CHAPTER XVII

Why Was the United States Behind in Turbojet Development?

Development of turbojet engines did not begin in the United States until 1941, five years after it had begun in both Germany and Britain. So great a delay naturally prompts the question whether this was not simply an historical accident but the result of some inherent characteristics of the American system of directing or financing the development of aeronautical materiel.

Some Alleged Explanations

The Technical Obstacles

The two technical prerequisites for a turbojet of usable performance characteristics which seemed most difficult to fulfill in the 1930's were sufficiently high efficiency and pressure ratio from the compressor and adequate strength at sufficiently high temperatures from the materials of which the turbine buckets were to be made. It is shown, however, in the appendix to this chapter, that neither of these difficulties is any explanation why the development of turbojets could not have begun in the United States as soon as it began in Britain and Germany, in 1936.

As regards bucket materials, the United States was actually far better off than either of those countries: materials were already available in 1930 which were vastly superior to any material ever available to the Germans and to any material available to the British at least until late in 1942. The first American turbojet to be considered adequate as a fighter power plant and to be put in full quantity production, the I-40 or J-33, had turbine buckets cast of Stellite alloy No. 21, a very close

relative of Stellite alloy No. 6, data on the hot strength of which had been published in 1930. It is true that fully satisfactory methods of fabricating buckets of the Stellite alloys did not exist until 1941, but this was only because it was not until then that it was realized that enough advantage could be gained from their use in the single existing application for such buckets, turbosuperchargers, to be worth the cost of developing the methods. The development of the methods, when it did take place, was a straightforward process which could have been begun just as well in 1930 if the need had been seen.

The situation in the 1930's as regards compressors of sufficiently high efficiency at sufficiently high pressure ratio was, it is true, less favorable in absolute terms than the situation as regards alloys for turbine buckets. The first American turbojets to be flown and produced had centrifugal compressors with efficiencies over 70% at pressure ratios of about 4:1, whereas the centrifugal compressors used in American superchargers at the beginning of the 1930's had efficiencies under 60% at a pressure ratio of 2:1, and in 1935 had an efficiency not better than 65% at this same pressure ratio.[1] But although the art of the centrifugal compressor was more advanced in Britain throughout the first half of the 1930's than it was in the United States, and it may have been somewhat more advanced in Germany, existing centrifugal compressors were far from adequate for turbojets in either country in 1936. After about 1937, furthermore, the superchargers developed by Wright Aero for its own engines were fully as good as anything available abroad. The fact was that foreign turbojets with centrifugal compressors were based, not on what had actually been achieved, but on what it was hoped would be achieved, and the same thing could equally well have been done in the United States.

The same thing was true of turbines with axial compressors. When the RAE undertook to develop such an engine in 1936, little more was known about this type of compressor in Britain than in the United States, and the same situation confronted

[1]These efficiencies are with axial inlets, as might have been used on turbojets. The efficiencies of the superchargers as actually installed on reciprocating engines were between 5% and 10% worse.

the Junkers Airplane Company in the same year in Germany. It was not until 1938 that the AVA announced the first results of its work on axial compressors in Germany, and in that same year the NACA began development of an axial compressor which soon proved very much superior to the designs of the AVA.

Most important of all, it is quite certain that the great progress which was ultimately made with both types of compressor was a result of development of the compressor as such and did not have to wait for some advance to be made in the underlying basic science of aerodynamics. Progress was made as soon as it was realized that it was worth the cost.

One more technical prerequisite for a successful turbojet does not concern the engine as such but the way in which it is used: at airplane speeds under about 500 mph even the turbojets finally developed by the end of the war consume too much fuel to be competitive with conventional propulsive systems. One of the reasons most frequently given for the late date at which the development of turbojets was begun is that it was necessary to wait until airplane speeds had approached this minimum. As far as the airframe itself is concerned, however, there were no really basic advances made between the airplanes of the mid-1930's and the jet-propelled aircraft actually designed and produced before the end of the war. The last fundamental changes in the airframe were the adoption of the internally braced monoplane construction and of retractable landing gear, both of which were almost universal by 1935. A great deal of refinement and cleaning up was done subsequently, but none of it was absolutely essential for the attainment of a speed of 500 mph, and a good deal of the cleaning up could and would have been done much sooner than it was if power plants had been available which made possible speeds high enough for the cleaning up to be worth while.

There was thus no fundamental technical obstacle to prevent the development of turbojets from being begun in the United States as soon as it was begun abroad, and the explanation why the United States was five years behind is to be sought elsewhere.

