Elements of Propulsion: Gas Turbines and Rockets

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Foreword by
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German Inventor of the Jet Engine

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I have been blessed to share my life with Sheila, my best friend and wife. She has been my inspiration and helper, and the one who sacrificed the most to make this work possible. I dedicate this book and the accompanying software to Sheila.

I would like to share with all the following passage I received from a very close friend about 30 years ago. This passage provides guidance and focus to my life. I hope it can be as much help to you.

FABRIC OF LIFE

I want to say something to all of you
Who have become a part
Of the fabric of my life
The color and texture
Which you have brought into
My being
Have become a song
And I want to sing it forever.
There is an energy in us
Which makes things happen
When the paths of other persons
Touch ours
And we have to be there
And let it happen.
When the time of our particular sunset comes
Our thing, our accomplishment
Won't really matter
A great deal.
But the clarity and care
With which we have loved others
Will speak with vitality
Of the great gift of life
We have been for each other.

Gregory Norbert, O.S.B.

Foreword to the Second Edition

We are very pleased to present the Second Edition of *Elements of Propulsion: Gas Turbines and Rockets* by Jack D. Mattingly. The original edition was a well-received, comprehensive, and in-depth treatment of these important topics. This new edition has updated the material and expanded the coverage, and we anticipate that it will be equally well received. An interesting feature of the first edition was a very extensive foreword by the jet engine pioneer, Hans Von Ohain. Indeed, it is so extensive and comprehensive that it is more a historical overview and introduction than a foreword. We deem it so useful that it is included in this edition as well. This Second Edition has ten chapters, seven appendices and more than 850 pages.

Jack Mattingly is extremely well qualified to write this book because of his broad expertise in the area. His command of the material is excellent, and he is able to organize and present it in a very clear manner. He is such a proficient author that he is the co-winner of the Martin Summerfield Book Award for another volume in this series.

The AIAA Education Series aims to cover a very broad range of topics in the general aerospace field, including basic theory, applications, and design. A complete list of titles can be found at http://www.aiaa.org. The philosophy of the series is to develop textbooks that can be used in a university setting, instructional materials for continuing education and professional development courses, and also books that can serve as the basis for independent study. Suggestions for new topics or authors are always welcome.

Joseph A. Schetz
Editor-in-Chief
AIAA Education Series

Foreword to the First Edition

Background

The first flight of the Wright brothers in December 1903 marked the beginning of the magnificent evolution of *human-controlled, powered flight.* The driving forces of this evolution are the ever-growing demands for improvements in

1) Flight performance (i.e., greater flight speed, altitude, and range and better maneuverability);
2) Cost (i.e., better fuel economy, lower cost of production and maintenance, increased lifetime);
3) Adverse environmental effects (i.e., noise and harmful exhaust gas effects);
4) Safety, reliability, and endurance; and
5) Controls and navigation.

These strong demands continuously furthered the efforts of advancing the aircraft system.

The tight interdependency between the performance characteristics of aerovehicle and aeropropulsion systems plays a very important role in this evolution. Therefore, to gain better insight into the evolution of the aeropropulsion system, one has to be aware of the challenges and advancements of aerovehicle technology.

The Aerovehicle

A brief review of the evolution of the aerovehicle will be given first. One can observe a continuous trend toward stronger and lighter airframe designs, structures, and materials—from wood and fabric to all-metal structures; to lighter, stronger, and more heat-resistant materials; and finally to a growing use of strong and light composite materials. At the same time, the aerodynamic quality of the aerovehicle is being continuously improved. To see this development in proper historical perspective, let us keep in mind the following information.

In the early years of the 20th century, the science of aerodynamics was in its infancy. Specifically, the aerodynamic lift was not scientifically well understood. Joukowski and Kutta's model of lift by circulation around the wing and Prandtl's boundary-layer and turbulence theories were in their incipient stages. Therefore, the early pioneers could not benefit from existent

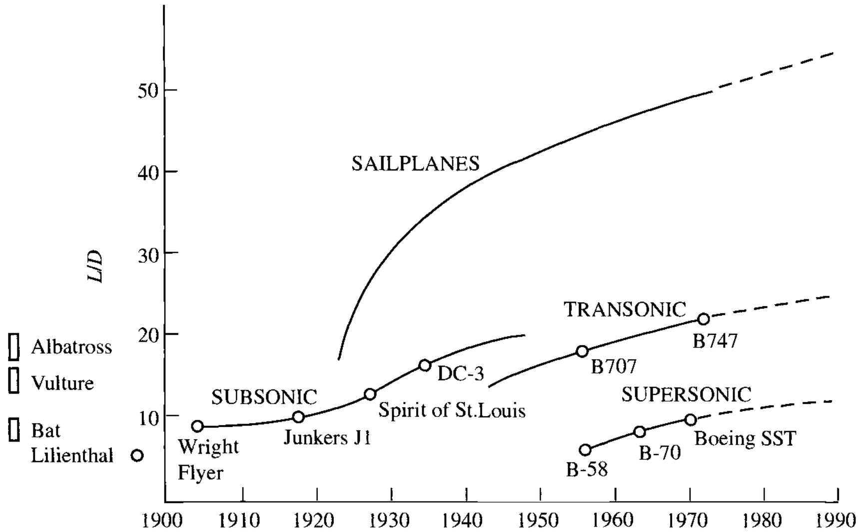

Fig. 1 Progress in lift/drag ratio L/D.

scientific knowledge in aerodynamics and had to conduct their own fundamental investigations.

The most desirable major aerodynamic characteristics of the aerovehicle are a low *drag coefficient* as well as a high *lift/drag ratio* L/D for cruise conditions, and a high *maximum lift coefficient* for landing. In Fig. 1, one can see that the world's first successful glider vehicle by Lilienthal, in the early 1890s, had an L/D of about 5. In comparison, birds have an L/D ranging from about 5 to 20. The Wright brothers' first human-controlled, powered aircraft had an L/D of about 7.5. As the L/D values increased over the years, sailplanes advanced most rapidly and now are attaining the enormously high values of about 50 and greater. This was achieved by employing ultrahigh wing aspect ratios and aerodynamic profiles especially tailored for the low operational Reynolds and Mach numbers. In the late 1940s, subsonic transport aircraft advanced to L/D values of about 20 by continuously improving the aerodynamic shapes, employing advanced profiles, achieving extremely smooth and accurate surfaces, and incorporating inventions such as the engine cowl and the retractable landing gear.

The continuous increase in flight speed required a corresponding reduction of the *landing speed/cruise speed* ratio. This was accomplished by innovative wing structures incorporating wing slots and wing flaps that, during the landing process, enlarged the wing area and increased significantly the lift coefficient. Today, the arrowhead-shaped wing contributes to a high lift for landing (vortex lift). Also, in the 1940s, work began to extend the high L/D value from the subsonic to the transonic flight speed regime by employing the swept-back wing and later, in 1952, the area rule of Whitcomb to reduce *transonic drag rise.* Dr. Theodore von Kármán describes in his memoirs, *The Wind and*

Beyond,* how the *swept-back wing* or simply *swept wing* for transonic and supersonic flight came into existence:

> The fifth Volta Congress in Rome, 1935, was the first serious international scientific congress devoted to the possibilities of supersonic flight. I was one of those who had received a formal invitation to give a paper at the conference from Italy's great Gugliemo Marconi, inventor of the wireless telegraph. All of the world's leading aerodynamicists were invited.
>
> This meeting was historic because it marked the beginning of the supersonic age. It was the beginning in the sense that the conference opened the door to supersonics as a meaningful study in connection with supersonic flight, and, secondly, because most developments in supersonics occurred rapidly from then on, culminating in 1946—a mere 11 years later—in Captain Charles Yeager's piercing the sound barrier with the X-1 plane in level flight. In terms of future aircraft development, the most significant paper at the conference proved to be one given by a young man, Dr. Adolf Busemann of Germany, by first publicly suggesting the swept-back wing and showing how its properties might solve many aerodynamic problems at speeds just below and above the speed of sound.

Through these investigations, the myth that sonic speed is the fundamental limit of aircraft flight velocity, the *sound barrier* was overcome.

In the late 1960s, the Boeing 747 with swept-back wings had, in transonic cruise speed, an L/D value of nearly 20. In the supersonic flight speed regime, L/D values improved from 5 in the mid-1950s (such as L/D values of the B-58 Hustler and later of the Concorde) to a possible L/D value of 10 and greater in the 1990s. This great improvement possibility in the aerodynamics of supersonic aircraft can be attributed to applications of artificial stability, to the area rule, and to advanced wing profile shapes that extend laminar flow over a larger wing portion.

The hypersonic speed regime is not fully explored. First, emphasis was placed on winged reentry vehicles and lifting bodies where a high L/D value was not of greatest importance. Later investigations have shown that the L/D values can be greatly improved. For example, the maximum L/D for a "wave rider" is about 6.† Such investigations are of importance for hypersonic programs.

The Aeropropulsion System

At the beginning of this century, steam and internal combustion engines were in existence but were far too heavy for flight application. The Wright brothers recognized the great future potential of the internal combustion engine and developed both a relatively lightweight engine suitable for flight application and an efficient propeller. Figure 2 shows the progress of the propulsion systems over the years. The Wright brothers' first aeropropulsion system had a shaft power of 12 hp, and its power/weight ratio (ratio of power output to total propulsion system weight, including propeller and transmission) was about 0.05 hp/lb.

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*Von Kármán, T., *The Wind and Beyond*, Little, Brown, Boston, 1967.

†Heiser, W. H., and Pratt, D.J., *Hypersonic Airbreathing Propulsion*, AIAA Education Series, AIAA, Washington, DC, 1994.

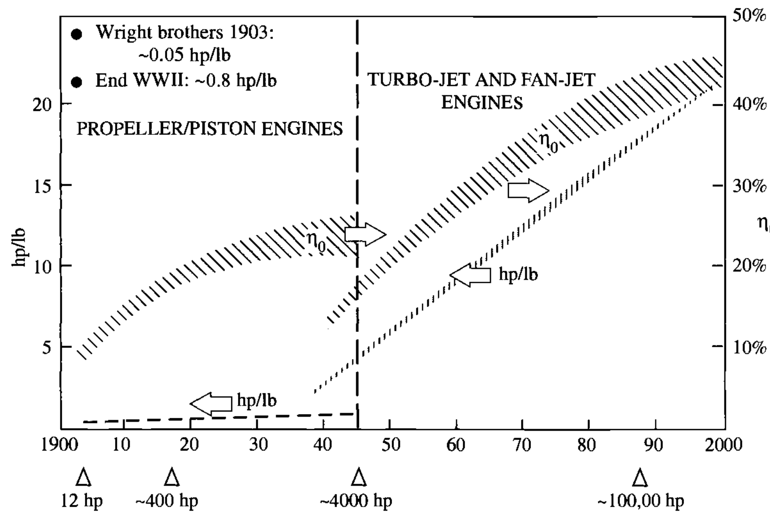


Fig. 2 Trends of power per weight (hp/lb) and overall efficiency (η_O) of aeropropulsion systems from 1900 to 2000.

Through the subsequent four decades of evolution, the overall efficiency and the power/weight ratio improved substantially, the latter by more than one order magnitude to about 0.8 hp/lb. This great improvement was achieved by engine design structures and materials, advanced fuel injection, advanced aerodynamic shapes of the propeller blades, variable-pitch propellers, and engine superchargers. The overall efficiency (engine and propeller) reached about 28%. The power output of the largest engine amounted to about 5000 hp.

In the late 1930s and early 1940s, the turbojet engine came into existence. This new propulsion system was immediately superior to the reciprocating engine with respect to the power/weight ratio (by about a factor of 3); however, its overall efficiency was initially much lower than that of the reciprocating engine. As can be seen from Fig. 2, progress was rapid. In less than four decades, the power/weight ratio increased more than 10-fold, and the overall efficiency exceeded that of a diesel propulsion system. The power output of today's largest gas turbine engines reaches nearly 100,000 equivalent hp.

