CHAPTER XII

The Background of the Development of Gas Turbines for Aircraft

THE most serious inferiority in American aeronautical development which appeared during the Second World War was in the field of jet propulsion. Had the Germans put their jet fighters in production a year sooner, as they were technically perfectly able to do, or had the Allied campaign in Europe come a year later, the use of jet fighters by the Germans might have had a most serious effect on the course of the war. No other example can show so clearly as this one the tremendous importance of avoiding delay in undertaking the development of a new kind of military materiel.

THE PRINCIPLES OF JET PROPULSION

The principle of propulsion by reaction is extremely ancient, and the basic principle of all reaction engines is the same. A gas is heated within the engine at greater than atmospheric pressure and then is allowed to escape to the atmosphere at the rear of the engine. As the pressure falls the gas expands, so that it is expelled from the engine with a considerable velocity. The reaction to the forces expelling the gas is the thrust which drives the engine forward.

In all practical engines of this sort the heat has been derived from the burning of a fuel. According to the source of the oxygen required for combustion, there are two quite different forms of practical reaction engine, generally distinguished today under the names rocket and jet. In the rocket, the oxygen as well as the fuel is carried with the vehicle, and the products of combustion are the only gases ejected to create the propulsion. In the jet engine, air is taken in from the atmosphere, the oxygen of the air is used to burn the fuel carried with the vehicle, and the ejected gases, which might be called the "working substance" of the engine, include the inert gases in the air and often a good deal of unburned oxygen as well as the products of combustion.

Rockets were known and used long before jet engines in the modern sense, since the engine required is far less complex. In its simplest form, the solid-fuel rocket, the "engine" is nothing but a hollow container with an opening to the rear. But because this type of engine has to carry all its own oxygen and all its own "working substance", a vehicle with rocket power must necessarily and under all circumstances carry with itself vastly more material in proportion to the motive power delivered by the engine than it carries with an engine which gets its oxygen and working substance "free." For this reason the rocket has never been considered as a primary power plant for aircraft except for flights beyond the earth's atmosphere or else for flights where power is used during so short a time that the simplicity of the engine reduces its weight enough to compensate for the enormous fuel consumption. The only manned airplanes flown before the end of the war in 1945 with rocket engines as their main power were the Heinkel He 176 experimental airplane, tested about 1939, and the Messerschmitt Me 163 interceptor, which actually saw service in 1945. The latter airplane with nearly 350 gallons of fuel could use its engine for only eight to twelve minutes. The real field for rocket engines in airplanes seems to be as auxiliary power plants for assisting take-off,[1] or perhaps for emergency use in combat.

In the modern internal-combustion jet engine, air is taken in and compressed, fuel is burned in it, and the heated mixture is expelled in a jet. If the engine is moving at high enough supersonic speed the air is sufficiently compressed simply by being "rammed" into the engine, but at subsonic speeds mechanical compression is necessary. The compressor can be of any type, and it may be driven by any convenient means, but usually weight is saved by combining the compressor-driving and the jet-producing functions in a single engine; after the air

[1]The familiar "jet-assisted take-off" (Jato) engine was really a rocket, not a jet engine in the now standard use of the term, and its name was officially changed late in 1949 to Rato.

is compressed and heated, a part of the heat energy is extracted to drive the compressor and the remainder is used to create the jet.

This, however, is exactly the way in which an ordinary internal-combustion engine works, and the exhaust of any such engine has only to be properly directed through a pipe of the proper design to create a jet which produces thrust. The only essential difference is that when the engine is used as a source of mechanical power (e.g., for driving a propeller), it is designed to extract as much as possible of the heat energy in mechanical form, only the irreducible minimum being left in the exhaust or jet, whereas in a pure jet engine only enough mechanical power is extracted to turn the unloaded engine, all the rest remaining in the exhaust or jet.

Until about the middle of the 1930's the energy in the exhaust of ordinary reciprocating aircraft engines was simply wasted,[2] but in the latter half of the decade jet exhaust stacks which obtained thrust from this energy were developed in both Germany and Britain, and similar work was done in the United States a few years later. If the reciprocating engine were not obliged to supply any power from its crankshaft, a much larger part of the energy could remain in the exhaust, and the engine could be used as a pure jet engine. This was in fact the first form of internal-combustion jet engine to be proposed (by the Frenchman René Lorin in 1908),[3] but its weight is unduly great and none has ever been built.

The gas turbine is another form of internal-combustion engine which works on the same basic principle as the reciprocating engine but uses an entirely different mechanical arrangement to do so. Instead of having a piston which acts alternately as a compressor and as a device for converting the energy of the hot gases into mechanical power, the turbine engine uses a turbine wheel to convert the energy and has a separate compressor, which may or may not be driven by the turbine wheel. Just as in the case of the reciprocating engine, the gas turbine is unable at best to convert all the energy of the hot gases into mechanical power, and a part goes into the exhaust.