Tactical Utility

Turbojet-propelled aircraft are inherently short-range aircraft, since at low speeds the system of jet propulsion is inevitably very inefficient compared with propulsion by means of a propeller, while at the high speeds where the efficiency of jet propulsion is as good or better than that of a propeller, more fuel is required per mile simply because of the greater drag at the higher speed.[2] It has often been asserted that because of the geography of the United States there was not the need in that country for fighters of extremely high performance gained at the cost of very short range which there was in Britain and Germany. It is a sufficient answer to this argument, however, to recall that the instant he learned of the development of turbojets in Britain the Chief of the Air Corps immediately set about having turbojets developed and produced in the United States. At no time in the 1930's was anyone in the Air Corps sure enough of the nature of a future war to say that a 300-mph long-range airplane would always and under all circumstances be superior to a 500-mph short-range airplane.

Availability of Funds

Another explanation commonly offered for the failure of the United States to develop turbojets during the 1930's is the general lack of funds for aeronautical development of any sort during that period. It is undoubtedly true that there was very much less money available for development of military aircraft in the United States than in Britain at any time in the 1930's or than in Germany at least after 1933, although to some extent this was compensated as far as the strength of the aircraft industry was concerned by the existence of commercial business on a much larger scale than abroad. But although the expenditure of very large sums of money was required before turbojets could be brought to a state where they were ready for service use, the amount required to bring them to the point where a reasonable judgment concerning their promise could be made was really very small: Power Jets spent only about $100,000

[2] Even if propulsive efficiency is as good at high speed as at low, the fuel required per mile traveled increases with the square of the speed.

between 1936 and 1939 to get a bench engine which gave a clear indication of what the turbojet was capable, and Heinkel's expenditures during this same period, which led to an actual turbojet-powered flight, were little if any greater than that. It must also be emphasized that the financial contribution of the British government to turbojet development before the middle of 1939 amounted to only about $5,000, while the contribution of the German government was nil. The work of the Junkers and Heinkel companies can be said to have been financed from profits of an aircraft industry being expanded in view of war, but the resources of Power Jets came from purely private sources having nothing to do with the aviation industry.

The True Explanation: Failure to Realize the Utility of the Turbojet

The real reason why development of turbojets was not begun in the United States sooner than it was was simply that no one realized how tremendous an increase in speed was made possible by the turbojet. The tactical officers of the Air Corps were never asked whether they would accept short range in order to have a speed of 500 mph or more, and the officers of Wright Field and the Bureau of Aeronautics were never asked whether they could find $100,000 for the development of such an engine. By far the largest part of American discussions in the 1930's concerning the use of gas turbines in aircraft did not even consider their use for jet propulsion but considered them as a substitute for a reciprocating engine in conjunction with a conventional propeller.

Subsequent history has fully justified the opinion held by the services in the 1930's, that it was not yet time to begin development of turboprops. The enthusiasts such as the RAE in Britain, Wagner of the Junkers Airplane Company in Germany, and Lasley in the United States were quite wrong in believing in the 1930's that a useful turboprop could be developed in the foreseeable future. Even by the middle of 1949 there was no turboprop in service, and even the fact that there were a few turboprops under service test was a result of an enormous acceleration of research and development of gas turbines

generally which could not be foreseen in the 1930's, being due to the war, which made vastly greater funds available for aeronautical development in general, and to the success of the turbojet, which secured the assignment of a large part of these funds to the problems common to all forms of gas turbines.

Every one of the early turbojet developments was begun, on the other hand, not to obtain a better engine for existing aircraft and existing airspeeds, but as a means of obtaining vastly higher speeds and was connected with the design or at least a notion of a new and suitable airframe. Whittle aimed at 500 mph, and was thinking of the great reductions in drag which B. M. Jones had indicated as possible in a properly designed airframe; both Heinkel and the Junkers airframe division began their developments in the hope of obtaining very greatly increased speed, and the program laid down by the first systematic student of the matter in the German Air Ministry called for the use of jet propulsion only above 480 mph; in the United States the Lockheed Aircraft Corporation's project was started as a means of obtaining speeds far higher than the 400 mph then believed possible with existing power plants.

The failure of most engineers to foresee the value of the turbojet engine sooner than they did was not due to a failure to consider this form of propulsive system at all. The basic principle of jet propulsion is hundreds of years old. The use of jet propulsion specifically for aircraft, and the production of the jet by the use of the exhaust of an internal-combustion engine was patented in France in 1908. The gas-turbine type of internal-combustion engine was patented in the eighteenth century, and gas turbines of the particular type used in modern turbojets were run in France in 1906 and in the United States in 1907. The first patent for a complete turbojet engine is a French one dating back to 1921. The performance of such an engine was studied theoretically in Germany in 1929, and the results were published in 1931. In the United States specifically, jet propulsion was studied theoretically by the NACA in 1923, and jet propulsion by the exhaust of a gas turbine was discussed by General Electric and Wright Field at least as early as the middle of the 1930's. What is more, General Electric turbos were capable by the middle of the 1930's of being run as gas turbines under their own power by running the compressed air through a combustion chamber and thence to the turbine, and such tests were actually made as a convenient means of testing the turbo; with the addition of a suitable exhaust nozzle, such a set-up *was* a turbojet. All that was lacking was development to adequate thrust and efficiency.