Impact on the Total Aircraft Performance

The previously described truly gigantic advancements of stronger and lighter structures and greater aerodynamic quality in aerovehicles and greatly advanced overall efficiency and enormously increased power output/weight ratios in aeropropulsion systems had a tremendous impact on flight performance, such as on flight range, economy, maneuverability, flight speed, and altitude. The increase in flight speed over the years is shown in Fig. 3. The Wright brothers began with the first human-controlled, powered flight in 1903; they continued to

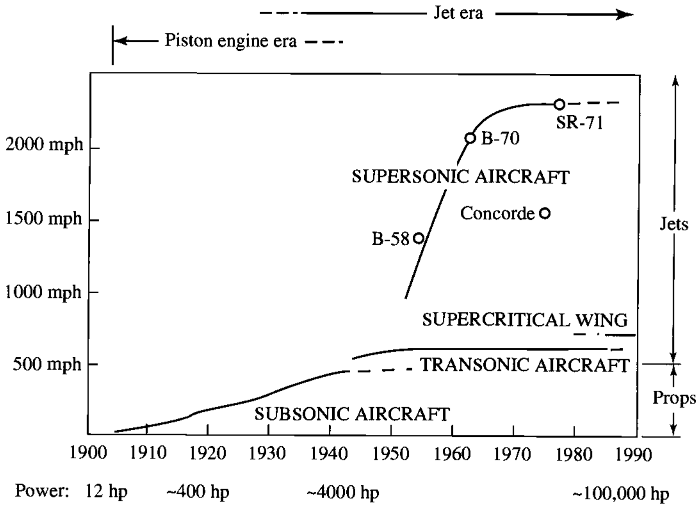


Fig. 3 Aircraft speed trends.

improve their aircraft system and, in 1906, conducted longer flights with safe takeoff, landing, and curved flight maneuvers. While the flight speed was only about 35 mph, the consequences of these first flights were enormous:

1) Worldwide interest in powered flight was stimulated.
2) The science of aerodynamics received a strong motivation.
3) The U.S. government became interested in power flight for potential defense applications, specifically reconnaissance missions.

In 1909, the Wright brothers built the first military aircraft under government contract. During World War I, aircraft technology progressed rapidly. The flight speed reached about 150 mph, and the engine power attained 400 hp. After World War I, military interest in aircraft systems dropped, but aircraft technology had reached such a degree of maturity that two nonmilitary application fields could emerge, namely:

1) Commercial aviation, mail and passenger transport (first all-metal monoplane for passenger and mail transport, the Junkers F13, in 1919, sold worldwide);
2) Stunt flying leading to general aviation (sport and private transportation).

In the period from 1920 to 1940, the speed increased from about 150 to 350 mph through evolutionary improvements in vehicle aerodynamics and engine technology, as discussed previously. At the end of World War II, the flight speed of propeller aircraft reached about 400–450 mph, and the power output of the largest reciprocating engines was about 5000 hp. This constituted almost the performance limit of the *propeller/reciprocating engine propulsion system.* Today, the propeller/reciprocating engine survives only in smaller, lower-speed aircraft used in general aviation.

In the late 1930s, jet propulsion emerged that promised far greater flight speeds than attainable with the propeller or piston engine. The first jet-propelled experimental aircraft flew in the summer of 1939 (the He-178), and in early 1941, the first prototype jet fighter began flight tests (He-280). In 1944, mass-produced jet fighters reached a speed of about 550 mph (Me-262).

In the early 1950s, jet aircraft transgressed the sonic speed. In the mid-1950s, the first supersonic jet bomber (B-58 Hustler) appeared, and later the XB-70 reached about Mach 3. Also during the 1950s, after more than 15 years of military development, gas turbine technology had reached such a maturity that the following commercial applications became attractive: 1) commercial aircraft, e.g., Comet, Caravelle, and Boeing 707; 2) surface transportation (land, sea); and 3) stationary gas turbines.

In the 1960s, the high-bypass-ratio engine appeared, which revolutionized military transportation (the C5A transport aircraft). At the end of the 1960s, based on the military experience with high-bypass-ratio engines, the second generation of commercial jet aircraft came into existence, the *widebody* aircraft. An example is the Boeing 747 with a large passenger capacity of nearly 400. Somewhat later came the Lockheed L-1011 and Douglas DC10. By that time, the entire commercial airline fleet used turbine engines exclusively. Advantages for the airlines were as follows:

1) Very high overall efficiency and, consequently, a long flight range with economical operation.
2) Overhaul at about 5 million miles.
3) Short turnaround time.
4) Passenger enjoyment of the very quiet and vibration-free flight, short travel time, and comfort of smooth stratospheric flight.
5) Community enjoyment of quiet, pollution-free aircraft.

By the end of the 1960s, the entire business of passenger transportation was essentially diverted from ships and railroads to aircraft. In the 1970s, the supersonic Concorde with a flight speed of 1500 mph (the third generation of commercial transport) appeared with an equivalent output of about 100,000 hp.

Summary

In hindsight, the evolution of aerovehicle and aeropropulsion systems looks like the result of a master plan. The evolution began with the piston engine and propeller, which constituted the best propulsion system for the initially low flight speeds, and had an outstanding growth potential up to about 450 mph. In the early 1940s, when flight technology reached the ability to enter into the transonic flight speed regime, the jet engine had just demonstrated its suitability for this speed regime. A vigorous jet engine development program was launched. Soon the jet engine proved to be not only an excellent transonic but also a supersonic propulsion system. This resulted in the truly exploding growth in flight speed, as shown in Fig. 3.

It is interesting to note that military development preceded commercial applications by 15–20 years for both the propeller engine and the gas turbine engine. The reason was that costly, high-risk, long-term developments conducted by the military sector were necessary before a useful commercial application could be envisioned. After about 75 years of powered flight, the aircraft has outranked all other modes of passenger transportation and has become a very important export article of the United States.

The evolutions of both aerovehicle and aeropropulsion systems have in no way reached a technological level that is close to the ultimate potential! The evolution will go on for many decades toward capabilities far beyond current feasibility and, perhaps, imagination.

How Jet Propulsion Came into Existence

The idea of airbreathing jet propulsion originated at the beginning of the 20th century. Several patents regarding airbreathing jet engines had been applied for by various inventors of different nationalities who worked independently of each other.

From a technical standpoint, *airbreathing jet propulsion* can be defined as a special type of internal combustion engine that produces its net output power as the rate of change in the kinetic energy of the engine's working fluid. The working fluid enters as environmental air that is ducted through an inlet diffuser into the engine; the engine exhaust gas consists partly of combustion gas and partly of air. The exhaust gas is expanded through a thrust nozzle or nozzles to ambient pressure. A few examples of early airbreathing jet propulsion patents are as follows:

1) In 1908, Lorin patented a jet engine that was based on piston machinery (Fig. 4a).
2) In 1913, Lorin patented a jet engine based on ram compression in supersonic flight (Fig. 4b), the *ramjet.*
3) In 1921, M. Guillaume patented a jet engine based on turbomachinery; the intake air was compressed by an axial-flow compressor followed by a combustor and an axial-flow turbine driving the compressor (Fig. 4c).

These patents clearly described the airbreathing jet principle but were not executed in practice. The reason lies mainly in the previously mentioned strong interdependency between aerovehicle and aeropropulsion systems. The jet engine has, in comparison with the propeller engine, a high exhaust speed (for example, 600 mph and more). In the early 1920s, the aerovehicle had a flight speed capability that could not exceed about 200 mph. Hence, at that time, the so-called propulsive efficiency of the jet engine was very low (about 30–40%) in comparison to the propeller, which could reach more than 80%. Thus, in the early 1920s, the jet engine was not compatible with the too-slow aerovehicle. Also, in the early 1920s, an excellent theoretical study about the possibilities of enjoying jet propulsion had been conducted by Buckingham of the Bureau of Standards under contract with NACA. The result of this study was clear—the jet engine could not be efficiently employed if the aerovehicle could not greatly exceed the flight speed of 200 mph; a flight speed beyond 400 mph seemed to be necessary. The consequences of the results of this study were that the aircraft engine industry and the scientific and engineering community had no interest in the various jet engine inventions. Thus the early jet engine

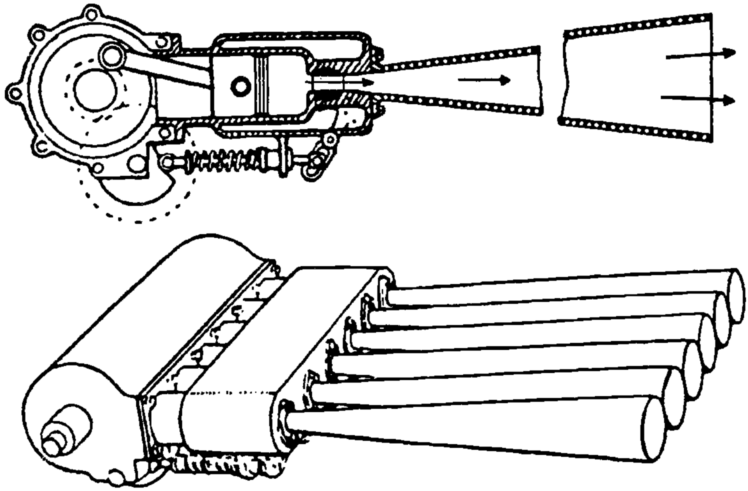


Fig. 4a Lorin's 1908 patent.

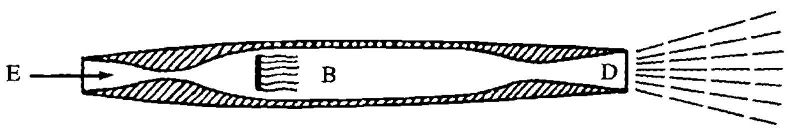


Fig. 4b Lorin's 1913 patent.

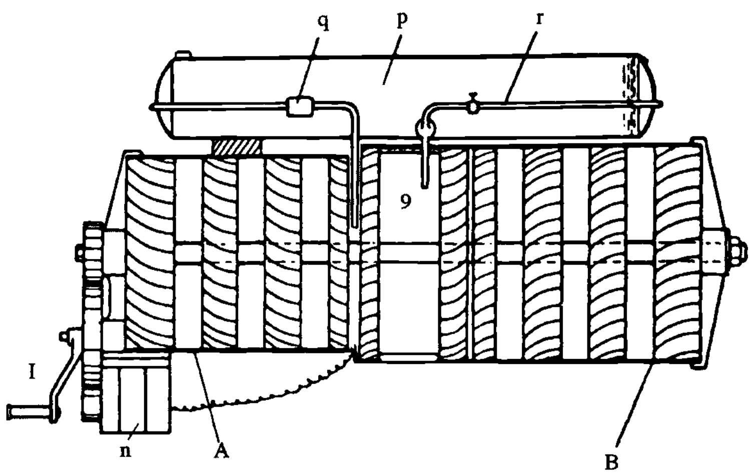


Fig. 4c 1921 Guillaume patent.

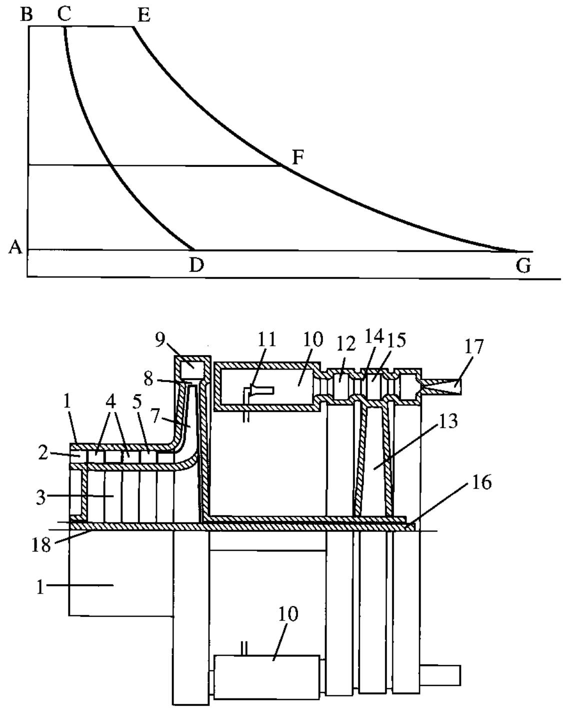


Fig. 5 Whittle's turbojet patent drawing. (National Air and Space Museum.)

concepts were forgotten for a long time. They were unknown to Sir Frank Whittle, to me, and to the British and German patent offices. In 1939, however, the retired patent examiner Gohlke found out about the early jet patents and published them in a synoptic review.

