professor, Department of
Aviation Technology
Purdue University*

Aircraft Gas Turbine Engine Technology

IRWIN E. TREAGER
Associate Professor, Department of
Aviation Technology
Purdue University

McGRAW-HILL BOOK COMPANY
New York St. Louis San Francisco London
Sydney Toronto Mexico Panama

Aircraft Gas Turbine Engine Technology

Library of Congress Catalog Card Number 69-17193
65128
1234567890 HDBP 7654321069

This book was set in Optima by Progressive Typographers, and printed on permanent paper by Halliday Lithograph Corporation, and bound by The Book Press, Inc. The designer was Edward Zytko; the drawings were done by J. & R. Technical Services, Inc. The editors were Cary F. Baker, Jr. and Albert Shapiro. William P. Weiss supervised the production.

Preface

Although the gas turbine, or jet engine, is a relative youngster to aviation, its growth and refinement have not only given new life to this industry, but also have been so rapid that keeping abreast of developments in this area has become very difficult. A great deal has been written about the gas turbine engine from an engineering viewpoint, but there is relatively little consolidated information treating this type of power plant at the technical level. This book is an attempt to correct this deficiency.

Although the text is designed primarily to provide a source of information about the gas turbine engine for aircraft technicians, it may be used by others interested in this type of power plant.

The author has tried to follow a logical presentation and to use the type of approach that does not assume a great deal of technical information on the part of the reader. Beginning with the background and development of the gas turbine engine the book ends with a discussion of several modern engines of this type. The section of the book dealing with the mathematical relationships, which are an integral part of any study dealing with this type of engine, has been simplified without, it is hoped, sacrificing clarity and completeness to any great degree. As the heading for Chapter 3 implies, all who can add and subtract should have little difficulty reading and understanding this part of the book. The part of Chapter 12 dealing with the fuel control is slightly more detailed than other sections because fuel metering is a critical factor in correct engine operation and because the fuel control is probably the most complicated and difficult to understand unit on the entire engine. The appendixes are devoted to a compilation of appropriate mathematical formulas, a glossary of terms related to the gas turbine engine, and several pages of applicable conversion factors and tables.

IRWIN E. TREAGER

Acknowledgments

The information contained in this book has been collected from a great number of sources. It represents the work of many people and organizations, without whose contributions this text could not have been completed. I wish to express my gratitude to the following organizations for their efforts in providing technical information, pictures, charts, tables, and other materials.

AiResearch Mfg. Co., Div. of the Garrett Corp., Phoenix, Ariz.
Air Training Command, U.S.A.F., Randolph A.F.B., Tex.
Allison Div., General Motors Corp., Indianapolis, Ind.
American Petroleum Institute, New York, N.Y.
American Society of Mechanical Engineers, New York, N.Y.
American Society of Tool and Manufacturing Engineers, Dearborn, Mich.
Aviation Power Supply Inc., Burbank, Calif.
Aviation Week and Space Technology, New York, N.Y.
Beech Aircraft Corp., Wichita, Kans.
Bell Helicopter Co., Fort Worth, Tex.
Bendix Products Aerospace Div., Bendix Corp., South Bend, Ind.
Boeing Airplane Co., Commercial Airplane Div., Renton, Wash.
Cessna Aircraft Co., Wichita, Kans.
Chandler Evans Corp., West Hartford, Conn.
Continental Aviation and Engineering Corp., Detroit, Mich.
Convair Div., General Dynamics Corp., San Diego, Calif.
Curtiss-Wright Corp., Wood-Ridge, N.J.
Department of the Air Force, Washington, D.C.
Douglas Aircraft Co., Long Beach and Santa Monica, Calif.
Ex-Cell-O Corp., Detroit, Mich.
Extension Course Institute, U.S.A.F., Gunter A.F.B., Ala.
Fairchild Hiller, Republic Aviation Div., Farmingdale, N.Y.
Federal Aviation Agency, Washington, D.C.
Gas Turbine Publications Inc., Stamford, Conn.
General Dynamics Corp., Fort Worth Div., Fort Worth, Tex.
General Electric Co., Cincinnati, Ohio
General Laboratory Associates Inc., Norwich, N.Y.
Grumman Aircraft Engineering Corp., Bethpage, N.Y.
Hamilton Standard Div., United Aircraft Corp., Windsor Locks, Conn.
Holley Carburetor Co., Warren, Mich.
Hughes Tool Co., Aircraft Div., Culver City, Calif.
Industrial Acoustics Co., Inc., New York, N.Y.
International Nickel Co., Inc., New York, N.Y.
Investment Casting Institute, Chicago, Ill.
Israel Aircraft Industries Ltd., Lod Airport, Israel
Kaman Aircraft Corp., Bloomfield, Conn.
Kelsey Hayes Co., Utica, N.Y.
Koopers Co. Inc., Sound Control Dept., Baltimore, Md.
Lear Jet Industries Inc., Wichita, Kans.
Ling-Temco-Vought Inc., Dallas, Tex.
Lockheed California Co., Div. of Lockheed Aircraft Corp., Burbank, Calif.
Lycoming Div., Avco Corp., Stratford, Conn.
Magnaflux Corp., Chicago, Ill.
Materials Systems Div., Union Carbide Corp., Indianapolis, Ind.
McDonnell Douglas Corp., St. Louis, Mo.
Misco Precision Casting Div., Howe Sound Co., Whitehall, Mich.
Mooney Aircraft Inc., Kerrville, Tex.
Naval Air Training Command, Washington, D.C.
North American Aviation Inc., Los Angeles and El Segundo, Calif.
Northrop Corp., Beverly Hills, Calif.
Pan American World Airways, New York, N.Y.
Pesco Products Div., Borg-Warner Corp., Bedford, Ohio
Phillips Petroleum Co., Bartlesville, Okla.
Philosophical Library Inc., New York, N.Y.
Power Equipment Div., Lear Siegler Inc., Cleveland, Ohio
Pratt & Whitney Aircraft Div., United Aircraft Corp., E. Hartford, Conn.
Rolls Royce Ltd., Derby, England
Ryan Aeronautical Co., San Diego, Calif.
Scintilla Div., Bendix Corp., Sidney, N.Y.
Shell Oil Co., New York, N.Y.
Sikorsky Aircraft Div., United Aircraft Corp., Stratford, Conn.
Society of Automotive Engineers, New York, N.Y.
Socony Mobil Oil Co., Inc., New York, N.Y.
Solar Div., International Harvester Co., San Diego, Calif.
Stalker Development Co., Bay City, Mich.
Sundstrand Aviation Div., Sundstrand Corp., Rockford, Ill.
Texaco, Inc., New York, N.Y.