Despite the fact that all the basic principles involved in the turbojet were continually being discussed in the United States in the 1930's, and that the turbojet itself was mentioned occasionally in these discussions, the first serious proposal to develop such an engine was not made until 1941, and then it was made, not by a manufacturer of aircraft engines or of turbo-superchargers, but by an airframe manufacturer, Lockheed. But if the origin of the turbojet abroad is considered, this does not seem so strange. The first work done in Germany was also done by an airframe manufacturer, Heinkel, and the next project was started by another airframe manufacturer, the airframe division of the Junkers company, while the only turbojet to be started in Britain before 1939 was the result of the efforts of an RAF officer backed by two other RAF officers and by venture capital from sources having nothing to do with the aviation industry at all. The regular aircraft-engine manufacturers entered the new field in Germany in 1939 only as the result of very considerable pressure from the government; in Britain they became interested only after the first flight of a jet-propelled airplane in that country, in 1941. Thus the aircraft-engine builders in the United States were really not behind their foreign colleagues at all; one company in the United States, the first one to be informed of the extent of the work being done in Britain, began negotiations for a license for the Whittle engine in the first half of 1941, as soon as any British engine manufacturer was really interested, and it was only the action of the American military services which prevented the entire American engine industry from becoming intensely interested in the new field as soon as it became known that jet-propelled aircraft were actually being flown.

There were certainly engineers in the engine industry in all countries who were as capable of calculating the performance of a turbojet engine as the outsiders who began the work; and

while one of the most critical facts about the new engine, its weight, was not subject to accurate calculation before an engine had been built and at least partially developed, certainly the people most capable of making a good estimate were those with the most experience with the design and development of aircraft engines of other types.

Power-plant engineers, however, both in the United States and elsewhere, were too exclusively occupied with the power plant as such to consider the possibility of the enormous increase in airplane speed which would justify the turbojet. The primary task of these specialists was to develop machines which would produce the greatest possible power at the crankshaft for the least possible weight and fuel consumption. It was natural that when they considered a completely new propulsive system, they looked primarily at what it would do if substituted for the existing system in an existing airplane and used to produce performance about equal to that of existing airplanes. The assumption that speeds would not be suddenly increased by a factor of 50% or more was additionally natural because the enormous cost of speed in terms of power[3] had made increases in speed come only very slowly in the past. Thus one American power-plant engineer, on hearing reports of Whittle's work in 1940, computed the performance of a turbojet engine and concluded, quite correctly, that its fuel consumption would be hopelessly high at 400 mph, the highest speed then contemplated for American fighters, and would become competitive only at about 500 mph and above. Five hundred mph, however, he considered quite unrealistic, completely failing to consider the really significant fact about the turbojet, that its effective power at that speed was so vastly greater than that of conventional propulsive systems of equal weight that it would be quite easy to install sufficient power in airframes very like existing ones to make possible this speed. This reasoning was not exceptional, but typical: the principal reason

[3]With a given type of engine and propulsive system, even doubling the power at no increase in weight or size of the engine would only increase the speed of the airplane by about 25%; doubling the power of the engine at the cost of nearly doubling the weight, the way in which power had always been gained in the past, would of course have brought a still smaller increase in speed. And it had taken from 1927 until about 1936 for the power of the largest American aircraft engine to be increased from 500 hp to 1,000 hp.

advanced against the development of turbojets in all countries in the 1930's seems to have been that it was necessary to wait for increased airplane speed.

It is not at all unlikely that if power-plant engineers had been assigned the task of designing a propulsive system which would make possible a speed of 500 mph, they would, like Schelp in Germany, have fairly quickly reached the conclusion that the turbojet was the best solution to the problem. As it was, they took the airplane and its performance virtually as given, and those companies which became interested in the turbine at all were interested in its propeller-driving form, which was indisputably the proper one for such aircraft. Thus when Rolls Royce first began work on turbines, it took up the RAE's counterrotating counterflow ducted fan, and when Pratt & Whitney began such work, it chose the Götaverken system for its advantages in fuel economy, even though it did not hope to gain an ounce in engine weight or a mile per hour of speed.