The first patent of a turbojet engine, which was later developed and produced, was that of Frank Whittle, now Sir Frank (see Fig. 5). His patent was applied for in January 1930. This patent shows a multistage, axial-flow compressor followed by a radial compressor stage, a combustor, an axial-flow turbine driving the compressor, and an exhaust nozzle. Such configurations are still used today for small- and medium-power output engines, specifically for remote-controlled vehicles.

Turbojet Development of Sir Frank Whittle

Frank Whittle[‡] was a cadet of the Royal Air Force. In 1928, when he was 21 years old, he became interested in the possibilities of rocket propulsion and

[‡]Boyne, W. J., and Lopez, D. S., *The Jet Age, Forty Years of Jet Aviation*, Smithsonian Inst. Press, Washington, DC, 1979.

propeller gas turbines for aircraft, and he treated these subjects in his thesis. He graduated and became a pilot officer, continuously thinking about airbreathing jet propulsion. In 1929, he investigated the possibilities of a ducted fan driven by a reciprocating engine and employing a kind of afterburner prior to expansion of the fan gas. He finally rejected this idea on the basis of his performance investigations. The same idea was conceived later in Italy and built by Caproni Campini. The vehicle flew on August 28, 1940, but had a low performance, as predicted by Sir Frank in 1929.

Suddenly, in December 1929, Frank Whittle was struck by the idea of increasing the fan pressure ratio and substituting a turbine for the reciprocating engine. This clearly constituted a compact, lightweight turbojet engine. He applied for a patent for the turbojet (Fig. 5) in January 1930.

Frank Whittle discussed this idea with fellow officers and his superior officer. They were very impressed, and a meeting was arranged between him and officials of the British Air Ministry, Department of Engine Development. This department, in turn, sought advice from Dr. A. A. Griffith, who was interested in the development of a propeller gas turbine. Dr. Griffith expressed doubts about the feasibility of Whittle's turbojet concept from a standpoint of too-high fuel consumption. Actually, *in high-speed flight*, the turbojet has great advantages over a propeller gas turbine due to the fact that the turbojet is much lighter than the propeller gas turbine and can fly faster because of the absence of the propeller. Whittle rightfully considered the turbojet as a fortunate synthesis or hybrid of the "propeller gas turbine" and "rocket" principles. As Sir Frank recalls, the department wrote a letter that, in essence, stated that any form of a gas turbine would be impractical in view of the long history of failure and the lack of turbine materials capable of withstanding the high stresses at high temperatures. Whittle's outstanding and very important views were that the flying gas turbine had great advantages over a stationary gas turbine power plant due to the efficient ram pressure recovery, low environmental temperature in high altitude, and high efficiency of the jet nozzle. Unfortunately, these views were ignored by the department.

Frank Whittle (Fig. 6) tried to interest the turbine industry in his concept of jet propulsion, but he did not succeed. Lacking financial support, Whittle allowed his patent to lapse. A long, dormant period was ahead for Frank Whittle's jet propulsion ideas.

After five years, in mid-1935, two former Royal Air Force (RAF) officers tried to revive Whittle's turbojet concept. Whittle was enthused and wrote, "the jet engine had, like the Phoenix, risen from its ashes."[§] At that time, Whittle was under enormous pressure. He was preparing for the examination in mechanical sciences (Tripos); his goal was to graduate with "First-Class Honors." Now, in addition, he had to design his first experimental jet engine in late 1935. In March 1936, a small company, Power Jets Ltd., was formed to build and test Whittle's engine, the W. U. (Whittle Unit). In spite of all the additional work, Whittle passed his exam in June 1936 with First-Class Honors.

[§]Boyne, W. J., and Lopez, D. S., *The Jet Age, Forty Years of Jet Aviation*, Smithsonian Inst. Press, Washington, DC, 1979.

Fig. 6 Frank Whittle using slide rule to perform calculations. (Bettman.)

In April 1937, Whittle had his bench-test jet engine ready for the first test run. It ran excellently; however, it ran out of control because liquid fuel had collected inside the engine and started to vaporize as the engine became hot, thereby adding uncontrolled fuel quantities to the combustion process. The problem was easily overcome. This first test run was the world's first run of a bench-test jet engine operating with liquid fuel (Fig. 7). In June 1939, the testing and development had progressed to a point that the Air Ministry's Director of Scientific Research (D.S.R.) promised Frank Whittle a contract for building a flight engine and an experimental aircraft, the Gloster E28/29 (Gloster/Whittle). On May 15, 1941, the first flight of the Gloster/Whittle took place (Fig. 8).

Senior ministry officials initially showed little interest, and a request for filming was ignored; however, during further flight demonstrations, interest in jet propulsion increased. Of particular interest was a performance demonstration given to Sir Winston Churchill. At that occasion, the Gloster/Whittle accelerated away from the three escorting fighters, one Tempest and two Spitfires.

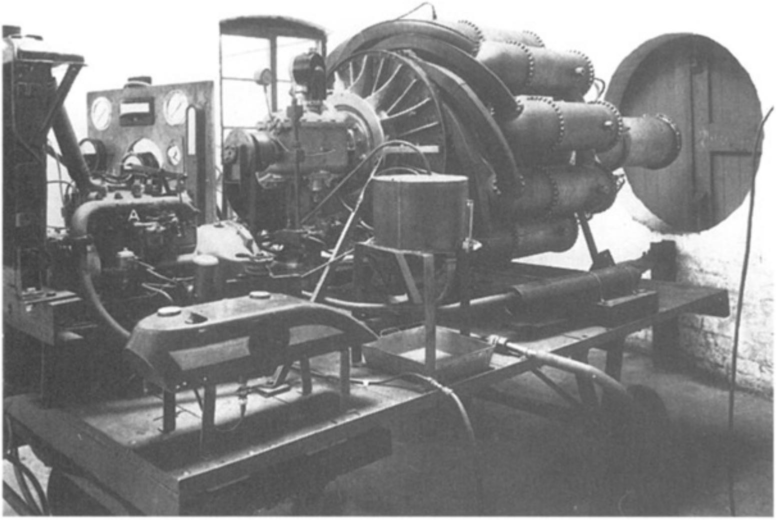


Fig. 7 Whittle's first experimental engine after second reconstruction in 1938. (National Air and Space Museum.)

Several British aircraft engine corporations adapted the work of Frank Whittle. Specifically, Rolls-Royce, due to the efforts of Sir Stanley G. Hooker,[¶] developed the first operational and the first production engine for the two-engine Gloster Meteor, Britain's first jet fighter. In March 1943, the Gloster Meteor prototype made its first flight, powered by two de Haviland (H-1) radial jet engines. In July 1944, the Meteor I, powered with two Rolls-Royce Welland engines, became operational. Its only combat action (in World War II) was in August 1944 in a successful attack against the German V1 flying bomb; it was the only fighter with sufficient level speed for the purpose. Mass production began with the Meteor III powered by two Rolls-Royce Dervents in 1945. The Meteor remained the RAF's first-line jet fighter until 1955.

From the beginning of his jet propulsion activities, Frank Whittle had been seeking means for improving the propulsive efficiency of turbojet engines.[¶] He conceived novel ideas for which he filed a patent application in 1936, which can be called a *bypass engine* or *turbofan.* To avoid a complete new design, Whittle sought an interim solution that could be merely "tacked on" to a jet engine. This configuration was later known as the *aft fan.* Whittle's work on *fan jets* or *bypass engines* and *aft fans* was way ahead of his time. It was of greatest importance for the future or turbopropulsion.

[¶]Schlaifer, R., and Heron, S. D., *Development of Aircraft Engines, and Fuels*, Pergamon Press, New York, 1970; reprint of 1950 ed.

Fig. 8 Gloster E28/29. (National Air and Space Museum.)

Whittle's Impact on U.S. Jet Development

In the summer of 1941, U.S. Army Air Corp General Henry H. Arnold was invited to observe flight demonstrations of the Gloster/Whittle. He was very impressed and decided this technology should be brought over to the United States. In September 1941, an agreement was signed between U.S. Secretary of War Stimson and Sir Henry Self of the British Air Commission. The United States could have the engine W1X and a set of drawings of the Whittle W2B jet engine, provided that close secrecy was maintained and the number of people involved were held to a minimum. Under these conditions, open bids for the jet engine development were not possible. General Arnold chose General Electric for jet engine development because of the great experience this company had in the development of aircraft engine turbosuperchargers. The W2B engine was built and tested on March 18, 1942, under the name *GE 1-A*. This engine had a static thrust of 1250 lb and weighed 1000 lb.[3] In the meantime, the Bell Aircomet (XP-59A) was being designed and built. On October 3, 1942, the Aircomet with two GE 1-A engines flew up to 10,000 ft. This aircraft, while in the first tests seemed to have good performance characteristics, had an incurable "snaking" instability and so provided a poor gun platform for a fighter pilot. Also, another serious shortcoming was that the top speed was not sufficiently above that of an advanced propeller fighter. For these reasons, the Bell XP-59A with two GE 1-A engines (W2B) did not become a production fighter. From these experiences, it appeared that an engine of more than 4000-1b thrust was required for a single-engine fighter that would be capable of more than 500 mph operational speed. Lockheed was chosen to design a new jet fighter because when the project was discussed with the engineering staff, Lockheed's Kelly Johnson assured them a single-engine jet fighter in the "500 plus" mph class could be built on the basis of a 4000-lb thrust engine.

General Electric developed the 4000-lb thrust engine, the 140 (an advanced version of Whittle's W2B engine), and Lockheed built the P80A Shooting Star, which flew on June 11, 1944. Although it did not enter combat during World War II, the Shooting Star became the United States' front-line fighter and outranked the Gloster Meteor with an international speed record (above 620 mph near the ground).

By about 1945, Frank Whittle had successfully completed, with greatest tenacity under the most adverse conditions, the enormous task of leading Great Britain and the United States into the jet age.

Other Early Turbojet Developments in the United States

Independent of European influence, several turbojet and propeller gas turbine projects had been initiated in the United States in 1939 and 1940. Although these projects had been terminated or prematurely canceled, they had contributed significantly to the know-how and technology of aircraft gas turbines, specifically their combustor and turbomachinery components.

One of these projects was the 2500-hp Northrop propeller gas turbine (Turbodyne) and a high-pressure-ratio turbojet under the excellent project leadership of Vladimir Pavelecka. Although the development goal of the large aircraft gas turbine engine was essentially met in late 1940, the project was canceled because the Air Force had lost interest in propeller gas turbines in view of the enormous advancement of the competitive jet engines.

Westinghouse had developed outstanding axial turbojet engines. The first very successful test runs of the Westinghouse X19A took place in March 1943. In the beginning of the 1950s, the Navy canceled the development contract, and top management of Westinghouse decided to discontinue work on turbojet engines.

The Lockheed Corporation began to work on a very advanced turbojet conceived by an outstanding engineer, Nathan C. Price. This engine was so far ahead of its time that it would have needed a far longer development time than that provided by the contract. The development contract was canceled in 1941.

Pratt & Whitney had started to work on its own jet propulsion ideas in the early 1940s but could not pursue these concepts because of the too-stringent obligations during wartime for the development and production of advanced aircraft piston engines. After World War II, Pratt & Whitney decided to go completely into turbojet development using axial-flow turbo-machinery. The company began with the construction of a gigantic test and research facility. The government gave Pratt & Whitney a contract to build a large number of 5000-lb thrust Rolls-Royce Nene engines with a radial compressor of the basic Whittle design. Subsequently, Pratt & Whitney developed its own large axial-flow, dual-rotor turbojet and later a fan-jet with a small bypass ratio for the advanced B52.

Turbojet Development of Hans von Ohain in Germany

My interest in aircraft propulsion began in the fall of 1933 while I was a student at the Georgia Augusta University of Gottingen in physics under

Prof. R. Pohl with a minor in applied mechanics under Prof. Ludwig Prandtl. I was 21 years old and beginning my Ph.D. thesis in physics, which was not related to jet propulsion.

The strong vibrations and noise of the propeller piston engine triggered my interest in aircraft propulsion. I felt the natural smoothness and elegance of flying was greatly spoiled by the reciprocating engine with propellers. It appeared to me that a steady, thermodynamic flow process was needed. Such a process would not produce vibrations. Also, an engine based on such a process could probably be lighter and more powerful than a reciprocating engine with a propeller because the steady flow conditions would allow a much greater mass flow of working medium per cross section. These characteristics appeared to me to be most important for achieving higher flight speeds. I made performance estimates for several steady flow engine types and finally chose a special gas turbine configuration that appeared to me as a lightweight, simple propulsion system with low development risks. The rotor consisted of a straight-vane radial outflow compressor back-to-back with a straight vane radial inflow turbine. Both compressor and turbine rotors had nearly equal outer diameters, which corresponds to a good match between them.