Thermal Dynamics Corp., Lebanon, N.H.
United Aircraft of Canada Ltd., Longueuil, Canada
Utica Div., Bendix Corp., Utica, N.Y.
Vertol Div., Boeing Airplane Co., Morton, Pa.
Welding Journal, American Welding Society, New York, N.Y.
Westinghouse Research Laboratory, Pittsburgh, Pa.
Woodward Governor Co., Rockford, Ill.
Wyman-Gordon Co., Worcester, Mass.

A special note of thanks to my wife for all her help and encouragement.

IRWIN E. TREAGER

Contents

PART 1

History and theory

Chapter **1**

Background and development

Long before man appeared on earth, nature had given some creatures of the sea, such as the squid and the cuttlefish, the ability to jet propel themselves through the water (Fig. 1-1).

There have been many examples of the utilization of the reaction principle during the early periods of recorded history, but because a suitable level of technical achievement in the areas of engineering, manufacture, and metallurgy had not been reached, there was a gap of over 2000 years before a practical application of this principle became possible.

THE AEOLIPILE

Hero, an Egyptian scientist who lived in Alexandria around 100 B.C. is generally given credit for conceiving and building the first "jet engine." His device, called an *aeolipile* (Fig. 1-2), consisted of a boiler or bowl which held a supply of water. Two hollow tubes extended up from this boiler and supported a hollow sphere which was free to turn on these supports. Attached to the sphere were two small pipes or jets whose openings were at right angles to the axis of rotation of the sphere. When the water in the bowl was made to boil, the steam shooting from the two small jets caused the sphere to spin, very much like the lawn sprinkler is made to spin from the reaction of the water leaving its nozzles. (This phenomenon will be explained in Chap. 3.) Incidentally, the aeolipile was only one of a number of inventions credited to Hero, which include a water clock, a compressed air catapult, and a hydraulic organ. He also wrote many works on mathematics, physics, and mechanics.

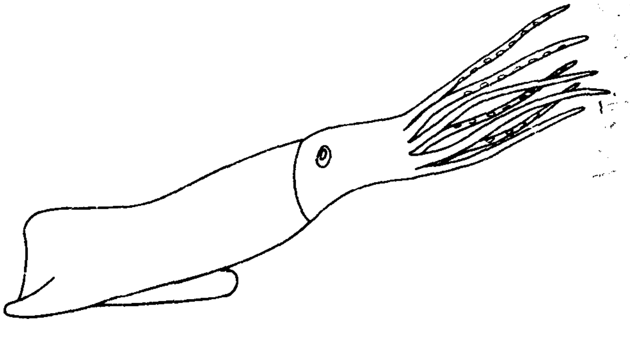

FIG. 1-1 *The squid, a jet-propelled fish.*

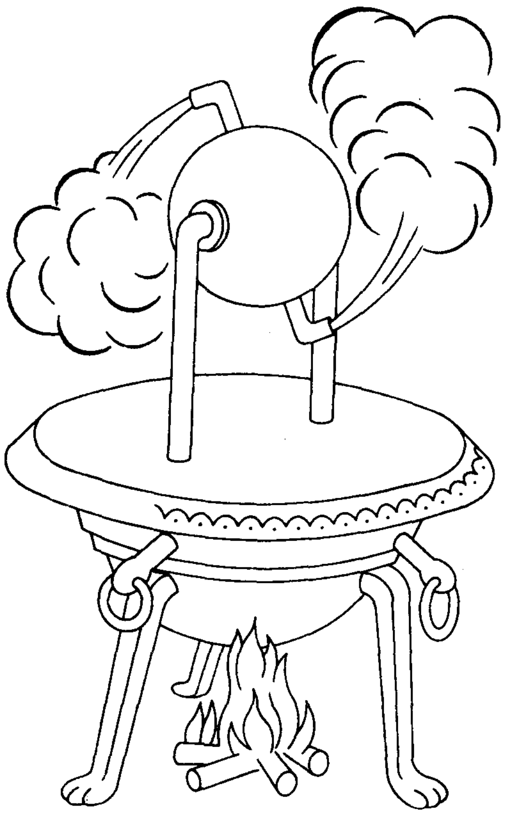

FIG. 1-2 *Hero's aeolipile.*

LEONARDO DA VINCI

Around A.D. 1500 Leonardo Da Vinci described the *chimney jack* (Fig. 1-3), a device which was later widely used for turning roasting spits. As the hot air from the fire rose, it was made to pass through a series of fanlike blades which, through a series of gears, turned a roasting spit, thus illustrating another application of the reaction principle.

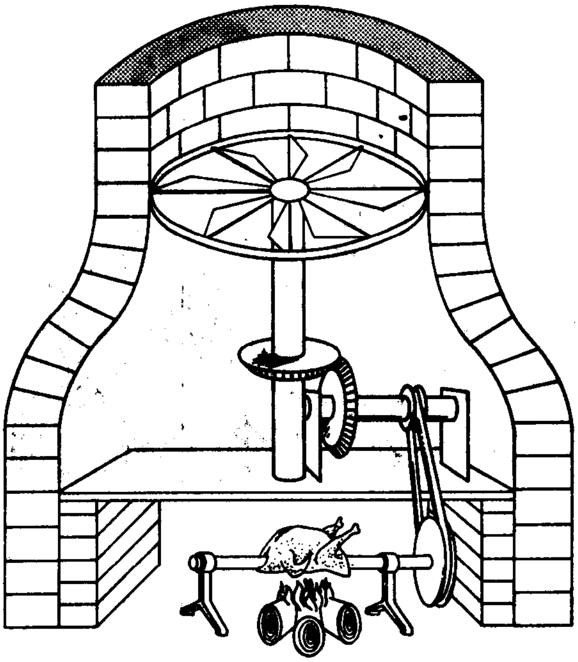

FIG. 1-3 *Da Vinci's chimney jack.*

ROCKETS AS A FORM OF JET PROPULSION

The invention of gunpowder allowed the continued development of the reaction principle. Rockets, for example, were constructed apparently as early as 1232 by the Mongols for use in war and for fireworks displays. One daring Chinese scholar named Wan Hu intended to use his rockets as a means of propulsion (Fig. 1-4). His plan was simple. A series of rockets were lashed to a chair under which sledlike runners had been placed. Unfortunately, when the rockets were ignited, the blast that followed completely obliterated Wan Hu and the chair, making him the first martyr in man's struggle to achieve flight. In later times rockets were used during several wars, including the Napoleonic Wars. The phrase "the rocket's red glare" in our national anthem refers to the use of rockets by the British in besieging Fort McHenry in Baltimore, during the war of 1812. And, of course, the German use of the V-2 rocket during World War II, and the subsequent development of space vehicles is contemporary history.