Governmental Policy Not Responsible

Thus we may conclude that it was not due to any peculiarity of the aircraft-engine industry in the United States that that country began the development of turbojets later than Britain and Germany. So radical an innovation, with such extensive effects on the whole airplane and its performance, came naturally from outside the engine industry in every country. The next question is whether the relative lateness of the United States was due to governmental policies or practices less favorable to such innovations than those of the British and German governments. This question, however, can very quickly be answered in the negative. Government support of turbojet development would certainly not have come in Germany when it did, late in 1938 on a very small scale and during 1939 on a practical scale, had not Heinkel and Junkers previously informed the government of the results of the work they were doing at their own expense and initiative. It is true that within the Air Ministry Schelp was already an enthusiastic advocate of jet propulsion before the work of Junkers and Heinkel was known, but had not the head of the special-propulsion section, Mauch, been impressed by the work of these

two firms (and by the rocket and pulse-jet developments of other firms) Schelp would have remained what he was, a voice crying in the wilderness. In Britain the case is even clearer: the aid given by the government to Power Jets up to the middle of 1939 amounted to only 16% of the total expenses of the company to that date; really important financial aid from the government came only after the work done to the middle of 1939 had demonstrated the promise of the engine. The American military services were at least as quick as the British and German governments to support the development of turbojets once they had any indication that progress was already being made. In fact, the work of the Durand committee was begun on the basis of even less knowledge of previous work than the British and Germans had had before they decided to support such development.

The Late Beginning of Turbojet Development in the United States a Historical Accident

Thus the question of why the United States was behind Germany and Britain in beginning the development of turbojets is answered: in no country was the origin of such development due to either of the agencies primarily concerned with the development of aircraft engines, the government or the aircraft-engine industry. In every case, including the United States, the initiative came from outsiders: from the airframe industry in Germany and the United States, from a flying officer and outside capital in Britain. The system of directing and financing the development of aircraft engines in the United States was at least no less effective than the systems used abroad, and even the lack of funds in the United States seems to have played no part. The relatively late date at which work began in the United States is simply the result of a historical accident: Whittle, von Ohain, and Wagner were not Americans.

Factors Delaying American Turbojet Development After 1941

The fact that the United States was still seriously behind Britain in gas-turbine development at the end of the Second World War was largely due to two deliberate choices of American military authorities. First these authorities did nothing to promote, and in fact actively discouraged, collaboration among the various firms developing gas turbines, whereas the British did everything possible to promote the fullest exchange of information among all private firms and public agencies in the field. Second, whereas the British not only permitted but encouraged some of their regular aircraft-engine companies to undertake turbine development as early as 1942, the American Army and Navy decided that the war would be fought with existing engine types, and absolutely forbade the engine companies to divert any of their resources to the new field until very late in the war.

Secrecy: Military and Competitive

The need for and effect of secrecy concerning research and development are relevant to the primary purpose of this study only as they are maintained in time of peace, and obviously a state of war makes greater difference in these respects than in almost any other factor influencing research and development. Nevertheless it is worth commenting on the role of secrecy in the wartime development of turbines in the United States because its results seem to indicate that an undue measure of secrecy can be definitely harmful, and this conclusion almost certainly applies also to times of peace.

After the Whittle engine was imported to the United States, it was soon recognized by Bell and by the Army that the design of the intake ducts on the P-59A would be highly critical, and in November 1941 Major General Oliver P. Echols at Wright Field requested permission from the Chief of the Air Corps to have tests made by the NACA in its wind tunnels, the only adequate ones in the United States. General Arnold refused permission, however, because the agreement made with the British when the Whittle engine was imported required absolute secrecy. Half a year later, in June 1942, Brigadier General Chidlaw reported that the performance of the type I engine was in poor agreement with the original calculations, partly because these calculations had been based on the result of experiments in the small wind tunnel at Wright Field after permission to bring in the NACA had been denied. In

April 1943, Chidlaw complained that the whole development had been slowed down by its supersecret status.

By 1943 even the British were anxious to reduce the degree of secrecy in which the Whittle engine was held, and Arnold then gave his permission to reduce its classification to "confidential". The NACA was at last invited to assist in the development with its superior facilities, which then included the new engine laboratory at Cleveland as well as the aerodynamic facilities at Langley Field.[4]

Private firms, of course, are on the whole at least as inclined to be secretive for competitive reasons as military agencies are for reasons of national security. Pratt & Whitney, for example, refused to give information on its PT-1 development even to the NACA. Nor is this peculiarly an American phenomenon; despite serious efforts by the German government to promote cooperation as early as 1939, German firms refused to reveal their developments to each other until the most desperate crisis was at hand.

An attempt to enforce collaboration would undoubtedly be useless at best and very probably harmful in a system which relies on competition as its mainspring. It is, furthermore, undoubtedly true that firms which will collaborate voluntarily in time of war will be far less willing to do so in time of peace. The Navy, however, seems from the beginning of its gas-turbine development program not only to have done nothing to encourage collaboration, but actually to have ordered each company to keep its work secret from all other companies and even from other government agencies. Thus the studies by the Turbo Engineering Corporation, begun early in 1941, were not revealed in detail to anyone until at least a year later, and in giving Westinghouse a contract for turbojet development in December of 1941 the Navy specifically instructed the company to pay no attention to work being done by others.