In early 1935, I worked out a patent for the various features of a gas turbine consisting of radial outflow compressor rotor, combustor, radial inflow turbine, and a central exhaust thrust nozzle. With the help of my patent attorney, Dr. E. Wiegand, a thorough patent search was made. A number of interesting aeropropulsion systems without a propeller were found, but we did not come across the earlier patents of Lorin, Guillaume, and Frank Whittle. (I learned for the first time about one of Frank Whittle's patents in early 1937 when the German Patent Office held one of his patents and one patent of the Swedish corporation Milo, against some of my patent claims.)

My main problem was finding support for my turbojet ideas. A good approach, it seemed to me, was to first build a model. This model should be able to demonstrate the aerodynamic functions at very low-performance runs. The tip speed of this model was a little over 500 ft/s. Of course, I never considered high-power demonstration runs for two reasons. The cost for building such an apparatus could easily be a factor of 10 or 20 times greater than that for building a low-speed model. Also, a test facility would be required for high-performance test or demonstration runs. I knew a head machinist in an automobile repair shop, Max Hahn, to whom I showed the sketches of my model. He made many changes to simplify the construction, which greatly reduced the cost. The model was built at my expense by Hahn in 1935 (Fig. 9).

In mid-1935, I had completed my doctoral thesis and oral examination and had received my diploma in November 1935. I continued working in Prof. Pohl's institute and discussed with him my project "aircraft propulsion." He was interested in my theoretical write-up. Although my project did not fit Pohl's institute, he was extremely helpful to me. He let me test the model engine in the backyard of his institute and gave me instrumentation and an electric starting motor. Because the combustors did not work, the model did not run without power from the starting motor. Long, yellow flames leaked out of the turbine. It looked more like a flame thrower than an aircraft gas turbine.

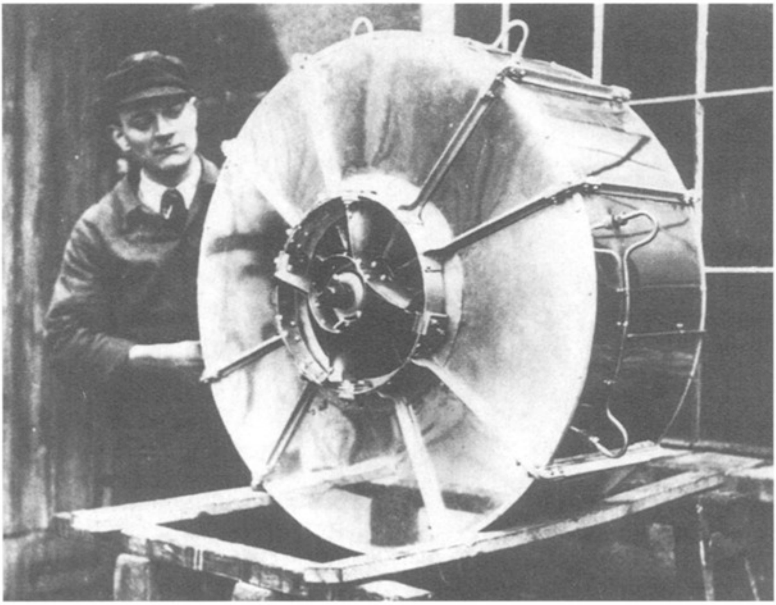


Fig. 9 Max Hahn with model engine. (National Air and Space Museum.)

I asked Prof. Pohl to write me a letter of introduction to Ernst Heinkel, the famous pioneer of high-speed aircraft and sole owner of his company. Professor Pohl actually wrote a very nice letter of recommendation. I had chosen Heinkel because he had the reputation of being an unconventional thinker obsessed with the idea of high-speed aircraft. Intuitively, I also felt that an aircraft engine company would not accept my turbine project. I learned later that my intuition was absolutely right. Today, I am convinced no one except Heinkel (see Fig. 10) would have supported my jet ideas at that time. Heinkel invited me to his home on the evening of March 17, 1936, to explain the jet principle to him. He, in turn, gave me a view of his plan. He wanted the jet development to be apart from the airplane factory. For this purpose, he intended to construct a small, temporary building near the Warnow River. I was very enthusiastic about this idea since it gave me a feeling of freedom and independence from the other part of the company and an assurance of Heinkel's confidence in me. Also, he strongly emphasized that he himself wanted to finance the entire jet development without involvement of the German Air Ministry. Finally, he explained to me that he had arranged a meeting between me and his top engineers for the next morning.

On March 18, 1936, I met with a group of 8 to 10 Heinkel engineers and explained my jet propulsion thoughts. Although they saw many problems, specifically with the combustion, they were not completely negative. Heinkel called me to a conference at the end of March. He pointed out that several uncertainties, specifically the combustion problems, should be solved before the gas

Fig. 10 Ernst Heinkel (left) and Hans von Ohain (right). (National Air and Space Museum.)

turbine development could be started. He wanted me to work on this problem and to report to him all the difficulties I might encounter. He offered me a kind of consulting contract that stated that the preliminary work (combustor development) could probably be completed in about two months. If successful, the turbojet development would then be started, and I would receive a regular employment contract. I signed this contract on April 3, 1936, and would start working in the Heinkel Company on April 15.

The first experiments with the model in early 1936 had convinced me that the volume of the combustion chambers was far too small for achieving a stable combustion. This was later substantiated in a discussion with combustion engineers at an industrial exhibit. I found a simple way to correct this condition. Cycle analysis of my model clearly showed that for high turbine inlet temperatures, such as 700°C and higher, a centrifugal compressor with a radial inflow turbine was most suitable as a basis for combustor development. My greatest problem was how to develop a functioning combustor in a few months. In my judgment, such a development would need at least six months, more likely one year, while Heinkel's estimate was two months. I had grave doubts whether Heinkel would endure such a long development time without seeing any visible progress, such as an experimental jet engine in operation. However, to avoid any combustor difficulties, I was considering a hydrogen combustor system with a nearly uniform turbine inlet temperature distribution. This hydrogen combustor system should be designed so that it could be built without any risk or need for preliminary testing.

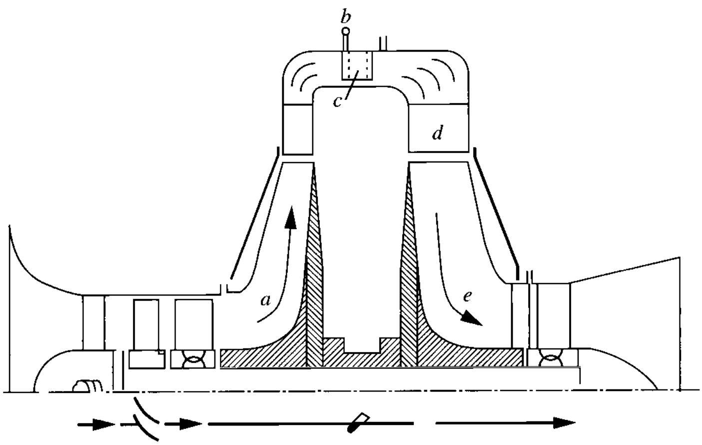
My idea was to separate the compressor and turbine on the rotor by a shaft and to employ an annular connecting duct from the exit of the compressor diffuser to the inlet of the turbine. Within this annular duct, I wanted to place a row of hollow vanes (about 60). These hollow vanes would have blunt trailing edges with many small holes through which hydrogen gas jets would be discharged into the air wakes behind the blunt trailing edges. In this way, the hydrogen combustion would be anchored at the blunt trailing edges of the hollow vanes. I was absolutely certain this combustor system would successfully function without any development or preliminary testing. I was also certain that no pretesting or development was necessary for the simple radial-flow turbomachinery. Testing of the hydrogen demonstrator engine (Fig. 11) showed that my judgment was correct on both points.

By mid-May 1936 I had nearly completed the layout of the hydrogen demonstrator engine. To build this engine was, for me, most important, not only for quick achievement of an impressive demonstration of the jet principle, but also for very significant technical reasons:

1) One reason was to obtain a solid basis for the design of the flight engine and the development of the liquid-fuel combustor, which should be started as a parallel development as soon as possible.

2) To achieve this solid basis, the hydrogen engine was the surest and quickest way when one does not have compressor and turbine test stands.

3) The anticipated step-by-step development approach: First testing the compressor-turbine unit with the "no-risk" hydrogen combustor and then



RADIAL TURBOJET (He S-1)
WITH HYDROGEN
(Built in 1936; tested in April 1937)

Radius of rotor-1 ft
Thrust-250 lb
10,000 rpm

Fig. 11 Von Ohain's hydrogen demonstrator engine.

using the tested turbomachine for exploring its interaction with the liquid-fuel combustor system seemed to be good protection against time-consuming setbacks.

Now came the greatest difficulty for me: How could I convince Heinkel that first building a turbojet with hydrogen gas as fuel would be a far better approach than trying to develop a liquid-fuel combustor under an enormous time pressure? According to my contract, of course, I should have worked on the liquid-fuel combustor with the (impossible) goal of having this development completed by June 1936. I briefly explained to Heinkel my reasons for the hydrogen engine and emphasized this engine would be a full success in a short time. I was well prepared to prove my point in case Heinkel wanted me to discuss this matter in a conference with his engineers. Surprisingly, Heinkel asked only when the hydrogen demonstrator could run. My shortest time estimate was half a year. Heinkel was not satisfied and wanted a shorter time. I told him that I had just heard that Wilhelm Gundermann and Max Hahn would work with me, and I would like to discuss the engine and its time schedule with them. So, Heinkel had agreed with my reasons to build the hydrogen jet demonstrator first.

About a week after my discussion with Heinkel, I joined Gundermann and Hahn in their large office. I showed them the layout of the hydrogen engine. Gundermann told me he had attended my presentation to the group of Heinkel's leading engineers in March 1936. He was surprised that I departed from the liquid-fueled turbojet program. I explained my reasons and also told about Heinkel's strong desire to have the hydrogen engine built in less than half a year. After studying my layout, both men came to the conclusion that it would not be possible to build this engine in less than six months, perhaps even longer. Gundermann, Hahn, and I began to work as an excellent team.

The engine was completed at the end of February 1937, and the start of our demonstration program was in the first half of March, according to Gundermann's and my recollections. The first run is clearly engraved in my memory: Hahn had just attached the last connections between engine and test stand; it was after midnight, and we asked ourselves if we should make a short run. We decided to do it! The engine had a 2-hp electric starting motor. Hahn wanted to throw off the belt-connecting starter motor and hydrogen engine if self-supporting operation was indicated. Gundermann observed the exhaust side to detect possible hot spots—none were visible. I was in the test room. The motor brought the engine to somewhat above 2000 rpm. The ignition was on, and I opened the hydrogen valve carefully. The ignition of the engine sounded very similar to the ignition of a home gas heating system. I gave more gas, Hahn waved, the belt was off, and the engine now ran self-supporting and accelerated very well. The reason for the good acceleration probably was twofold: the relatively low moment of inertia of the rotor and the enormously wide operational range of the hydrogen combustion system. We all experienced a great joy that is difficult to describe. Hahn called Heinkel, and he came to our test stand about 20 minutes later, shortly before 1:00 a.m. We made a second demonstration run. Heinkel was enthused—he congratulated us and emphasized that we should now begin to build the liquid-fuel engine for flying.

The next day and until the end of March, Heinkel began to show further demonstration runs to some of his leading engineers and important friends. The next day following our "night show," Heinkel visited us with Walter and Siegfried Guenther (his two top aerodynamic designers) for a demonstration run. They were very impressed and asked me about the equivalent horsepower per square meter. I replied, "A little less than 1000," but hastened to add that the flight engine would have more than 2500 hp/m^2 because of the much greater tip speed and greater relative flow cross sections. During April, we conducted a systematic testing program.

After the first run of the hydrogen engine, Heinkel ordered his patent office to apply for patents of the hydrogen engine. Because of earlier patents, the only patentable item was my hydrogen combustion system.

I became employed as division chief, reporting directly to Heinkel, and received an independent royalty contract, as I had desired. An enormous amount of pressure was now exerted by Heinkel to build the flight engine.