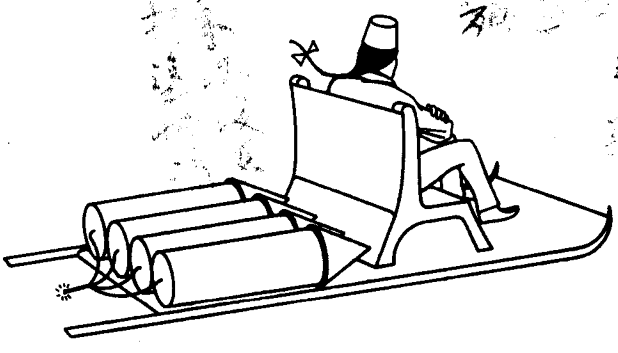

FIG. 1-4 *Chinese rocket sled.*

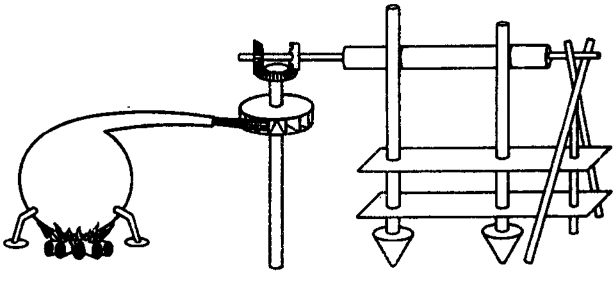

FIG. 1-5 *Branca's jet turbine.*

BRANCA'S STAMPING MILL

A further application of the jet-propulsion principle, utilizing what was probably the first actual impulse turbine, was the invention of a stamping mill built in 1629 by Giovanni Branca, an Italian engineer (Fig. 1-5). The turbine was driven by steam generated in a boiler. The jet of steam from a nozzle in this boiler impinged on the blades of a horizontally mounted turbine wheel which, through an arrangement of gearing, caused the mill to operate.

SIR ISAAC NEWTON

It was at this point in history (1687) that Sir Isaac Newton formulated the laws of motion (discussed in detail in Chap. 3) on which all devices utilizing the jet-propulsion theory are based. The vehicle illustrated in Fig. 1-6, called Newton's wagon, applied the principle of jet propulsion. It is thought that Jacob Gravesand, a Dutchman, actually designed this "horseless carriage," and that Isaac Newton may have only supplied the idea. The wagon consisted essentially of a large boiler

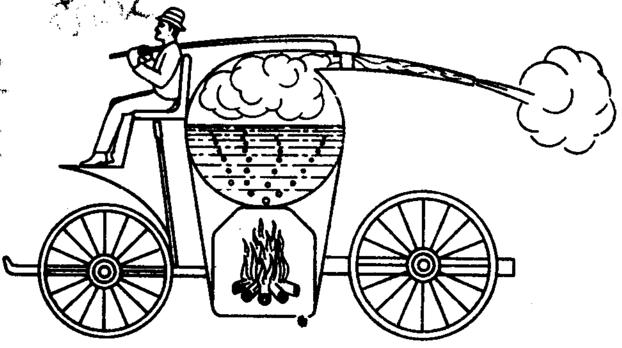

FIG. 1-6 *Newton's steam wagon.*

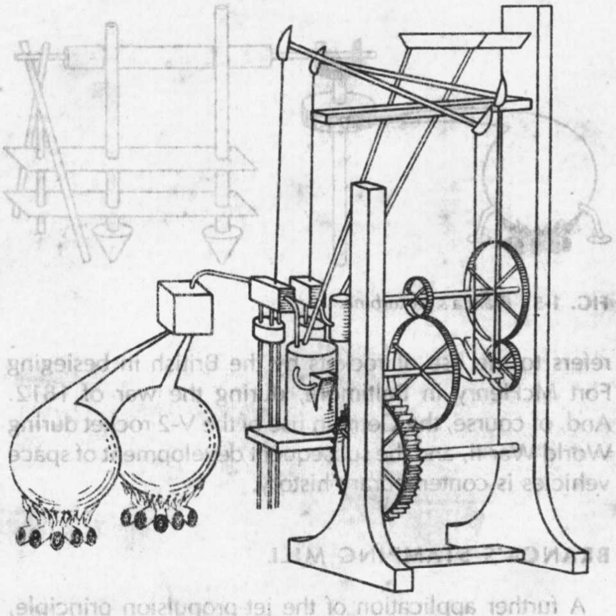

FIG. 1-7 *Barber's British patent—1791.*

mounted on four wheels. Steam generated by a fire built below the boiler was allowed to escape through a nozzle facing rearward. The speed of the vehicle was controlled by a steam cock located in the nozzle.

向后方

THE FIRST GAS TURBINE

In 1791 John Barber, an Englishman, was the first to patent a design utilizing the thermodynamic cycle of the modern gas turbine and suggested its use for jet propulsion (Fig. 1-7). The turbine was equipped with a chain-driven reciprocating type of compressor, but was otherwise basically the same as the modern gas turbine in that it had a compressor, a combustion chamber, and a turbine.

链条驱动

SIR FRANK WHITTLE

During the period between 1791 and 1930, many men supplied ideas which laid the foundation for the modern gas turbine engine as we know it today. When in 1930 Frank Whittle submitted his patent application for a jet aircraft engine, he had the contributions of many men to draw from. For example:

Sir George Caley—Invented the reciprocating hot air engine. This engine (1807) operated on the same cycle principle as the modern closed cycle gas turbine.