Certainly one can count on the normal action of competition to secure all the "independence" of development which is

[4] A special building with two test cells for jet engines was begun at Cleveland in July 1943, and by September a small program on the I-16 engine was begun with a staff of eight people. The facilities were rapidly enlarged, and by the end of the war the major part of the activities of the Cleveland laboratory was devoted to jet propulsion.

needed and more, and it is impossible to understand why the Navy prohibited all interchange of information, especially when the type of engine being developed was so new that it was obviously necessary to develop a vast amount of basic knowledge which would have to be incorporated in all successful engines, regardless of the differences among them. The British policy of securing all the collaboration to which the companies would consent seems far sounder. According to the Army officer in charge of gas turbine work, Colonel D. J. Keirn, the British success could not have been achieved without collaboration.[5]

The Exclusion of the Aircraft-Engine Builders

The second principal factor delaying development of gas turbines in the United States after 1941, the decision of the services to exclude the aircraft-engine firms from the new field, was due to the belief that for the short-run purpose of winning the war the most effective use would be made of the limited resources of these firms if they were not diverted from the development of the conventional engines actually in service. This decision may have been justified in view of the special military situation facing the United States, which did not seem to offer much use for short-range interceptors. If, however, the Germans had put their jet-propelled fighters into production as soon as they were technically able to, about a year before they actually did, the United States would probably have had a very great need of similar fighters for the campaign in Europe. It should be pointed out, moreover, that the British succeeded in taking advantage of the experience of the aircraft-engine firms without appreciably sacrificing the development of conventional engines. The facilities used in Britain for turbine development were largely created specially for that purpose, just as in the United States, and only a very few key engineers were actually taken from reciprocating-engine development to direct the new work, most of the personnel being acquired elsewhere.

[5] *Journal of the Aeronautical Sciences* 13, 1946, pp. 84-85.

Summary of Chapters XII through XVII

Development of the turbojet began almost simultaneously in Britain and Germany in 1935-1936. All its elements were old, and even the precise combination of elements was patented over a decade before development began. In both Britain and Germany the actual beginning of development was due to the enthusiasm of engineers who were not employed by the aircraft engine industry, and in both cases the projects were backed by capital which came from neither the aircraft engine industry nor the government. In both countries this private work first awoke the interest and obtained the support of government, and it was still later that the engine industry began to take a hand. In the end, however, development of turbojets in these two countries to full readiness for service was accomplished only by experienced builders of conventional engines.

The United States was five years behind Britain and Germany in undertaking the development of turbojets, but it would seem that no particular significance can be attached to this fact: the actual beginning of work in those two countries depended on chains of accidents which simply did not happen to occur in the United States. The development could technically have begun in all three countries years before it did. The fact that the United States was still behind in turbojet development in 1945 was due in part to its late start, and the record of General Electric's development of turbojets starting from British data in 1941 is nearly as good as the British record itself. In part, however, it was due to the ill-advised policy of the services, particularly the Navy, which prevented any interchange of information among the interested firms.

APPENDIX TO CHAPTER XVII

The Technical Obstacles Delaying the Beginning of Gas Turbine Development in the United States

Materials For Gas Turbine Buckets

Until the actual development of gas turbines for aircraft began in the United States in 1941, the only need in aircraft engines for materials capable of supporting very high stresses at high temperatures was in exhaust valves and in the turbine blades or buckets of turbo-superchargers.[6] The properties required in valve materials were enough different from those required in buckets that results obtained by development of valves could not be directly applied to the development of buckets.

From 1918 until 1922 turbo buckets were made of a steel known as SAE 6150, and from 1922 to 1928 of a steel known as Silchrome No. 1.[7] The hot strength of these materials was not significantly greater than that of the ordinary steels used for beams and columns. Silchrome No. 1 did, however, make a considerably better bucket material than SAE 6150, for the same reason that it had been originally introduced as an exhaust-valve material: it was only slightly subject to oxidation by combustion gases and thus did not scale off and lose strength by losing size as did SAE 6150.

In the early 1920's the Army became aware of the high hot strength of the British steel known as Kayser and Ellison 965,[8] which was widely used in England for aircraft exhaust valves, and in 1928 KE-965 was adopted for turbo buckets. It was the first material to be used for this purpose which had been really developed to have high hot strength; it permitted the blade temperature of the turbo to be raised from less than 1,100°F to nearly 1,400°F and on

[6]In the 1920's and 1930's the standard material for the buckets of steam turbines was the type of stainless steel known as "12% Chrome", which could operate at blade temperatures up to about 1,000°F. Better efficiency could have been obtained by an increase in temperature, but this would have created a number of serious problems outside the turbine buckets — e.g., in the turbine stator and in the pipes carrying the steam from the boiler to the turbine — and it was highly probable that a bucket material which could be used at higher temperature would be more expensive, more difficult to fabricate, and less good in fatigue strength than 12% Chrome. For this reason there was almost no pressure at all to develop a higher-temperature alloy for use in steam turbines, and steam turbines contributed nothing at all to the development of alloys suitable for use in gas turbines.