During the last months of 1937, Walter and Siegfried Guenther began with predesign studies of the first jet-propelled aircraft (He-178) and specified a static thrust of 1100 lb for the flight engine (He.S3). The aircraft was essentially an experimental aircraft with some provisions for armament.

In late 1937, while I was working on different layouts of the flight engine, Max Hahn showed me his idea of arranging the combustor in the large unused space in front of the radial-flow compressor. He pointed out that this would greatly reduce the rotor length and total weight. Hahn's suggestion was incorporated into the layout of the flight engine (see Fig. 12). In early 1938, we had a well-functioning annular combustor for gasoline. The design of the flight engine was frozen in the summer of 1938 to complete construction and testing by early 1939.

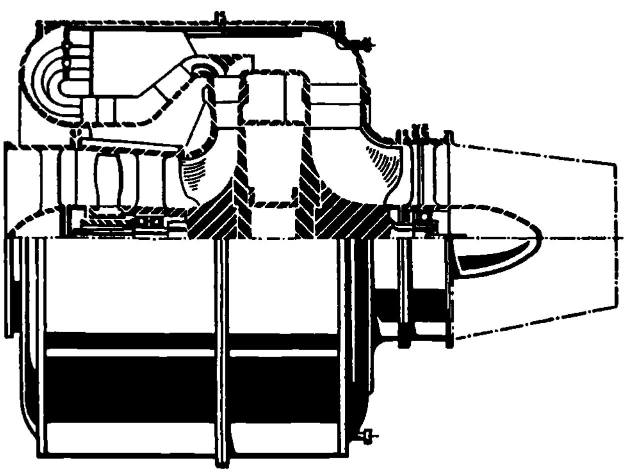


Fig. 12 1937 design of the He.S3 turbojet engine.

In spring 1939, aircraft and engine were completed, but the engine performance was too low: about 800-lb thrust, while a thrust of 1000–1100 lb was desirable to start the aircraft from Heinkel's relatively short company airfield. We made several improvements, mostly optimizing the easily exchangeable radial cascades of the compressor-diffuser and turbine stator. In early August, we had reached 1000 lb of thrust. We made only several one-hour test runs with the flight engine. However, upon suggestion of the Air Ministry, we completed a continuous 10-hour test run with a rotor that was not used for flight tests.

On August 27, 1939, the first flight of the He-178 with jet engine He.S3B was made with Erich Warsitz as pilot (Fig. 13). This was the first flight of a turbojet aircraft in the world. It demonstrated not only the feasibility of jet propulsion, but also several characteristics that had been doubted by many opponents of turbojet propulsion:

1) The flying engine had a very favorable ratio of net power output to engine weight—about 2 to 3 times better than the best propeller/piston engines of equal thrust power.

2) The combustion chambers could be made small enough to fit in the engine envelope and could have a wide operational range from start to high altitude and from low to high flight speed.

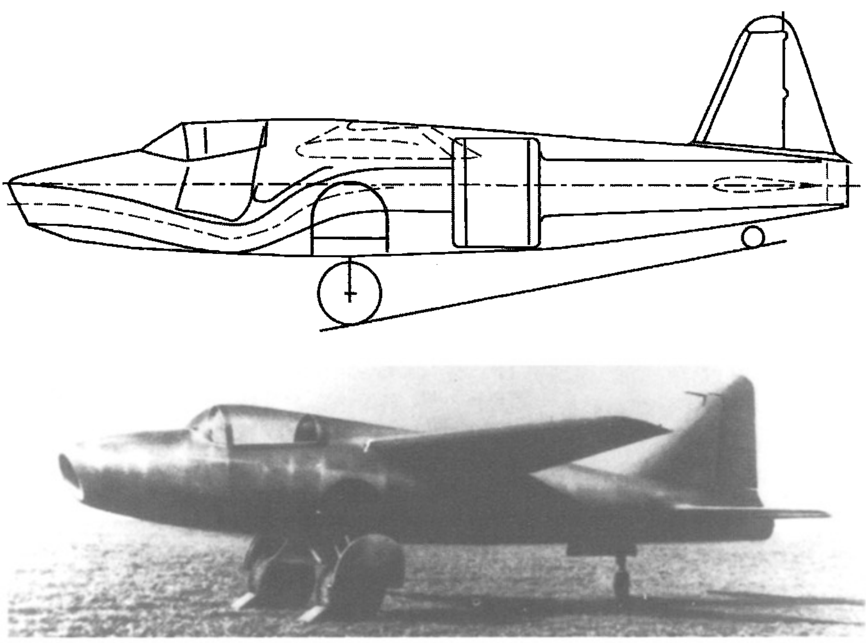


Fig. 13 The world's first jet-powered aircraft, the Heinkel He-178, was powered by the von Ohain–designed He.S3B turbojet engine. (National Air and Space Museum.)

The advantages of developing a flight demonstration turbojet in Heinkel's aircraft company were unique. Among the advantages were complete technical freedom, lack of importance attached to financial aspects, no government requirements, and no time delays; the aircraft was, so to speak, waiting for the engine. These great advantages were true only for the initial phases of jet engine development up to the first flight demonstrator. For making a production engine, however, enormous disadvantages included complete lack of experts in fabrication (turbomachinery, etc.), materials, research (turbines), accessory drives, control systems, no machine tools or component test stands, etc. Heinkel was very aware of this situation. His plan was to hire engineers from the aircraft engine field and to purchase an aircraft engine company.

Other Early Turbojet Developments in Germany

The following events developed at the same time, which was of great importance for the early phases of the turbojet evolution:

1) Professor Herbert Wagner privately started an aircraft gas turbine development project.
2) The Air Ministry became aware of Heinkel's turbojet project in 1938 and exerted a strong influence on the engine industry to start turbo development projects.
3) Heinkel purchased an aircraft engine corporation and received a contract for development and production of a high-performance turbojet engine.

In 1934, Wagner conceived the idea of an axial-flow propeller gas turbine while he was a professor of aeronautics in Berlin and formed a corporation to pursue these ideas. (I heard about Wagner's project for the first time in spring of 1939.) By introducing a design parameter that was the ratio of propeller power input to total net power output, he had conceived a gas turbine engine that was a cross between a turbojet and a propeller gas turbine.

Wagner first explored what would happen if the propeller power input was 50% of the total power output. This condition was favorable for long-range transport. Then in 1936, he investigated the "limiting case" of zero propeller power input, which constituted a turbojet. This engine was of great interest for high-speed aircraft because of its light weight.

The unique feature of Wagner's design was the utilization of 50% reaction turbomachinery (or *symmetric blading*). A compressor with 50% reaction blading has the greatest pressure ratio and efficiency for a given blade approach Mach number; but the design is difficult because of the inherently strong three-dimensional flow phenomena. This problem was solved by one of Wagner's coworkers, Rudolf Friedrich.

At the time Wagner was working on the turbojet engine, in about 1936, he became technical director of the Junkers Airframe Corporation in Dessau. The jet engine work was conducted in the Junkers machine factory, which was located in Magdeburg. The head of his turbojet development was Max A. Mueller, his former "first assistant."

In late fall, 1938, Wagner had decided to leave the Junkers Corporation, but he wanted to obtain funds from the Air Ministry for the continuation of his turbojet development work. The Air Ministry agreed to Wagner's request under the condition that the jet development be continued at the Junkers Aircraft Engine Company in Dessau. This seemed to be acceptable to Herbert Wagner. However, his team of about 12 very outstanding scientists and engineers (among them the team leader, Max A. Mueller, and the highly regarded Dr. R. Friedrich) refused to join the Junkers Aircraft Engine Company under the proposed working conditions. Heinkel made them very attractive work offers that convinced Wagner's former team to join the Heinkel Company. Heinkel added Wagner's axial turbojet to his development efforts (designated as the He.S30). Thus, in early 1939, Heinkel had achieved one goal—to attract excellent engineers for his turbojet development.

In early 1938, the Air Ministry had become aware of Heinkel's private jet propulsion development. The Engine Development Division of the Air Ministry had a small section for special propulsion systems that did not use propellers and piston engines, but rather used special rockets for short-time performance boost or takeoff assistance. Head of this section was Hans Mauch. He asked Heinkel to see his turbojet development in early summer 1938, more than one year before the first flight of the He-178. After he saw Heinkel's hydrogen turbojet demonstrator in operation and the plans for the flight engine, he was very impressed. He thanked Heinkel for the demonstration and pointed out that turbojet propulsion was, for him, a completely *unknown* and new concept. He soon became convinced that the turbojet was the key to high-speed flight. He came, however, to the conclusion that Heinkel, as an airframe company, would never be capable of developing a production engine because the company lacked engine test and manufacturing facilities and, most of all, it lacked engineers experienced in engine development and testing techniques. He wanted the Heinkel team to join an aircraft engine company (Daimler-Benz) and serve as a nucleus for turbojet propulsion development. Furthermore, he stated that Ernst Heinkel should receive full reimbursement and recognition for his great pioneering achievements. Heinkel refused.

In the summer of 1938, Mauch met with Helmut Schelp, who was in charge of jet propulsion in the Research Division of the Air Ministry. Mauch invited Schelp to join him in the Engine Development Division. Schelp accepted the transfer because he saw far greater opportunities for action than in his Research Division. In contrast to Mauch, Schelp was very well aware of turbojet propulsion and was convinced about its feasibility. He was well versed in axial and radial turbomachinery and with the aerothermodynamic performance calculation methods of turbojet, ramjet, and pulse jet. Like Mauch, he was convinced of the necessity that the aircraft engine companies should work on the development of turbojet engines. However, Schelp did not see a necessity for Heinkel to discontinue his jet engine development. He saw in Heinkel's progress a most helpful contribution for convincing the engine industry to also engage in the development of turbojets, and for proving to the higher echelons of the Air Ministry the necessity of launching a turbojet development program throughout the aircraft engine companies.

Schelp worked out the plans and programs for jet propulsion systems, decided on their most suitable missions, and selected associated aircraft types. Schelp's goal was to establish a complete jet propulsion program for the German aircraft engine industry. He also talked with Hans Antz of the Airframe Development Division of the Air Ministry to launch a turbojet fighter aircraft development as soon as possible. This became the Me-262. To implement the program, Mauch and Schelp decided to visit aircraft engine manufacturers—Junkers Motoren (Jumo), Daimler-Benz, BMW Flugmotorenbau, and Bradenburgische Motorenweke (Bramo). Mauch and Schelp offered each company a research contract to determine the best type of jet engine and its most suitable mission. After each study was completed and evaluated, a major engine development contract might be awarded.

The industry's response to these proposals has been summed up by Schlaifer in *Development of Aircraft Engines, and Fuels*: "The reaction of the engine companies to Mauch's proposals was far from enthusiastic, but it was not completely hostile."**

Anselm Franz and Hermann Oestrich were clearly in favor of developing a gas turbine engine. Otto Mader, head of engine development at Jumo, made two counter arguments against taking on turbojet propulsion developments. He said, first, that the highest priority of Jumo was to upgrade the performance of its current and future piston engines, and that this effort was already underpowered; and, second, Jumo did not have workers with the necessary expertise in turbomachine engine development! After several meetings between Mader and Schelp, however, Mader accepted the jet engine development contract and put Franz in charge of the turbojet project. At that time, Dr. Anselm Franz was head of the supercharger group. Daimler-Benz completely rejected any work on gas turbine engines at that time. Meanwhile, BMW and Bramo began a merger, and after it was finalized, Hermann Oestrich became the head of the gas turbine project for BMW.

These developments show that the aircraft engine industries in Germany did not begin to develop jet engines on their own initiative, but rather on the initiative and leadership of Mauch, and specifically of Helmut Schelp of the technical section of the German Air Ministry. Without their actions, the engine companies in Germany would not have begun development work on turbojet propulsion. The net result of Schelp's planning efforts was that two important turbojet engine developments were undertaken by the German aircraft engine industry, the Junkers Engine Division and BMW.

The Jumo 004 (shown in Fig. 14), developed under the leadership of Anselm Franz, was perhaps one of the truly unique achievements in the history of early jet propulsion development leading to mass production, for the following reasons:

1) It employed axial-flow turbomachinery and straight throughflow combustors.

2) It overcame the nonavailability of nickel by air-cooled hollow turbine blades made out of sheet metal.