Dr. F. Stoltz—Designed an engine (1872) approaching the concept of the modern gas turbine engine. The engine never ran under its own power because component efficiencies were too low.

Sir Charles Parsons—Took out many comprehensive gas turbine patents (1884).

Dr. Sanford A. Moss (Fig. 1-8)—Did much work on the gas turbine engine, but whose chief contribution lies in the development of the turbosupercharger. Credit for the basic idea for the turbosupercharger is given to Rateau of France; it is in reality very similar to a jet engine, lacking only the combustion chamber (Fig. 1-9).

Dr. A. A. Griffith—Member of the British Royal Aircraft establishment who developed a theory of turbine design based on gas flows past airfoils, rather than through passages.

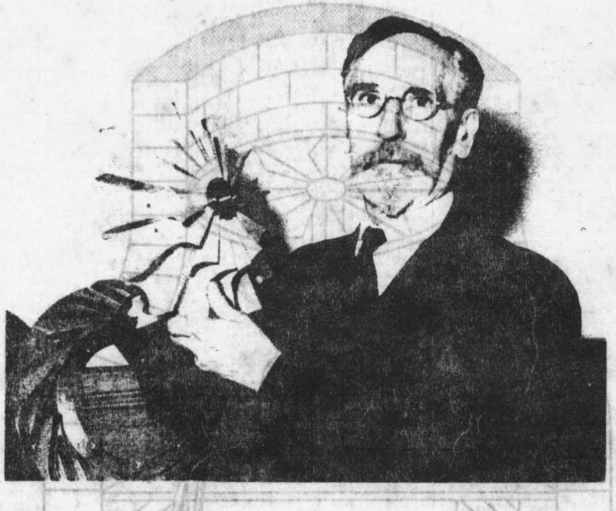

FIG. 1-8 *Dr. Sanford Moss.*

The work of many others, in addition to those mentioned, preceded Whittle's efforts. In addition, there were several jet-engine developments occurring concurrently in other countries. These developments are discussed on the following pages. Whittle is considered by many to be the father of the jet engine, but his contribution lies mainly in the application to aircraft of this type of engine which, as indicated previously, was already somewhat refined.

同时

In 1928, at the time that Dr. Griffith was involved in his work with compressors and other parts of the gas

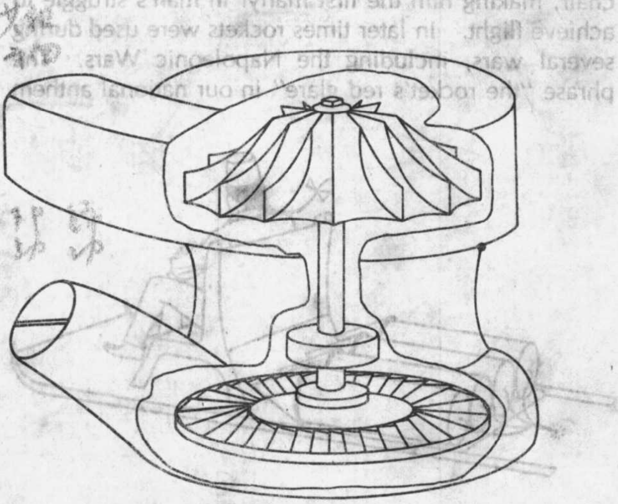

FIG. 1-9 *A turbosupercharger.*

turbine, Whittle , then a young air cadet at the R.A.F. College in Cramwell, England, submitted a thesis in which he proposed the use of the gas turbine engine for jet propulsion. It was not until 18 months later that this idea crystallized, and he began to think seriously about using the gas turbine engine for jet propulsion. By January of 1930, Whittle's thinking on the subject had advanced to the point that he submitted a patent application on the use of the gas turbine for jet propulsion (Fig. 1-11). In this patent was included ideas for the athodyd, or ramjet, but this was removed from the specifications when it was determined that the ramjet idea had already been proposed.

The period between 1930 and 1935 was one of frustration for Whittle and his coworkers. During this time his idea had been turned down by the British Air Ministry, and by several manufacturing concerns because the gas turbine was thought to be too impractical for flight. In 1935, while he was at Cambridge studying engineering, he was approached by two former R.A.F. officers, Williams and Tinling, with the suggestion that Whittle should acquire several patents (he had allowed the original patent to lapse), and they would attempt to raise money in order to build an experimental model of Whittle's engine. Eventually, with the help of an investment banking firm, Power Jets Ltd. was formed in March of 1936.

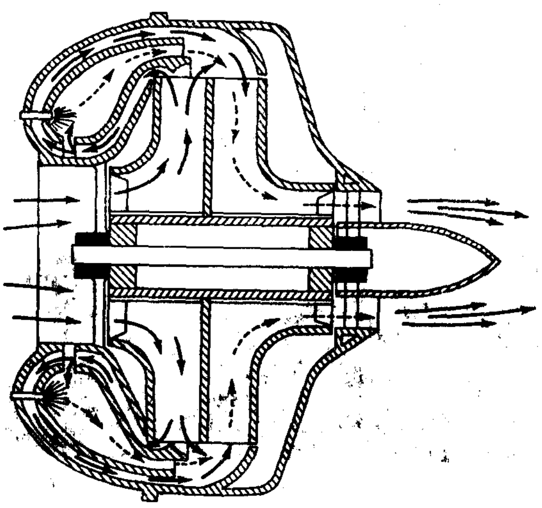

FIG. 1-11 *Whittle's patent drawing. (G. G. Smith, "Gas Turbines and Jet Propulsion," Philosophical Library, Inc., New York, 1955.)*

Before the new company was formed, the banking firm had placed an order with the British Thomson-Houston Company at Rugby for the actual construction of the engine, minus the combustion chamber and instrumentation. Originally Whittle had planned to build and test each component of the engine separately, but this proved to be too expensive. As planned, the new engine was to incorporate specifications beyond any existing gas turbine. As Whittle explains in his book, "Jet—The Story of a Pioneer":