[7]SAE 6150: 0.5% C, 1 Cr, 0.2 V, 0.3 Si, balance Fe; primarily a spring steel. Silchrome No. 1: 0.5 C, 8.5 Cr, 3 Si, balance Fe.

[8]Composition: approximately 14 Cr, 14 Ni, 3 W, 0.4 C, balance Fe.

the whole was quite satisfactory in use. The Army was unwilling, however, to rely on a foreign material the supply of which might be cut off in time of war, and the search for an American substitute led to development by the Universal Cyclops Steel Corporation of 17W,[9] a modification of KE-965. 17W was adopted for turbo buckets in 1933.

In this same year, 1933, the Army tried out a set of buckets made of Stellite alloy No. 6, which had hot strength very much superior to that of 17W. This material was of a class of cobalt-base alloys which was remarkable for retaining its strength even after considerable periods of overheating. A large variety of alloys of this class had been developed and were sold by the Haynes Stellite Company, a unit of the Union Carbide and Carbon Corporation, under the brand name Stellite. The first of these alloys had been developed before the First World War by Elwood Haynes as materials for high-speed metal cutting, and had proved excellent for this purpose because of their great hardness and toughness at high temperature. Although they had not been developed for strength at high temperature, and although strength is not directly proportional to hardness, the Stellite alloys were soon discovered to be extraordinarily strong at temperatures as high as 1,832°F.

Data on the hot strength of Stellite alloy No. 6 were published by the maker in 1930 and almost immediately came to the attention of Wright Field. As a result of Wright Field research this alloy soon came to be very widely used for valve facings, and its great hot strength made it naturally indicated for turbo buckets as well. It was so hard at high temperatures that it could not be forged into buckets as previous materials and 17W were fabricated, but a set of buckets was fabricated in 1933 by the Austenal Laboratories by a lost-wax casting process which Austenal had developed for use in manufacturing dentures.[10]

This process had been developed by 1933 to a point where it was fully satisfactory for dentures, but it proved unsatisfactory at

[9]Composition: 14 Cr, 19 Ni, 2.5 W, 0.5 Mo, 0.4 C, balance Fe.

[10]Austenal had originally made dentures of stainless steel, but about 1929 had set out to find a way of producing them at lower cost by casting. Gold dentures were already cast with great accuracy by the lost-wax process, but Austenal wanted a material which would be cheaper than gold and yet very resistant to corrosion. It was fairly apparent that a cobalt-base alloy could be readily developed to have the desired properties, but these alloys could not be cast in plaster molds like gold because they had to be cast at a very much higher temperature. Application by Austenal to a number of likely suppliers led to the discovery that tetraethyl silicate, which was being studied by Union Carbide and Carbon Research Laboratories, would be a satisfactory mold-binding material, and the Haynes Stellite Company developed for Austenal a special grade of Stellite alloy by modification of the existing Stellite alloy No. 6 used for valve facing. The Austenal Company sold this new material, fabricated into dentures, under the brand name Vitallium.

this time for turbo buckets: a large proportion of the castings were defective, and even the sound ones had to be finished by machining, which was extremely difficult owing to the great hardness of the alloy, or by grinding, which was equally difficult because of the shape of the buckets. The result was that although the strength of the material was very interesting, the whole idea of making buckets of it was given up as impractical for a number of years after 1933.

In 1936 the Army became interested in a new group of alloys which seemed to have better hot strength than 17W and yet were somewhat easier to fabricate than the Stellite alloys. These were the nickel-molybdenum alloys sold by the Haynes Stellite Company under the brand name "Hastelloy". These alloys, of which there were four altogether, A, B, C, and D, had been originally developed, not for strength at high temperature, but for resistance against corrosion by acids and chlorides at ordinary temperatures, for use in chemical processes. The Union Carbide and Carbon Research Laboratories had begun intensive development of the alloys in 1926, and the first grades were offered for sale by Haynes Stellite in 1929. In trying to produce the alloys in wrought form, such as wire and sheet, it was discovered that although they had not been developed for that property they had remarkable strength at high temperatures. Data showing this for wrought Hastelloy alloy A and the cast C and D alloys were published in 1931, but the importance of these data was not realized for some years by engineers interested in the turbosupercharger. It was only when data on the hot strength of the wrought B grade were published in 1936 that Wright Field became interested and asked Haynes Stellite to investigate its suitability for turbo buckets.