3) The manufacturing cost of the engine amounted to about one-fifth that of a propeller/piston engine having the equivalent power output.

4) The total time from the start of development to the beginning of large-scale production was a little over four years (see Table 1).

5) It incorporated a variable-area nozzle governed by the control system of the engine, and model 004E incorporated afterburning.

**Schlaifer, R., and Heron, S. D., *Development of Aircraft Engines, and Fuels*, Pergamon Press, New York, 1970; reprint of 1950 ed.

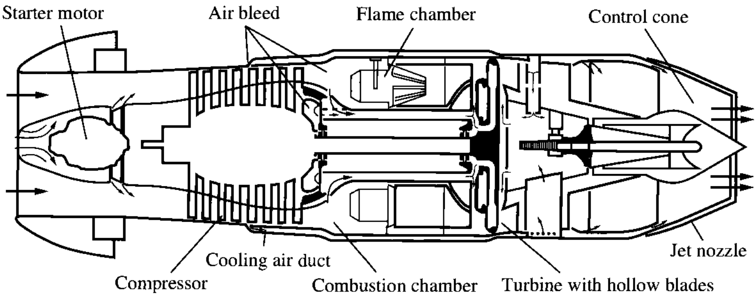


Fig. 14 Drawing of Jumo 004B turbojet engine showing air cooling system [thrust = 2000 lb, airflow = 46.6 lb/s, pressure ratio = 3.14, turbine inlet temperature = 1427°F, fuel consumption = 1.4 (lb/h)/h, engine weight = 1650 lb, diameter = 30 in., length = 152 in., efficiencies: 78% compressor, 95% combustor, 79.5% turbine].

The preceding points reflect the design philosophy of Dr. A. Franz for the Jumo 004, which was lowest possible development risk, shortest development time, dealing with a complete lack of heat-resistant materials, and minimizing manufacturing cost. From this design philosophy, it is understandable that the Jumo 004 engine, while fully meeting the requirements, did not have the highest overall performance compared to some contemporary experimental axial-flow engines, such as the He.S30 and others. If it had been possible for the Jumo 004 to employ heat resistant materials, then the engine thrust, the thrust/weight ratio, and the efficiency would have been increased substantially. Also the engine life could have been drastically increased from about 25 h to well over 100 h. However, because the combat life of a German fighter was well below 25 h, the economical optimum could tolerate a short engine life and the avoidance of nickel. Furthermore, to avoid any development risk or time delay, the compressor type chosen for the Jumo 004 was one where essentially all the static pressure increase occurs in the rotor and none in the stator (a free-vortex type of compressor having constant axial velocity over the blade span). Although such a compressor type does not have the best performance, at that time it was best understood. The previously described points show that the Jumo 004 represented an outstanding compromise between engine performance, the existent design constraints due to materials shortage, the need for short development time, and earliest possible production.

Table 1 Jumo 004 development and production schedule

Start of development	Fall 1939
First test run	Oct. 11, 1940
First flight in Me-262	July 18, 1942
Preproduction	1943
Beginning of production	Early 1944
Introduction of hollow blades	Late 1944
About 6000 engines delivered	May 1945

The BMW 003 turbojet engine, which was developed under the leadership of Hermann Oestrich, was also a resounding success. Because its thrust was smaller than that of the Jumo 004, it was ideally suited for the He-162. After World War II, Oestrich and a group of prominent scientists and engineers from Germany went to France and helped lay the foundation for France's turbojet industry.

Now I would like to go back to the end of 1939, when Heinkel began to make plans for buying an engine company. After the first flight of the He-178 on August 27, 1939, Heinkel invited high officials of the Air Ministry to see a flight demonstration of the He-178. This demonstration took place on November 1, 1939. At that occasion, Heinkel offered the development of a jet fighter, the He-280, which had two outboard engines under the wing. Heinkel received a contract for this aircraft in early 1940. In addition, I believe Udet and Heinkel had made an agreement that Heinkel would get official permission to buy the Hirth Engine Company, if the first flight of the He-280 could be demonstrated by April 1941.

The He-280 had severe restrictions with respect to distance of the engine nacelle from the ground. It actually was designed for the axial engine He.S30 (the Wagner turbojet engine). It appeared, however, unlikely that the He.S30 would be ready in time. On the other hand, it was impossible to use an engine of the He.S3B type, which had powered the He-178, because the diameter of this engine type would have been far too large. Under these conditions, I could see only one possible solution for succeeding in time, and this solution had extreme high risk. I employed a radial rotor similar to that of the He.S3B and combined it with an axial (adjustable) vane diffuser and a straight throughflow annular combustor.

The company designation of this engine was He.S8A. We had only about 14 months for this development, but we were lucky—it worked surprisingly well, and Heinkel could demonstrate the first flight of the He-280 on April 2, 1941. The government pilot was Engineer Bade. Earlier flights in late March were done by Heinkel's test pilot, Fritz Schaefer.

A few days after this demonstration, Heinkel obtained permission to buy the Hirth Motoren Company in Stuttgart, which was known for its excellent small aircraft engines. This company had outstanding engineers, scientists, machinists, precision machine tools, and test stands. Heinkel relocated the development of the He.S30 to his new Heinkel-Hirth engine company to make use of the excellent test and manufacturing facilities. In the summer of 1942, the He.S30 was ready for testing. It performed outstandingly well. The continuous thrust was about 1650 lb. From a technical standpoint, this engine had by far the best ratio of thrust to weight in comparison to all other contemporary engines. The superiority of the He.S30 was, in large part, the result of its advanced 50% reaction degree axial-flow compressor, designed by Dr. R. Friedrich. However, the success of the He.S30 came too late. The He-280 had been thoroughly tested. While it was clearly superior to the best contemporary propeller/piston fighter aircraft, the He-280 had considerably lower flight performance than the Me-262 with respect to speed, altitude, and range. Also, the armament of the He-280 was not as strong as that of the Me-262. For these reasons, the He.S8 and the He.S30 were canceled in the fall of 1942; the He-280 was officially

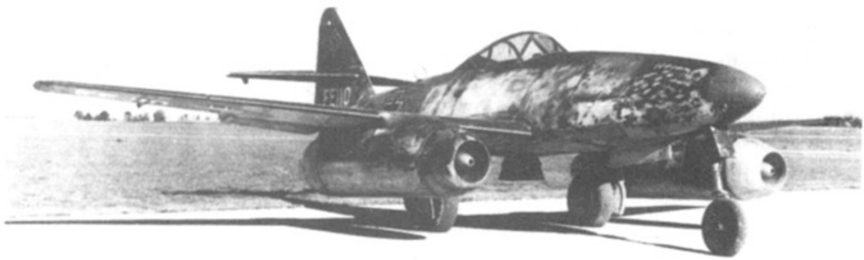


Fig. 15 Messerschmitt Me-262 jet fighter. (National Air and Space Museum.)

canceled in early 1943. The Me-262 (Fig. 15) went on to become the first operational jet fighter powered by two Jumo 004B turbojet engines. The Air Ministry did give full recognition to the excellence of the 50% reaction degree compressor type as most suitable for future turbojet developments.

Thus, in the fall of 1942, Heinkel had lost his initial leadership in jet aircraft and turbojet engines. Ironically, this happened when he had just reached his goal of owning an aircraft engine company with an outstanding team of scientists and engineers. It was the combined team of the original Hirth team, the Heinkel team, and Wagner's team. These conditions made Heinkel fully competitive with the existent aircraft engine industry. The Air Ministry had recognized the excellence of Heinkel's new team and facilities. Helmut Schelp, who in the meantime had become the successor of Hans Mauch, was in favor of the Heinkel-Hirth Company's receiving a new turbojet engine development contract. He clearly foresaw the need for a strong engine for the advanced Me-262, the Arado-234, the Junkers-287, and others. This new engine was supposed to have a thrust of nearly 3000 lb with a growth potential to 4000 lb as well as a high pressure ratio for improving the fuel economy. We began working on the He.S011 engine in the fall of 1942. The He.S011 was an axial-flow design with 50% reaction degree compressor blading, similar to that designed by Dr. Friedrich, and a two-stage, axial-flow, air-cooled turbine. Note that Helmut Schelp not only had established the performance specifications, but also had contributed to the overall design with excellent technical input and suggestions pertaining to the advanced diagonal inducer stage, the two-stage air-cooled turbine, and the variable exhaust nozzle system.

I was in charge of the He.S011 development, while the local director of the Heinkel-Hirth plant, Curt Schif, was in charge of He.S011 production. The top engineer of the Hirth Corporation was Dr. Max Bentele. He was well known for his outstanding knowledge in dealing with blade vibration problems. Upon special request of the Air Ministry, he had solved the serious turbine blade vibration problems of the Jumo 004 in the summer of 1943.

Dr. Bentele was responsible for the component development of the He.S011. After considerable initial difficulties, he achieved excellent performance characteristics of compressor and turbine that made it possible, by the end of 1944, for the performance requirements of the 011 to be met or surpassed. He also contributed to the preparation for production of the 011, which was planned to start in June 1945. The end of World War II, of course, terminated the production plan before it had started. Only a few He.S011 engines are in existence today, and they are exhibited in several museums in the United States and Great Britain.

In other countries, such as Russia and Japan, interesting developments in the field of propeller gas turbines and turbojets had also been undertaken. It is, however, not sufficiently known to what extent these developments were interrelated with, or influenced by, the previously described jet developments and what their development schedules had been.

In summary, at the end of the 1930s and in the first half of the 1940s, turbojet propulsion had come into existence in Europe and the United States. It had been demonstrated that the turbojet is, for high-speed flight, uniquely superior to the propeller/piston engines because of the following two major characteristics:

1) The ratio of power output to weight of the early turbojets was at least 2 or 3 times greater than that of the best propeller/piston engines. This is one necessary condition of propulsion systems for high-speed flight and good maneuverability.

2) Because, in the turbojet, the propeller is replaced by ducted turbomachinery, the turbojet is inherently capable as a propulsion system of high subsonic and supersonic flight speeds.

In the following, it will be discussed how the turbojet engine progressed to the performance capabilities of today.

Evolution of Airbreathing Turbopropulsion Systems to the Technology Level of Today

The early turbojets were used as propulsion systems for high-speed fighter and reconnaissance aircraft. For these applications, the early turbojets (because of their superior power/weight ratios) were far more suitable propulsion systems than the traditional propeller/piston engines. However, the early turbojets were not suitable for those application areas where greatest fuel economy, highest reliability, and a very long endurance and service life were required. For making airbreathing turbojet propulsion systems applicable for all types of aircraft, ranging from helicopters to high-speed, long-range transports, the following development goals were, and still are, being pursued:

1) Higher overall efficiency (i.e., the product of thermodynamic and propulsion efficiencies),
2) Larger-power-output engines,
3) Larger ratios of power output to engine weight, volume, and frontal area,
4) Greater service life, endurance, and reliability,
5) Strong reduction of adverse environmental exhaust gases,
6) Reduced noise.

To achieve these goals, parallel research and development efforts were undertaken in areas such as

1) Fundamental research in combustion processes, development, and technology efforts for increasing specific mass flow through combustors and reducing the total pressure drop; and for achieving nearly 100% combustion efficiency with a more uniform temperature profile at combustor exit.
2) Minimizing the excitation of vibrations (including aeroelastic effects) and associated fatigue phenomena.
3) Continuous improvement of the structural design and structural materials, such as composite materials, heat- and oxidation-resistant alloys and ceramics.
4) Increasing the turbine temperature capability by improving air cooling effectiveness. Also increasing the polytropic turbine efficiency.
5) Improvement of the compressor with respect to greater specific mass flow, greater stage pressure ratio, greater overall pressure ratio, and greater polytropic efficiency.
6) Advanced controllable-thrust nozzles and their interactions with the aircraft.
7) Advanced control systems to improve operation of existing and new engines.

All of these research and development areas were, and still are, of great importance for the progress in turbopropulsion systems; however, the compressor can perhaps be singled out as the key component because its advancement was a major determining factor of the rate of progress in turbo engine development. This will become apparent from the following brief description of the evolution of the turbopropulsion systems.

Development of High-Pressure-Ratio Turbojets

The first step to improve the early turbojets was to increase their overall efficiency. To do this, it was necessary to increase the thermodynamic cycle efficiency by increasing the compressor pressure ratio. The trend of compressor pressure ratio over the calendar years is shown in Table 2.