[2]Unless it was used in a turbosupercharger.
[3]French patent 390,256; see Gohlke, *Aircraft Engineering* 14, 1942, p. 32.

Ordinary gas turbines are designed, like ordinary reciprocating engines, to take out as much energy as possible in mechanical form. The aircraft engine now known as a turboprop is of this type; the air is compressed by a rotary compressor, fuel is injected and burnt, and the hot gases pass through a turbine wheel which extracts as much as possible of their energy, part being used to drive the compressor and the residue to drive the propeller. The energy inevitably left in the exhaust is directed to give jet thrust. If, however, the turbine wheel of a gas turbine engine is designed to take only enough energy to drive the compressor, all the remaining energy being left in the exhaust, we have the now well-known turbojet, the only form of pure jet engine which has yet been used for propulsion of manned airplanes. As a propulsive system it is identical to Lorin's 1908 proposal using a reciprocating engine; the reason why turbojets have succeeded where Lorin's proposal did not is simply that the turbine weighs very much less for a given thrust.

Whereas the reciprocating internal-combustion engine was already well established in both aeronautical and other uses before the First World War, there were no successful gas turbines of any sort until shortly before the Second World War. Since jet propulsion at speeds in the range 400 to 650 mph was practical only when the jet was created by a gas turbine, it is impossible to trace the history of jet propulsion without tracing the history of the gas turbine.

A gas turbine appears in an English patent of 1791, and even the notion of using the exhaust of such a turbine for jet propulsion goes back at least to 1921, when it was proposed by the Frenchman M. Guillaume.[4] Our story is thus by no means one of invention in the popular or legal sense of that word. It is rather one of gradual development of basic knowledge to the point where the turbojet at last became practical, and then of the recognition of this fact and the development of the turbojet engine.

[4]French patent 534,801; see Gohlke, loc. cit.

Industrial Gas Turbines: 1900-1940

Although the principle of the gas turbine was known in the eighteenth century, almost a hundred years passed before the state of general engineering knowledge permitted any practical work to be undertaken. It was not until after 1900 that anyone succeeded in building a gas turbine which could even run under its own power, let alone have power left over for some useful application.

The first gas turbine of the modern type, with continuous combustion, capable of running under its own power, was developed in France between 1900 and 1906 by C. Lemale and René Armengaud, working for the Société anonyme des Turbomoteurs. By 1906 they had an engine which could run and even develop a small amount of useful power, but its efficiency was only about 3%. In the United States Sanford Moss, a graduate student at Cornell, had started to work on a gas turbine in 1901; his work aroused the interest of men in the General Electric Company, and by 1907 Moss had developed for them an operating gas turbine. Like the engine of Lemale and Armengaud, however, its efficiency was only about 3%.

Reciprocating internal-combustion engines had efficiencies as high as 30% at this time, and there was no economic use for an internal-combustion engine with 3% efficiency. Moreover, it was clear, as a result of the work done by 1907, that it was impossible at that time to build a gas turbine with satisfactory efficiency. There were three principal reasons: compressor efficiency was too low, the efficiency of turbine wheels themselves was too low, and the materials available for turbine buckets set too low a limit on the temperature of the gases passing through them. Consequently General Electric's attempts to develop a gas turbine were abandoned in 1907, and the Société des Turbomoteurs was liquidated in 1909. The next attempts at gas turbine prime movers of the modern type were not made until the 1930's.[5]

[5]The one gas turbine intensively developed in the interval was of the explosion type, which Karl Holzwarth developed beginning in 1905 and continuing until the outbreak of the Second World War. The Holzwarth turbine was more efficient than the continuous-combustion type in the 1920's and early 1930's, but it became hopelessly complex and as a result was less attractive than other types of engines.

Although gas turbines were too inefficient to be useful in ordinary applications, they or their close relatives could be of use even before 1910 in cases where the heat which drove them was a by-product which would otherwise have been completely lost. The Swiss firm of Brown-Boveri et Compagnie was pre-eminent in the development of such machines throughout the period from about 1905 to 1940. The first successful machine of this sort was a turbo-blower for supplying compressed air to blast furnaces; the furnace gases were burned in a combustion chamber and the products of combustion drove a turbine wheel which in turn drove the compressor that supplied the air to the furnace. Such turbo-blowers were sold by Brown-Boveri before 1910 and were subsequently built by many other concerns.

The Velox boiler, first built by Brown-Boveri in 1931-1932, is another example of a quasigas turbine. This type of boiler has a firebox supplied with air by a compressor in order to have a greater intensity of combustion than is possible in an ordinary firebox; the products of combustion drive a turbine wheel which drives the compressor. The whole arrangement is thus really a gas turbine used not as a source of power but as a source of heat. Although the turbine wheels of the first Velox boilers required outside help to turn the compressor, by the end of the 1930's the turbine not only ran the compressor but delivered a certain excess of power which was used to generate electricity.