> Our compressor was of the single stage centrifugal type generally similar to, but much larger than, an aero-engine supercharger (or fan unit of a vacuum cleaner). The turbine was also a single stage unit. Thus the main moving part of the engine—the rotor—was made up of the compressor impeller, the turbine wheel and the shaft connecting the two. It was designed to rotate at 17,750 revolutions per minute, which meant a top speed of nearly 1500 feet per second for the 19 inch diameter impeller and 1250 feet per second for the 16½ inch diameter turbine. [Author's note: $\text{fps} = (\pi D/12)(\text{rpm}/60)$.]
>
> Our targets for performance for the compressor, combustion chamber assembly and turbine were very ambitious and far beyond anything previously attained with similar components.
>
> The best that had been achieved with a single stage centrifugal compressor was a pressure ratio of 2.5 with an efficiency of 65 percent (an aero-engine supercharger). Our target was a pressure ratio of 4.0 with an efficiency of 80 percent.
>
> Our designed airflow of 1500 pounds per minute (25 pounds per second) was far greater in proportion to size than anything previously attempted (that was one of the reasons why I expected to get high efficiency). For this pressure ratio and airflow the compressor required over 3000 horsepower to drive it. Power of this order from such a small single stage turbine was well beyond all previous experience. Finally, in the combustion chamber, we aimed to burn nearly 200 gallons of fuel per hour in a space of about six cubic feet. This required a combustion intensity many times greater than a boiler furnace.

The design and manufacture of the combustion chamber, which was let to an oil burner firm, Laidlaw, Drew and Company, proved to be one of the most difficult design problems in the engine. But by April 1937, testing on the first engine began, and although the engine's performance did not come up to specifications and there was much heartbreaking failure, the machine showed enough promise to prompt the official entry of the Air Ministry into the picture (Fig. 1-12). With new funds, the original engine was rebuilt and the combustion chamber design was improved somewhat. Testing was continued at a new site because of the danger involved.

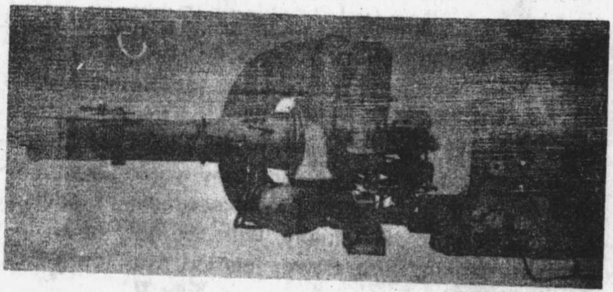

FIG. 1-12 *Whittle's first experimental engine—1937. (G. C. Smith, "Gas Turbines and Jet Propulsion," Philosophical Library, Inc., New York, 1955.)*

The original engine was reconstructed several times (Fig. 1-13). Most of the rebuilding was necessitated by turbine blade failures due to faulty combustion. But enough data had been collected to consider the engine a success, and by the summer of 1939, the Air Ministry awarded to Power Jets Ltd. a contract to design a flight engine. The engine was to be flight tested in an experimental airplane called the Gloster E28. On May 15, 1941, the W1 Whittle engine installed in the Gloster E28 made its first flight, with Flight Lieutenant P. E. G. Sayer as pilot. In subsequent flights during the next few weeks, the airplane achieved a speed of 370 mph in level flight, with 1000 lb of thrust. The Gloster/Whittle E28/39 is shown in Fig. 1-14. Sayer was later killed flying a conventional aircraft.

授予

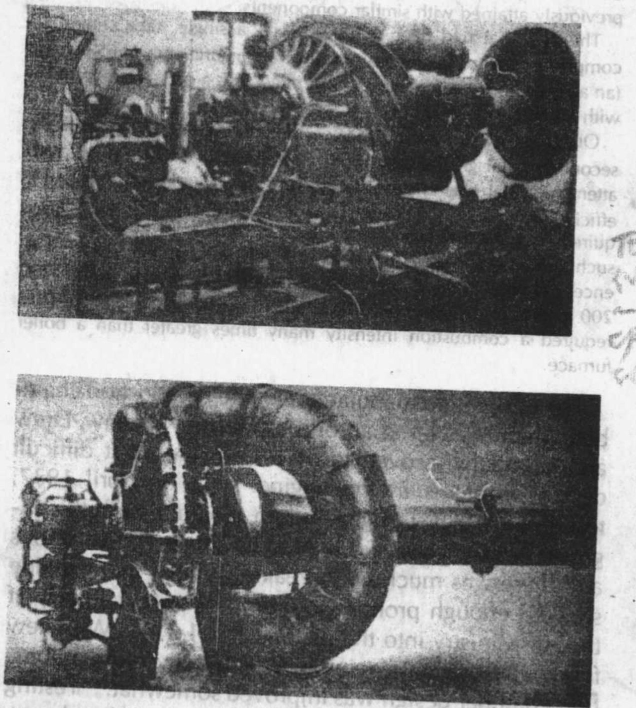

FIG. 1-13 *Early Whittle engine designs.*

FIG. 1-14 *The Gloster E28/39, which flew in 1941.*

GERMAN DEVELOPMENT

Work on the gas turbine engine was going on concurrently in Germany with Whittle's work in Britain. Serious efforts toward jet propulsion of aircraft were started in the middle 1930s. Two students at Gottingen, Germany, Hans von Ohain and Max Hahn, apparently unaware of Whittle's work, patented, in 1936, an engine for jet propulsion based on the same principles as the Whittle engine. These ideas were adapted by the Ernst Heinkel Aircraft Company and the second engine of this development made a flight with Erich Wahrsitz as pilot on August 27, 1939, which is now generally considered to be the *earliest date* of modern jet propulsion. The HE178 was equipped with a centrifugal flow jet engine, the Heinkel HeS-3b, which developed 1100 lb of thrust and had a top speed of over 400 mph (Fig. 1-15).