In the early 1940s, it was well understood that a high-pressure-ratio (above 6:1), single-spool, fixed-geometry compressor can operate with good efficiency only at the design point, or very close to it. The reason is that at the design

Table 2 Trend in compressor pressure ratios

Calendar years	Compressor pressure ratio
Late 1930 to mid-1940	3:1 to about 5:1
Second half of 1940s	5:1 and 6:1
Early 1950	About 10:1
Middle to late 1960s	20:1 to about 25:1
End of century (2000)	30:1 to about 40:1

point, all compressor stages are matched on the basis of the compressibility effects. Consequently, under off-design conditions where the compressibility effects are changed, the stages of a high-pressure-ratio compressor are severely mismatched, resulting in a very low off-design efficiency. For example, at an operational compressor rpm (which would be substantially below the design rpm), the compressibility effects are small. Under such off-design conditions, the front stages tend to operate under *stalled* conditions, while the last stages tend to work under *turbining* conditions. Such compressor characteristics are unacceptable for the following reasons:

1) There are enormous difficulties in starting such an engine.
2) Very poor overall efficiency (or poor fuel economy) exists under part-load operation.
3) Very low overall efficiency exists at high supersonic flight speed (because the corrected rpm is very low as a result of the high stagnation temperature of the air at the compressor inlet).

By the end of the 1940s and early 1950s, excellent approaches emerged for the elimination of these shortcomings of simple high-pressure-ratio compressors. Pratt & Whitney, under the leadership of Perry Pratt, designed a high-pressure-ratio jet engine (the J57) with a *dual-rotor* configuration. (In later years, triple-rotor configurations were also employed.) The ratio of rpm values of the low- and high-pressure spools varies with the overall pressure ratio and, in this way, alleviates the mismatching effects caused by the changes in compressibility. At approximately the same time, Gerhard Neumann of General Electric conceived a high-pressure-ratio, single-spool compressor having automatically controlled *variable stator blades*. This compressor configuration was also capable of producing very high pressure ratios because it alleviated the mismatching phenomena under off-design operation by stator blade adjustment. In addition, the controlled variable-stator-compressor offers the possibility of a quick reaction against compressor stall. The variable-stator concept became the basis for a new, highly successful turbojet engine, the J79, which was selected as the powerplant for many important supersonic Air Force and Navy aircraft. A third possibility to minimize mismatching phenomena was *variable front-stage bleeding*, which was employed in several engines.

Before I continue with the evolution of the turbo engines toward higher overall efficiencies, a brief discussion about the research and development efforts on compressor bladings and individual stages is in order. Such efforts existed to a small degree even before the advent of the turbojet (in Switzerland, Germany, England, and other countries). However, in the mid-1940s, those research efforts began to greatly intensify after the turbojet appeared. It was recognized that basic research and technology efforts were needed to continuously increase 1) stage pressure ratio and efficiency and 2) mass throughflow capability.

Very significant contributions had been made by universities, research institutes, and government laboratories (NACA, later NASA; Aero Propulsion Laboratory, and others), and industry laboratories. Many outstanding research results were obtained from universities in areas of rotating stall, three-dimensional and nonsteady flow phenomena and transonic flow effects, novel flow visualization techniques for diagnostics (which identified flow regions having improvement possibilities), understanding of noise origination, and many others.

Two examples where government laboratories had achieved very crucial advancements that were later adapted by industry were the following: In the early 1950s, the NACA Lewis Research Center, under the leadership of Abe Silverstein, advanced compressor aerodynamics to transonic and supersonic flow, critical contributions for increasing the compressor-stage pressure ratio. He initiated a large transonic and supersonic compressor research program. Many in-depth studies furnished information for utilizing this new compressor concept. Later, the Air Force Propulsion Laboratory, under the leadership of Arthur Wennerstrom, conducted advanced compressor research and introduced a very important supersonic compressor concept, which was particularly applicable for front stages because it solved the most difficult combined requirements of high mass flow ratio, high pressure ratio, high efficiency, and broad characteristics.

The continuous flow of research and technological contributions extended over the last four decades and is still going on. The total cost may have been several hundred million dollars. Some of the results can be summarized as follows: The polytropic compressor efficiency, which was slightly below 80% in 1943, is now about 92%; the average stage pressure ratio, which was about 1.15:1 in 1943, is now about 1.4:1 and greater; the corrected mass flow rate per unit area capability grew over the same time period by more than 50%.

The improvement in compressor efficiency had an enormous impact on engine performance, specifically on the overall engine efficiency. The substantially increased stage pressure ratio and the increased corrected mass flow rate per unit area capability resulted in a substantial reduction of engine length, frontal area, and weight-per-power output.

Let us now return to the 1950s. As previously stated, the new turbojets employing a dual-rotor configuration or controlled variable-stator blades were capable of substantially higher pressure ratios than the fixed-geometry, single-spool engines of the 1940s. Engine cycle analysis showed that the high power-per-unit mass flow rate needed for the advanced engines required higher turbine inlet temperatures. This requirement led to continuous major research efforts to achieve high-efficiency combustion with low pollution, to increase the effectiveness of turbine blade-cooling methods, and to improve the temperature capabilities of materials. Thus the turbojets of the 1950s had made substantial progress in thermodynamic efficiency and propulsive thrust per pound of inlet air per second. The latter characteristic means that the velocity of the exhaust gas jet had increased.

Development of High-Bypass-Ratio Turbofans

For supersonic flight speeds, the overall efficiency of these turbojets was outstanding. However, for high subsonic and transonic flight speeds (around 500–600 mph), the velocity of the exhaust gas jet was too high to obtain a good propulsive efficiency. Under these conditions, the *bypass engine* (also called *turbofan* or *fan-jet*) became a very attractive approach for improving the propulsive efficiency. The first fan-jets had a relatively small bypass ratio of about 2:1. (*Bypass ratio* is the ratio of mass flow bypassing the turbine to mass flow passing through the turbine.) In the early 1960s, the U.S. Air Force had established requirements for military transports capable of an extremely long

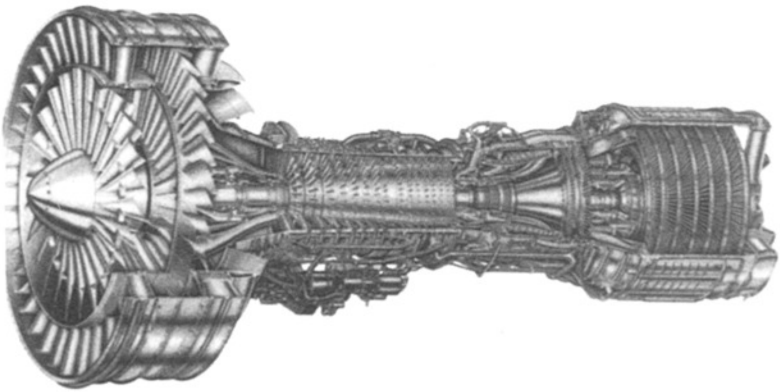


Fig. 16 The TF39 high-bypass-ratio turbofan engine used on the Lockheed C5 transport. (Courtesy of General Electric Aircraft Engines.)

range at high subsonic cruise speeds. Such requirements could be met only by employing propulsion systems of highest possible thermodynamic and propulsive efficiencies, which led to the following engine characteristics:

1) Very high compressor pressure ratios between 20:1 and 30:1, which could be achieved by combining the concepts of variable stator and dual rotor,
2) Very high turbine inlet temperatures,
3) Very high bypass ratios, around 8:1.

The first engine of this type was the TF39 (Fig. 16), a military transport engine developed by General Electric under the leadership of Gerhard Neumann. Four of the TF39 turbofan engines powered the Lockheed C5A.

The Air Force Propulsion Laboratory, under the leadership of Cliff Simpson, had played a key role in the establishment of these requirements. Simpson also succeeded in convincing the highest Air Force and Department of Defense echelons of the significance of this new type of airbreathing propulsion system, which he considered a technological breakthrough. (At that time, it was difficult to generate interest in advanced airbreathing propulsion system concepts, since the nation's attention was focused on rocket propulsion for space exploration.)

The advantages of the high-bypass-ratio turbofan engines can be summarized as follows:

1) High overall efficiency, resulting in a long flight range,
2) Strong increase in propulsive thrust at low flight speeds, which is important for takeoff, climbing, and efficient part-load operation,
3) Lower jet velocity, which leads to great noise reduction, and
4) Low fuel consumption, which reduces chemical emissions.

These characteristics had been demonstrated in the late 1960s and early 1970s. They also became of great interest for commercial aircraft and led to the development of the *widebody* passenger aircraft.

During the 1980s, the continuous flow of advanced technology of turbo engine components had brought a high degree of maturity to the various aircraft gas turbine engine types, such as the following: 1) the previously discussed high-bypass-ratio engines, 2) the low-bypass-ratio engines with afterburning for supersonic flight, and 3) the pure turbojet for high supersonic flight Mach numbers of approximately 3.

The small and medium aircraft shaft-power gas turbines also benefited enormously from the continuous improvement of turbomachinery technology. These small gas turbines are used in helicopters and subsonic propeller aircraft. The high power/weight ratio and the high thermodynamic efficiency of the advanced shaft-power gas turbine engines played a key role in the advancement of helicopters.

Future Potential of Airbreathing Jet Propulsion Systems

In the future, major advancement of airbreathing jet propulsion systems can be expected from

1) Evolutionary improvements of the established large-bypass-ratio turbofan engines for transonic flight speeds and the low-bypass-ratio turbofan, or pure turbojet engines, for supersonic flight speeds,
2) Improvements and new approaches to engine-airplane integration, and
3) New approaches to airbreathing propulsion systems for high supersonic and hypersonic flight speeds.

The evolutionary improvements of established engine types will result in greater fuel economy and better performance characteristics. By the end of the century, one can expect polytropic efficiencies of turbine and compressor of nearly 95%. Furthermore, one will see considerably increased single-stage pressure ratios; significantly higher turbine inlet temperatures resulting from better heat- and oxidation-resistant materials, and more effective blade-cooling methods; and much lighter structural designs and materials (composite materials). This technological progress may result in an overall engine efficiency increase of about 20% and in a weight reduction for given horsepower output by probably a factor of 2 and higher.

For the evolution of high-bypass-ratio engines at cruise speeds between 500 and 600 mph, the following trend is important; the greater the turbine inlet temperature and the higher the polytropic efficiencies of the compressor and the turbine, the higher the optimum pressure ratio of the gas turbine engine and the bypass ratio of the fan. In the future, this trend will lead to larger bypass ratios; hence, the fan shroud will become relatively large in diameter and will contribute substantially to the weight and external drag of the propulsion system. Several solutions are conceivable to alleviate this problem, but at this time it is not possible to predict the most promising approach.

One way is to eliminate the fan shroud by using an unshrouded fan (having a multiplicity of swept-back fan blades, see Fig. 17), also called a *prop-fan*. This configuration is currently in an experimental state and may become very important in the future for improving fuel economy. Another possibility

Fig. 17 PW-Allison 578DX propulsion system. (Courtesy of Allison Gas Turbine Division.)

may lie in the development of a transonic airframe configuration in which the large fan shrouds have a dual function: They contribute, in part, to the stability of the aircraft (horizontal and vertical stabilizer surfaces) while serving at the same time as a shroud for the fan. Finally, it may be conceivable that, in the future, a practical airframe and wing configuration can be developed that will be capable of extending a high lift/drag ratio to a flight speed regime that is very close to the speed of sound (a kind of well-known "supercritical" airframe configuration proposed by Whitcomb of NASA). If such an airframe configuration could be developed, the bypass ratio at these relatively high flight speeds would be substantially lower than that for flight speeds around 500 mph and, therefore, a shrouded fan would be most applicable.

Perhaps a most interesting question is: Can one expect a future supersonic passenger transport that is economically feasible in view of the progress of future transonic passenger transports? The general trend of the airplane lift/drag ratio is decreasing with increasing flight Mach number, while the overall efficiency of aeropropulsion systems increases with increasing flight Mach number. Currently, the lift/drag ratio of the Boeing 747 compared to that of the supersonic Concorde is about 3:1. In the future, the corresponding ratio may decrease to about 2:1, and the structural weight of the supersonic aircraft will greatly be improved. Such improvements may be the result of advancements in the aerodynamic shape, the structure, the structural airframe materials, and the best use of artificial stability. The overall efficiency of the supersonic flight engine can also be improved, including its capability of cruising subsonically with only one engine. This is important in case one of the two engines fails. Under this condition, the mission must be completed at subsonic speed without requiring an additional fuel reserve. It appears that advanced supersonic-cruise aircraft systems have the potential to achieve these conditions and, thus, become economically acceptable in the future.