Beginning in 1936 Brown-Boveri built turbo-blowers for use in the Houdry cracking process. The primary purpose of these machines, as of the blast-furnace blowers, is to supply compressed air, but the Houdry turbines have no combustion chamber of their own, the hot by-product gases of the cracking process being used directly to drive the turbine. Like the later Velox boilers, the Houdry turbo-blowers had a net power output which was used to generate electricity.

By the end of the 1930's the efficiencies of turbine wheels and of the axial-flow compressors developed especially by Brown-Boveri during that decade were remarkably high, each being in the neighborhood of 85%. It was the substitution of axial for centrifugal compressors which brought a net power output from the Velox boiler, and the over-all efficiency of Brown-

Boveri's Houdry gas turbines was as low as it was — not much over 15% — chiefly because the temperatures used were very low.[6] The inlet temperature of these turbines was never higher than 1,000°F, and usually closer to 900°F, because at higher temperatures the life of the turbine wheels was too short to be economical.

Even with efficiencies only a little over 15%, gas turbines could be used as independent engines in special circumstances: where low first cost outweighed high operating cost, as in a standby plant, or where the engine replaced by the turbine was particularly inefficient, as in a railroad locomotive. In 1939 Brown-Boveri delivered gas turbines for a 4,000-hp standby electric plant for the city of Neuchatel in Switzerland and for a locomotive for the Swiss Federal Railways, and by 1940 it had built four more engines like the one in Neuchatel. The Neuchatel engine, with 84% compressor efficiency, 86% turbine efficiency, and 1,022°F inlet temperature, had an over-all efficiency of 17%.

By the end of the 1930's it was beginning to be thought that the low limit on inlet temperature set by the turbine buckets, which was the last obstacle to the production of gas turbines with efficiencies fully competitive with steam or Diesel engines, was about to be overcome. During the 1930's a good deal of work was done in Europe on internal cooling of the buckets both by water and by air, and manufacturers of alloys both abroad and in the United States were claiming much improved high-temperature strength for various new materials. A committee set up by the American National Academy of Sciences in 1940 reported[7] that operation at 1,500°F might soon be possible even without resort to cooling of the buckets. With a compressor and turbine wheel of the same efficiencies as those of the Neuchatel plant, an increase in inlet temperature from 1,200°F to 1,500°F would raise the over-all efficiency from 17% to 26%, or to about two-thirds of the efficiency of the much heavier and more expensive Diesel engine.

[6]Additional losses were suffered because the air lost more pressure in the cracking process than it would have in a regular combustion chamber.

[7]U. S. Navy Department, Bureau of Ships, *An Investigation of the Possibilities of the Gas Turbine for Marine Propulsion*, Bureau of Ships Technical Bulletin 2 (Washington: Government Printing Office, 1941).

The Turbosupercharger

Another side product of the early turbine work was the turbosupercharger, where the exhaust of a reciprocating engine drives a turbine wheel coupled to a compressor or supercharger which supplies air to the engine. Since the energy in the exhaust would be completely lost without the turbo (except in the case of jet exhaust of aircraft engines), there is a net gain even from a very inefficient machine.

The turbosupercharger was first proposed by the Swiss Alfred Buechi of Brown-Boveri in 1906, and the first tests were made in 1911. The turbosupercharger was first applied to aircraft engines in 1916 by Auguste Rateau in France; turbos of his design were flown before the end of the First World War. In 1917 a Rateau turbo or the design of one was sent to the American Army; the Army was told of Moss's early work on gas turbines at GE and persuaded GE to develop a turbo under Moss's direction. In Britain James E. Ellor of the Royal Aircraft Factory (later RAE) had before the end of the war designed a turbosupercharger in cooperation with the Metropolitan Vickers Company; the design was later considerably modified under the influence of Rateau's machines.

After the war, development of the aviation turbo lagged in France. In Britain the RAE, with the cooperation of several engine manufacturers, developed its turbo energetically in the first half of the 1920's, but by 1926 or 1927 the British had shifted most of their efforts to the gear-driven supercharger and the turbo was virtually shelved. The one country where the aviation turbo was intensively developed throughout the period between the wars was the United States.[8] The GE turbo was submitted to the Army for test in 1918, and in the same year E. H. Sherbondy submitted a turbosupercharger developed under his direction by the De Laval Steam Turbine Company from Rateau's plans. The Army concluded from its tests that only the GE machine was worth further development. From 1919 through the Second World War the Army paid the entire

[8]Germany did not begin development of turbosuperchargers for gasoline engines until after the middle of the 1930's.

costs of continuous development of this product by a team at the Lynn works of GE, headed until 1937 by Sanford Moss.