不知

Subsequent German development of turbojet-powered aircraft produced the ME262, a 500-mph fighter, powered by two axial flow engines. (The terms centrifugal flow and axial flow will be examined in Chap. 2.) More than 1600 ME262 fighters were built in the closing stages of World War II, but they reached operational status too late to seriously challenge the overwhelming air superiority gained by the Allies (Fig. 1-16). These engines were far ahead of contemporary British developments and they foreshadowed many of the features of the more modern engine, such as blade cooling, ice prevention, and the variable area exhaust nozzle. An interesting sidelight to the German contribution was

挑战

预示

FIG. 1-15 *The HE178 was the first true jet-propelled aircraft to fly (1939). (J. V. Casamassa and R. D. Bent, "Jet Aircraft Power Systems," 3d ed., McGraw-Hill Book Company, New York, 1965.)*

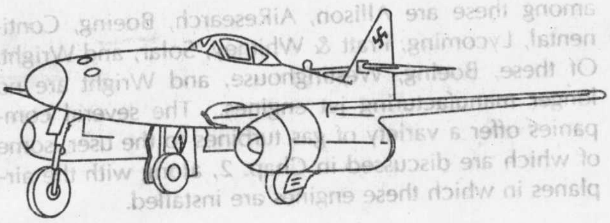

FIG. 1-16 *The ME262 German operational jet fighter.*

滑翔机

that on September 30, 1929, a modified glider using Opel rockets was the world's first airplane to achieve flight using a reaction engine.

ITALIAN CONTRIBUTION

Although strictly speaking not a gas turbine engine in the present sense of the term, an engine designed by Secundo Campini of the Caproni Company in Italy utilized the reaction principle (Fig. 1-17). A successful flight was made in August 1940, and was reported, at the time, as the first successful flight of a jet-propelled aircraft (Fig. 1-18). The power plant of this aircraft was not a "jet" because it relied upon a conventional 900-hp reciprocating engine instead of a turbine to operate the three-stage compressor. Top speed for this aircraft was a disappointing 205 mph, and the project was abandoned in late 1948.

令人失望

放弃

开始 发射出现 设计 制图

DEVELOPMENT IN AMERICA

America was a late-comer to the jet-propulsion field, although it must be said that at the time it was felt that the war would have to be won with airplanes using conventional reciprocating engines.

In September of 1941, under the auspices of the N.A.C.A. (National Advisory Committee for Aeronautics), the W.1X engine, which was the forerunner of the W.1, and a complete set of plans and drawings for the more advanced W.2B gas turbine, were flown to the United States under special arrangements between the British and American governments. A group of Power Jets engineers was also sent. The General Electric Corporation was awarded the contract to build an American version of this engine because of their previous experience with turbosuperchargers and Moss' pioneering work in this area.

先驱者

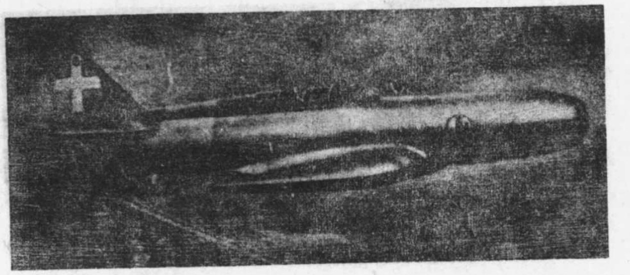

FIG. 1-18. *The Caproni-Campini CC-2 flew using the engine configuration shown in Fig. 1-17.* (G. G. Smith, *"Gas Turbines and Jet Propulsion," Philosophical Library, Inc., New York, 1955.*)

The first jet airplane flight in this country was made in October 1942, in a Bell XP-59A (Fig. 1-19) with Bell's chief test pilot Robert M. Stanley at the controls. The two General Electric I-A engines (Fig. 1-20) used in this experimental airplane were adaptations of the Whittle design. But while the Whittle engine was rated at 850 lb of thrust, the I-A was rated at about 1300 lb of thrust and with a lower specific fuel consumption. (Specific fuel consumption will be defined later in the book.) To make the story even more dramatic, both engine and airframe were designed and built in one year. A project of similar proportions would take several years at the present time.

戏剧性的

General Electric's early entry into the jet-engine field gave the company a lead in the manufacturing of gas turbines, but they were handicapped somewhat by having to work with preconceived ideas, after having seen Whittle's engine and drawings. Now, the N.A.C.A. Jet Propulsion Committee began to look about for a manufacturer to produce an all-American engine. Their choice was the Westinghouse Corporation, because of this company's previous experience with steam

妨碍

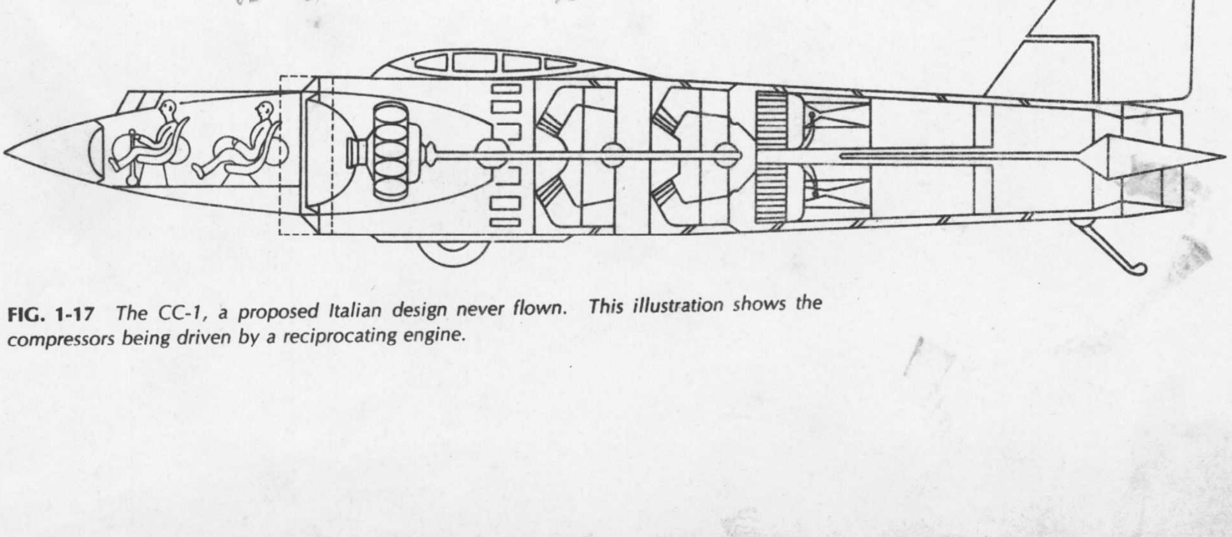

FIG. 1-17 *The CC-1, a proposed Italian design never flown. This illustration shows the compressors being driven by a reciprocating engine.*