New Approaches to Engine–Airplane Integration

In general, the investigations of engine–airplane integration have the goal to avoid or minimize losses due to adverse interface phenomena between the engine inlet stream or exhaust jet and the air vehicle. However, many favorable effects can be achieved by properly integrating functions of the propulsion system with functions of the airplane. Historically, Prof. Ackeret (University of Zurich, Switzerland) had first suggested, in 1921, reaccelerating the boundary-layer air near the trailing edge of the wing. He showed that this method of producing the propulsive thrust can result in substantial gains in overall efficiency of the propulsion system. In the 1970s, various investigations had shown that similar results can be obtained by using momentum exchange of the high-pressure bypass air with the boundary-layer air.

Other uses of bypass air are to energize the boundary layer at proper locations of the wing to prevent boundary-layer separation and to increase the circulation around the wing (often called *supercirculation*). This method may become important for advanced short-takeoff-and-landing (STOL) applications. For future V/STOL applications, new methods of thrust vectoring and thrust augmentation may have very attractive possibilities. Also, bypass air may be used for boundary-layer suction and ejection in advanced laminar systems.

Airbreathing Propulsion Systems for High Supersonic and Hypersonic Speeds

In airbreathing propulsion systems, the combined compression by ram and turbo compressor is of great benefit to the thermodynamic propulsion process up to flight Mach numbers approaching 3. When the flight Mach number increases further, the benefits of the turbo compressor begin to decrease and the engine begins to operate essentially as a ramjet. When the flight Mach number exceeds about 3.5, any additional compression by a turbo compressor would be a disadvantage. Thus, if the engine operates best as a pure subsonic combustion ramjet, it fits in a flight Mach number regime from about 3.5 to 5. Beyond flight Mach numbers of about 6, the pressure and temperature ratios would be unfavorably high if the engine continued to operate as a subsonic combustion ramjet. The reasons are as follows:

1) High degree of dissociation of the combustor exhaust flow, reducing the energy available for exhaust velocity,

2) Pressures far too high for Brayton cycle operations or for the structure to withstand.

For these reasons, the cycle will be changed from a subsonic to a supersonic combustion ramjet, and hydrogen will be used as fuel because hydrogen has the greatest 1) combustion heat and fuel-air concentration range, 2) diffusion speed and reaction speed, and 3) heat-sink capabilities.

This supersonic combustion ramjet cycle is characterized by a reduction of the undisturbed hypersonic flight Mach number to a somewhat lower hypersonic Mach number with an increase in entropy, which should be as low as possible. The deceleration process must be chosen in such a manner that the increases in static pressure and entropy correspond to a high-performance Brayton cycle. The internal thrust generated by the exhaust gas must be larger than the external drag forces acting on the vehicle.

To minimize the parasitic drag of the ramjet vehicle systems, various external ramjet vehicle configurations have been suggested. However, theoretical and experimental investigations will be necessary to explore their associated aero-thermochemical problems.

For the experimental research, one may consider investigations using free-flight models or hypersonic wind tunnels with true temperature simulation. Historically, it may be of interest that many suggestions and investigations had been made as to how to achieve clean hypersonic airflows with true stagnation temperatures. I remember much work and many discussions with Dr. R. Mills, E. Johnson, Dr. Frank Wattendorf, and Dr. Toni Ferri about "air accelerator" concepts, which aimed to avoid flow stagnation and the generation of ultrahigh static temperatures and chemical dissociation.

Since the Wright brothers, enormous achievements have been made in both low-speed and high-speed airbreathing propulsion systems. The coming of the jet age opened up the new frontiers of transonic and supersonic flight (see Fig. 3). While substantial accomplishments have been made during the past several decades in the field of high supersonic and hypersonic flight (see Ref. 2), it appears that even greater challenges lie ahead.

For me, being a part of the growth in airbreathing propulsion over the past 60 years has been both an exciting adventure and a privilege. This foreword has given you a view of its history and future challenges. The following book presents an excellent foundation in airbreathing propulsion and can prepare you for these challenges. My wish is that you will have as much fun in propulsion as I have.

Hans von Ohain
German Inventor of the Jet Engine
December 14, 1911–March 13, 1998

Preface

This undergraduate text provides an introduction to the fundamentals of gas turbine engines and jet propulsion. These basic elements determine the behavior, design, and operation of the jet engines and chemical rocket motors used for propulsion. The text contains sufficient material for two sequential courses in propulsion: an introductory course in jet propulsion and a gas turbine engine components course. It is based on one- and two-course sequences taught at four universities over the past 25 years. The author has also used this text for a course on turbomachinery.

The outstanding historical foreword by Hans von Ohain (the German inventor of the jet engine) gives a unique perspective on the first 50 years of jet propulsion. His account of past development work is highlighted by his early experiences. He concludes with predictions of future developments.

The text gives examples of existing designs and typical values of design parameters. Many example problems are included in this text to help the student see the application of a concept after it is introduced. Problems are included at the end of each chapter that emphasize those particular principles. Two extensive design problems for the preliminary selection and design of a gas turbine engine cycle are included. Several turbomachinery design problems are also included.

The text material is divided into five parts:

1) Introduction to aircraft and rocket propulsion (Chapter 1),
2) Review of fundamentals (Chapter 2),
3) Rocket propulsion (Chapter 3),
4) Analysis and performance of airbreathing propulsion systems (Chapters 4–8),
5) Analysis and design of gas turbine engine components (Chapters 9 and 10).

Chapter 1 introduces the types of airbreathing and rocket propulsion systems and their basic performance parameters. Also included is an introduction to aircraft and rocket systems that reveals the influence that propulsion system performance has on the overall system. This material facilitates incorporation of a basic propulsion design problem into a course, such as new engines for an existing aircraft.

The fundamental laws of mass conservation, momentum, and thermodynamics for a control volume (open system), the properties of perfect gases, and compressible flow properties are reviewed in Chapter 2. New material on analysis of one-dimensional gas dynamics [enthalpy-kinetic energy (H-K) diagram] is presented in Chapter 2 to help student understanding of engine cycles from scramjets to afterburning turbofans. Fundamentals of thermochemistry are presented for later use in analysis of chemical rockets in Chapter 3.

Chapter 3 presents the fundamentals of rocket propulsion. Emphasis in this chapter is on chemical propulsion (liquid and solid) with coverage of rocket motor performance. The chapter also covers requirements and capabilities of rocket propulsion.

The analysis of gas turbine engines begins in Chapter 4 with the definitions of installed thrust, uninstalled thrust, and installation losses. This chapter also reviews the ideal Brayton cycle, which limits gas turbine engine performance.

Two types of analysis are developed and applied to gas turbine engines in Chapters 5–8: parametric cycle analysis (thermodynamic design point) and performance analysis. The text uses the cycle analysis methods introduced by Frank E. Marble of the California Institute of Technology and further developed by Gordon C. Oates (deceased) of the University of Washington and Jack L. Kerrebrock of the Massachusetts Institute of Technology. The steps of parametric cycle analysis are identified in Chapter 5 and then used to model engine cycles from the simple ramjet to the complex, mixed-flow, afterburning turbofan engine. Families of engine designs are analyzed in the *parametric analysis* of Chapters 5 and 7 for ideal engines and engines with losses, respectively. Chapter 6 develops the overall relationships for engine components with losses. The *performance analysis* of Chapter 8 models the actual behavior of an engine and shows why its performance changes with flight conditions and throttle settings. The results of the engine performance analysis can be used to establish component performance requirements. To keep the size of the new edition down, the analysis of some engine cycles has been moved to the electronic Supporting Materials available with this book.

Chapter 9 covers both axial-flow and centrifugal-flow turbomachinery. Included are basic theory and mean-line design of axial-flow compressors and turbines, quick design tools (e.g., repeating-row, repeating-stage design of axial-flow compressors), example multistage compressor designs, flow path and blade shapes, turbomachinery stresses, and turbine cooling. Example output from the COMPR and TURBN programs is included in several example problems.

Inlets, exhaust nozzles, and combustion systems are modeled and analyzed in Chapter 10. The special operation and performance characteristics of supersonic inlets are examined and an example of an external compression inlet is designed. The principles of physics that control the operation and design of main burners and afterburners are also covered.

The appendices contain tables with properties of standard atmosphere and properties of combustion products for air and $(CH_2)_n$. There is also material on turbomachinery stresses as well as useful data on existing gas turbine engines and liquid-propellant rocket engines.

Eight computer programs are provided for use with this textbook:

1) AFPROP, properties of combustion products for air and $(CH_2)_n$
2) ATMOS, properties of the atmosphere
3) COMPR, axial-flow compressor mean-line design analysis
4) EQL, chemical equilibrium analysis for reactive mixtures of perfect gases

5) GASTAB, gas dynamic tables
6) PARA, parametric engine cycle analysis of gas turbine engines
7) PERF, engine performance analysis of gas turbine engines
8) TURBN, axial-flow turbine mean-line design analysis

The AFPROP program can be used to help solve problems of perfect gases with variable specific heats. The ATMOS program calculates the properties of the atmosphere for standard, hot, cold, and tropical days. The EQL program calculates equilibrium properties and process end states for reactive mixtures of perfect gases, for different problems involving hydrocarbon fuels. GASTAB is equivalent to traditional compressible flow appendices for the simple flows of calorically perfect gases. It includes isentropic flow; adiabatic, constant area frictional flow (Fanno flow); frictionless, constant area heating and cooling (Rayleigh flow); normal shock waves; oblique shock waves; multiple oblique shock waves; and Prandtl-Meyer flow. The PARA and PERF programs support the material in Chapters 5–8. PARA is very useful in determining variations in engine performance with design parameters and in limiting the useful range of design values. PERF can predict the variation of an engine's performance with flight condition and throttle (Chapter 8). Both are very useful in evaluating alternative engine designs and can be used in design problems that require selection of an engine for an existing airframe and specified mission. The COMPR and TURBN programs permit preliminary design of axial-flow turbomachinery based on mean-line design.

As already suggested, the author has found the following two courses and material coverage very useful for planning.

Introductory Course

Chapter 1, all
Chapter 2, as needed
Chapter 3, all
Chapter 4, all
Chapter 5, Sections 5.1–5-9
Chapter 6, Sections 6.1–6.9
Chapter 7, Sections 7.1–7.4
Chapter 8, Sections 8.1–8.5

Gas Turbine Engine Components Course

Chapter 2, as needed
Chapter 8, Sections 8.1–8.3
Chapter 9 and Appendix E, all
Chapter 10, all

The material in Chapters 2 and 9 along with Appendix E of this text have also been used to teach the major portion of an undergraduate turbomachinery course.

Jack D. Mattingly
April 2006

Acknowledgments

I am deeply indebted to Professor Gordon C. Oates (deceased) and Dr. William H. Heiser. Professor Oates taught me the basics of engine cycle analysis during my doctoral studies at the University of Washington and later until his untimely death in 1986. While Dr. Heiser was a Distinguished Visiting Professor at the U.S. Air Force Academy from 1983 to 1985, we developed an outstanding engine design course and wrote the first edition of the textbook *Aircraft Engine Design*. We have continued to work and teach together over the past 23 years, and he has been my friend and mentor.

Special thanks to Brigadier General Daniel H. Daley (USAF, retired, and former Head, Department of Aeronautics, U.S. Air Force Academy), who sponsored my studies under Professor Oates and guided me during the compilation of the teaching notes "Elements of Propulsion." These notes were used for over a decade in the Academy's propulsion courses before the publication of *Elements of Gas Turbine Propulsion* in 1996 and are the basis for this textbook. Most recently General Daley helped me develop Chapters 2 and 3 and the general content of this new textbook—I couldn't have done this book without his help.

I also thank all of the students who have been in my propulsion courses and my coworkers at the Department of Aeronautics, U.S. Air Force Academy, Colorado; the Air Force Institute of Technology (AFIT), Wright-Patterson Air Force Base, Ohio; the Air Force Aero Propulsion and Power Laboratory, Wright-Patterson Air Force Base, Ohio; Seattle University; and University of Washington. Many of these students and coworkers provided insight and guidance in developing this material.

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