The most difficult problem in the development of the turbosupercharger was the construction of a turbine wheel which could withstand the exhaust temperature of a gasoline engine, and the one field in which the development of the turbo made a real contribution to the development of the gas turbine was in this field of metallurgy. Both in Germany and in the United States the really useful background for the solution of the metallurgical problems of the gas turbine was acquired in this way, as will be shown later, and the British suffered until late 1942 from the fact that they did not have a similar metallurgical background.

In the other two critical problems of the gas turbine, however, the improvement of the efficiencies of the compressor and the turbine wheel, the turbosupercharger contributed nothing at all. There was available in the exhaust of the reciprocating engine so much more energy than was required for supercharging that there was no real need for improving the efficiency of either component. The turbosupercharger itself was quite tolerably satisfactory by the middle of the 1930's, when it was installed on the production PB-2A's, and the chief remaining problems were with the controls.[9]

The Usual Attitude toward Gas Turbines for Aircraft: 1920-1940

Immediately after the First World War gas turbines were being proposed as primary power plants for aircraft. The common reaction then and for 20 years thereafter to all proposals for aircraft gas turbines is shown, however, in a report made by W. J. Stern of the British Air Ministry's South Kensington laboratory and issued by the Aeronautical Research Committee in 1920.[10] This report is of great interest, not because of

[9]The next production use of the turbo after the PB-2A was on the B-17B, in the latter half of 1939, but it had performed very well experimentally before this, e.g., on the XP-37 in 1937, and the chief reasons urged against its adoption after 1937 were difficulties with installation and control, not with the turbo itself.

[10]*Engine Subcommittee Report* 54, dated September 1920 (London: His Majesty's Stationery Office, 1921).

its merits, but because its arguments are typical of almost all subsequent discussion of aircraft gas turbines until the 1940's.

The engine which Stern considered the best possible would use a seven-stage centrifugal blower with 10:1 pressure ratio and a two-stage Curtis impulse turbine with the blades operating at a temperature of 890°F and a rim speed of about 800 fps. The pressure ratio was selected as being the greatest possible with a rotary blower, the turbine temperature and speed as being the greatest possible with existing materials. In estimating the efficiency of the components Stern was fairly optimistic: he assumed 70% isothermal for the compressor (attained by water cooling), although the best yet attained by such compressors was only 65%. For the turbine he assumed 70%, which was reasonable enough on his assumption that all the kinetic energy in the exhaust would be lost, as virtually all of it would have been at existing airplane speeds. Combustion efficiency was tacitly assumed to be 100%, and radiation losses were explicitly assumed to be zero. These assumptions yielded an over-all efficiency of 15%, corresponding to a fuel consumption of a little under 1 lb/hp hr, which would have been a good beginning for a turboprop in 1940.

In estimating the weight and size of the engine, however, Stern was very far from right and unnecessarily so, essentially because he simply followed industrial practice and took no account whatever of the possibility of designing for light weight and small size. According to him, the seven-stage centrifugal compressor would measure 3 ft x 3 ft x 6 ft and would weigh 2,000 lb. This corresponds quite well with industrial compressors of the same rating[11] even in 1949, but present-day aircraft compressors are very much lighter than industrial compressors simply because they are carefully designed to be light.[12] Stern's combustion chamber was to be of cast iron as in commercial practice. This was far from being the best-suited material available even in 1920, since it not only is heavy but cannot withstand high temperatures, and although the best modern alloys were not available then, stainless steels

[11]Five hundred lb of air per minute at a pressure ratio of 10:1, at 4,000 rpm.

[12]Some aircraft compressor rotors in 1949 were aluminum forgings, which were not available in 1920, but others even at this time were steel.

were available which would have been not only very much lighter but very much more durable than cast iron. Stern's limit of about 800 fps for turbine rim speed was likewise taken from commercial practice, and even in 1920 could have been considerably increased in an aircraft engine. Finally, Stern allowed 1,250 lb for "fuel pump, gearing, etc.", several times the amount necessary even in the then existing state of the art of aircraft engines.

Thus Stern arrived at a total weight of 6,000 lb for a 1,000-hp engine, or 6 lb/hp. Since contemporary reciprocating aircraft engines weighed only about 2.5 lb/hp, and since the fuel consumption of the gas turbine would be twice as great, Stern rejected the gas turbine as impractical for aircraft.

What is really remarkable is not that Stern was this far off in 1920, but that 20 years later, in 1940, industrial-turbine engineers were making estimates of the minimum weight of gas turbines which were twice as high as Stern's, despite all the progress in basic knowledge which had intervened (cf. Chapter XIV, p. 443). The following chapters will trace the circumstances under which these ideas were overcome, first in Britain and Germany, and then, much later, in the United States.