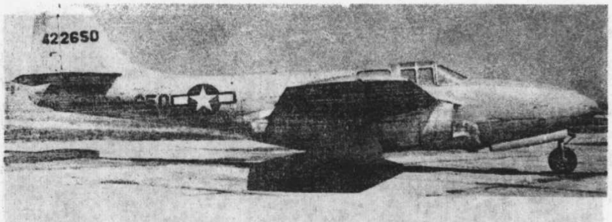

FIG. 1-19 *America's first jet airplane, the Bell XP-59A powered by two General Electric I-A engines.*

[illegible]

turbines. The contract was let late in 1941 by the Navy, but it was decided not to inform the Westinghouse people of the existence of the Whittle engine. As it turned out, this decision was a correct one, for the Westinghouse engineers designed an engine with an axial compressor and an annular combustion chamber. Both of these innovations, or variations thereof, have stood the test of time and are being used in contemporary engines. 当代

Shortly thereafter, several other companies began to design and produce gas turbine engines. Notable among these are Allison, AiResearch, Boeing, Continental, Lycoming, Pratt & Whitney, Solar, and Wright. Of these, Boeing, Westinghouse, and Wright are no longer manufacturing jet engines. The several companies offer a variety of gas turbines to the user, some of which are discussed in Chap. 2, along with the airplanes in which these engines are installed.

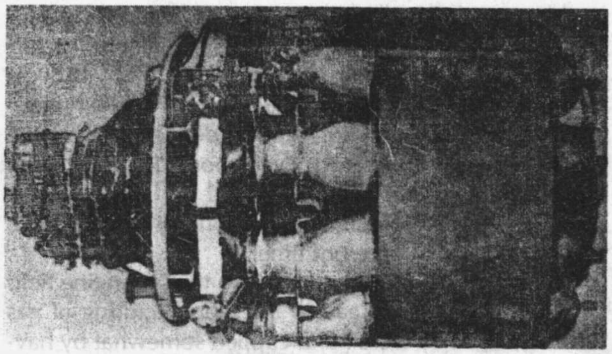

FIG. 1-20 *General Electric I-A, the first jet engine built in the U.S.*

REVIEW AND STUDY QUESTIONS

1 How old is the idea of jet propulsion?

2 Describe the first practical device utilizing the reaction principle.

3 What was Leonardo Da Vinci's contribution to the development of a jet engine?

4 Who were the first people to use rockets? Give an example of the use of rockets in war.

5 Between the years 1600 and 1800, who were the contributors to the development of the gas turbine engine? What were those contributions?

6 What was Sir Frank Whittle's chief contribution to the further development of the gas turbine engine?

7 Give a brief outline of the efforts of Whittle and his company to design a jet engine.

8 Describe the German contributions to the jet engine.

9 Which country was the first to fly a jet-powered aircraft? What was the designation of this airplane and with what type of engine was it equipped?

10 When considering who was first with the development of a jet engine, why should the Italian engine be discounted?

11 What American company was chosen to build the first jet engine? Why?

12 Describe the series of events leading up to the first American jet airplane. Who built this plane?

13 List several American companies who manufacture gas turbine engines.

Chapter **2**

Types, variations, and applications

THE GAS TURBINE ENGINE

Gas turbine engines can be classified according to the type of compressor used, the path the air takes through the engine, and how the power produced is extracted or used (Fig. 2-1).

Compressor types fall into three categories:

1. Centrifugal flow
2. Axial flow
3. Centrifugal-axial flow

while power usage produces the following divisions:

1. Turbojet engines
2. Turbofan engines
3. Turboprop engines
4. Turboshaft engines

Compression is achieved in a centrifugal-flow engine by accelerating air outward perpendicular to the longitudinal axis of the machine, while in the axial-flow type, air is compressed by a series of rotating and stationary airfoils moving the air parallel to the longitudinal axis. The centrifugal-axial design uses both kinds of compressors to achieve the desired compression.

In relation to power usage, the turbojet engine directly uses the reaction resulting from a stream of high-energy gas emerging from the rear of the engine at a higher velocity than it had at the forward end. The turbofan engine also uses the reaction principle, but the gases exiting from the rear of this engine type, have a lower energy level, since some power has to be extracted to drive the fan. (See pages 59–60 for a more detailed explanation of the operating principles of the fan engine.)

Turboprop and turboshaft engines both convert the majority of the kinetic (energy of motion), static (energy of pressure), and temperature energies of the gas into torque to drive the propeller in one case, and a shaft in the other. Very little thrust from reaction is produced by the exiting gas stream.

From these basic types of gas turbine engines have come the literally dozens of variations that are either in actual service, or are in various stages of development. Many combinations are possible, since the centrifugal- and axial-flow compressor engines can be used for turbojet, turbofan, turboprop, or turboshaft applications. Furthermore, within the major classifications, are a host of variations, some of which are discussed on the following pages.

CENTRIFUGAL COMPRESSOR ENGINES

Variations of this type of compressor include the single-stage, two-stage, and single-stage double-entry compressor (Fig. 2.2). The centrifugal design works well for small engines where a high compression ratio (pressure rise across the compressor) is not too essential, or where other design or operational considerations may take precedence.

The principal advantages of the compressor are:

1. Light weight
2. Ruggedness, and therefore resistance to foreign object damage
3. Simplicity
4. Low cost

Probably the most famous example of this type of power plant is the Allison J33 (Fig. 2-3), used in the first U.S.A.F. jet, the Lockheed P-80. Newer versions are still being used in the T-33 (Fig. 2-4), which is a training version of the P-80. Centrifugal compressors have found wide acceptance on smaller gas turbine engines. An example of this application is the Continental J69 (Fig. 2-5). Models of this engine are being used in the Cessna T-37 (Fig. 2-6), the U.S.A.F.'s primary trainer. Another example of an engine equipped with a form of the centrifugal compressor is the Rolls Royce Dart (Fig. 2-7). This is a highly produced turboprop engine incorporating a two-stage compressor and integral propeller reduction gearbox (see Fig. 2-33 for an example of an engine equipped with a separate propeller reduction gearbox) and is used in the Convair Conversion 600, Grumman Gulfstream, and Fairchild F-27 (Fig. 2-8).