Cooperative research by Haynes Stellite and General Electric into the possibility of using Hastelloy alloy A, B, or C as a material for turbosupercharger buckets was begun in 1937. Forging was extremely difficult because of the great hardness and strength of these alloys at high temperature, but GE eventually developed a successful technique, the first one to succeed in drop-forging a Hastelloy alloy into any finished shape. Tests were also made of buckets which were cast to size by Austenal, but they were not liked so well as the forged buckets, both because it was extremely difficult to produce sound, accurate castings and because the casting process gave a much larger grain than forging, while experience to date was believed to indicate that fine grain was essential for turbine buckets. The result was that by the middle of 1941 GE had decided that the best available method of producing turbo buckets was to forge them

of Hastelloy alloy B.[11] Eventually research done by GE on cast and forged Hastelloy buckets led to the discovery that at the 1,500°F-1,600°F blade temperature of the turbo the large grain of castings actually gave superior strength after 200 or 300 hours of life, but it would seem that this had not yet been fully realized by the middle of 1941.[12]

By this time, however, it was clear that because of the war, buckets for turbosuperchargers would have to be made in enormous quantities, and that there was not nearly enough forging capacity in the United States for the use of that method of production, particularly since Hastelloy alloy B was so hard at the forging temperatures that the dies wore out very quickly. The result was that Austenal set to work in cooperation with GE to develop its lost-wax casting process to be really satisfactory for casting turbo buckets, and to make it suitable to true mass production.[13] Austenal found it much easier to produce good castings of the Haynes Stellite alloy closely related to Stellite No. 6 which Austenal sold in dentures under the name Vitallium than of any of the other alloys tried. It was only then that tests were made by GE which revealed that Vitallium had really superior properties as a bucket material. The casting process had been developed to the point where it was satisfactory for buckets by the end of 1941, and Austenal then developed from the denture alloy a slightly modified composition which contained less carbon and hence was less brittle and better suited for turbine buckets. As soon as this casting process and alloy were approved for production by the Army, the Haynes Stellite Company was called on to assist in working out methods for mass production. The modified denture alloy was further improved by Haynes Stellite; the resulting material was designated Stellite alloy No. 21.[14] This proved an excellent material for the purpose and actually far better than Hastelloy alloy B would have been, since the latter material contained no chromium and had very poor resistance to oxidation above about 1,400°F.[15]

[11] Composition: 28 Mo, 0.6 Mn, 0.4 Si, 5 Fe, 0.06 C, balance Ni.

[12] It had been known some time before this from work on steam turbines that above a certain temperature cast steel crept (stretched) less under a given stress than the same steel in the forged condition, but it was believed that the castings were too brittle and subject to fatigue failure to be useful as buckets.

[13] 2,100,000 buckets were eventually produced in one month by Austenal and Austenal's licensees.

[14] Composition: 28.7 Cr, 2.0 Ni, 5.6 Mo, 1.0 Fe, 0.25 C, 0.3 Mn, 0.6 Si, balance Co. This Stellite alloy No. 21 was sold in the fabricated form by Austenal under the same name, Vitallium, which it gave to the dental alloy.

[15] It was eventually realized that because of its superior resistance to corrosion, Hastelloy alloy C, which contained 17% chromium, would have been better than Hastelloy alloy B above 1,400°F, despite its inferior fabrication properties and

(Footnote continued on next page)

When General Electric began the development of the I-series gas turbines, the first successful aircraft turbines to be produced in the United States, the turbine buckets were made of materials already known from the work done on turbosuperchargers. At the very beginning of the development of the Whittle engine in this country, in October 1941, GE adopted forged buckets of Hastelloy alloy B, which proved to be a far better material than the Rex 78 which the British were using at that time. The maximum blade temperatures on the I-16, which was the American production version of the original Whittle engine, were in fact within the range (about 1,200°F to 1,350°F) for which Hastelloy alloy B was best suited. Forged Hastelloy alloy B was also used on the first experimental engines of the larger I-40 type, development of which began in 1943. Lack of forging capacity prevented the use of this material in production I-40's, but by the time quantity production of this engine was actually under way, in 1945, methods had been developed for making fully satisfactory cast buckets of Stellite alloy No. 21, even though these buckets weighed 35 times as much as those of the type B turbosupercharger which was produced in quantity during the war. The General Electric Schenectady steam-turbine division's independently designed axial turboprop, the TG-100, development of which began in 1941, originally used cast blades of Stellite alloy No. 21. The Westinghouse 19 turbojet, the first engine of purely American design to be flown, was developed with blades of the Westinghouse alloy K-42-B, but part of the quantity production was done with cast Stellite alloy No. 23, a close relative of No. 21.