Several illustrations of the centrifugal compressor used in ground power or auxiliary engines are shown in Figs. 2-9, 2-10, and 2-11. An interesting feature to note on some of these engines is the radial inflow gas-producer turbine shown in Fig. 2-11*a* and *b*, and the "free-power" turbine shown in Figs. 2-10 and 2-11a

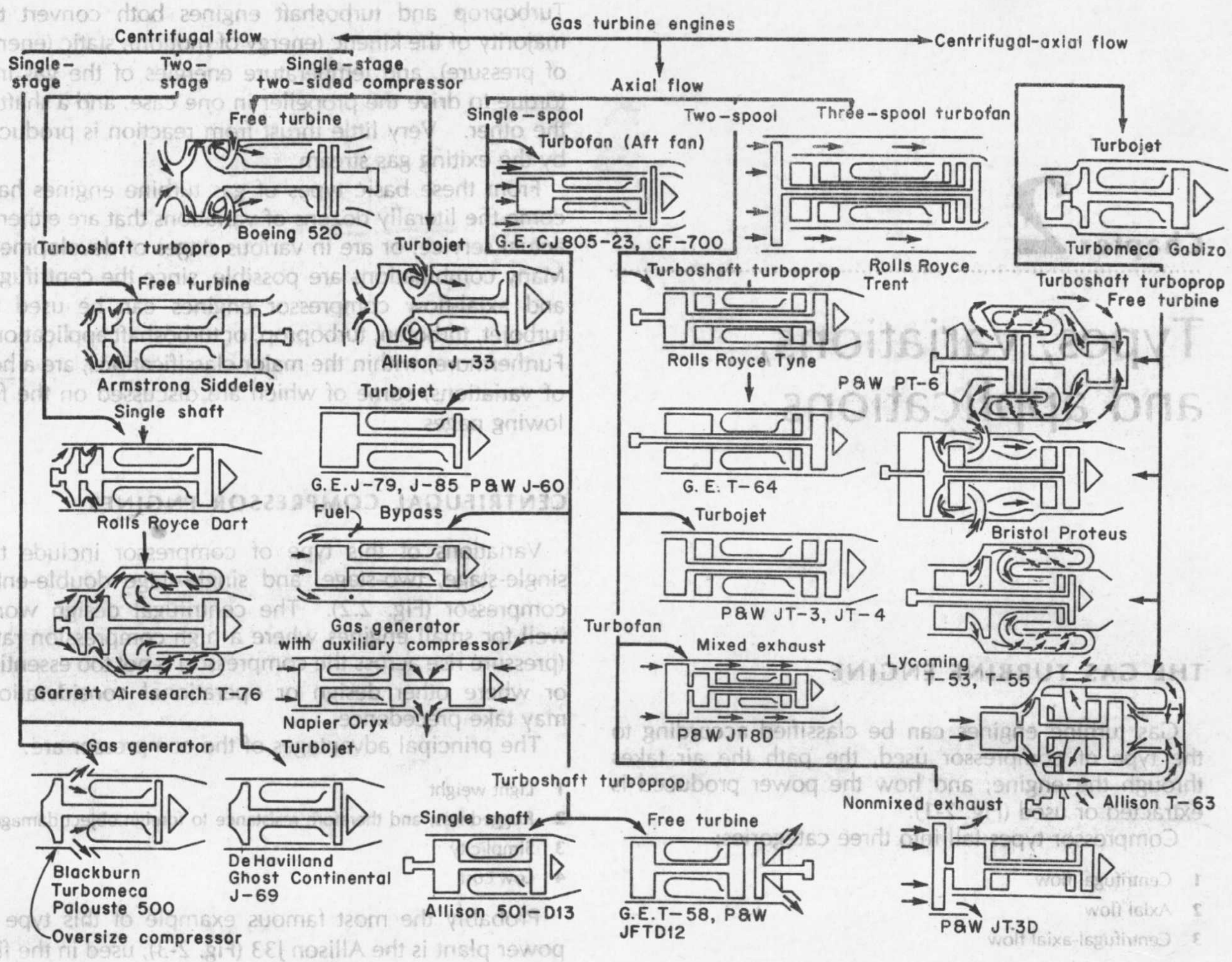

FIG. 2-1 *The family tree.*

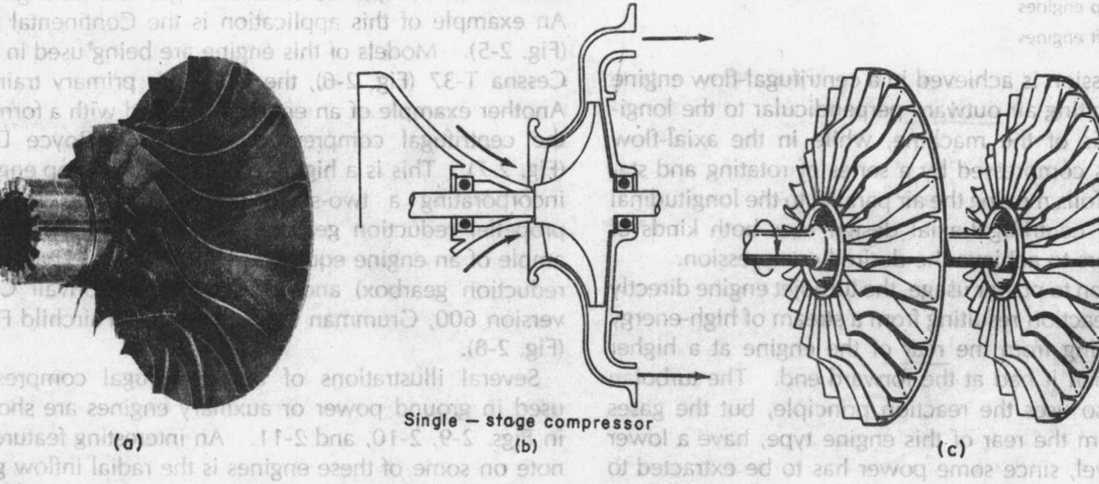

FIG. 2-2 *Drawings showing the three basic forms of centrifugal compressors and schematics showing the airflow through each.* **(a)** *and* **(b)** *Single-stage compressor.* **(c)** *Two-stage compressor. (Continued on following page.)*