There is no question that either the Stellite or the Hastelloy alloys were greatly superior to any material available to the Germans for use in their gas turbine buckets, the reason being that the Germans suffered from severe shortages of critical constituents, particularly cobalt and nickel. As has already been remarked, these American alloys were unquestionably superior to the Rex 78 used by the British from 1940 to late 1942, and vastly superior to the Stayblade which the British had used until 1940. It is disputed whether Hastelloy alloy B or Stellite alloy 21 was superior to Nimonic 80, which the British adopted late in 1942 and used on all their production engines, but in any case virtually all American engineers were agreed in preferring the American materials.[16]

ductility. The type C alloy had not been available as wrought bar stock at the time the original development of Hastelloy buckets was done, and by the time it was available, the Stellite alloys had been recognized to be still better for use in the turbosupercharger.

[16]All high-temperature alloys obtain at least the larger portion of their hot strength from so-called intermetallic compounds finely distributed through the

Thus it simply cannot be maintained that inadequate progress in metallurgy was in any degree responsible for delaying the development of aircraft gas turbines in the United States. Alloys which were generally considered by American engineers to be superior to anything used by either the British or the Germans already existed in 1930 either in their final form (in the case of Hastelloy alloy B) or in a form which could have been quickly developed to yield the final form (in the case of Stellite alloy No. 6, which was developed into No. 21), and it was these alloys which were in fact used for the first American production turbines in the 1940's.

It is true that it was not until the end of the 1930's or even later that the properties of these alloys at high temperature were accurately known. The real reason for this, however, was that no one had seen a need much before this time to investigate those properties. Had a serious search been made in 1930 for materials with the highest possible strength at high temperature, it is as certain as such things can be that both the Hastelloy and the Stellite alloys would have been systematically tested.

material. These compounds are formed when the alloy is originally solidified, and exist in larger quantity than can be held dissolved in saturated solid solution at the temperature at which the alloy is to be used, so that when the alloy is cooled down a certain amount of the intermetallic compound is precipitated. It is this precipitate which, if properly distributed through the alloy, gives it its strength at high temperature.

There are in general two classes of these high temperature alloys, the difference being in the rapidity with which the intermetallic compounds are precipitated when the alloy is cooled. In the first class, which includes the British Rex 78 and Nimonic 80, the German Tinidur, and Westinghouse K-42-B, the precipitation is quite rapid. Adequate hot strength can be produced in these materials only if they are heat-treated after fabrication. They are first "solution-treated", i.e., raised to a very high temperature to put all the intermetallics in solution, after which they are "quenched" or suddenly chilled to hold the compounds in solution, and then "age hardened" by being held at the proper intermediate temperature for the proper amount of time to produce the best possible distribution of the particles of intermetallic compound through the rest of the material. This class of materials has the rather serious weakness of losing its hot strength quite rapidly if subjected to temperatures equal to or greater than the aging temperature, since the intermetallics then coagulate into large particles. The successful use of Nimonic 80 and Tinidur in gas turbines depended on very careful design and operation which avoided subjecting the buckets to excessive temperatures even for short periods of time.

The Hastelloy and Stellite alloys belong to a second class, in which the intermetallic compounds precipitate out of solution rather slowly; ordinary cooling does not produce excessively large globules of these compounds and heat treating is not necessary to produce hot strength. In some cases the strength and other properties are somewhat improved by age-hardening, i.e., by intentionally holding the metal at an elevated temperature for a certain amount of time, but in general solution-treating is not used. The important fact about the alloys of this class is not, however, the method by which they are prepared, but the fact that the same slowness of precipitation which makes solution-treating unnecessary also means that there is not the rapid coagulation of the intermetallics when the alloys are overheated which quickly destroys the hot strength of the alloys of the first class.

Because no systematic search had been made for materials suitable for use in aircraft gas turbines of turbosuperchargers until shortly before the war, the data which were available on the hot strength of existing alloys were not of the most significant sort. The existing data on these alloys were mostly on their hot "tensile" strength, measured by rapidly increasing the stress on the material until it breaks. Since almost all materials will support an appreciably greater stress at high temperature for a short time than for a longer time, these tests could only be used as design criteria if a large factor of safety was allowed. "Stress-rupture" tests measuring the stress which could be withstood for a given time at a given temperature were not made on turbosupercharger bucket materials in the United States until shortly before the war, probably because existing materials were fairly satisfactory in the turbosupercharger and there was no pressing need to find better ones, while tests over a period of time were obviously more expensive than short-time tests.

In gas turbines even stress-rupture tests give inadequate data for design, since some materials stretch a good deal more than others before they break. In the turbosupercharger this fact was of little significance: there was no casing outside the turbine blade tips, so that even the greatest amounts of "creep", as this stretching is called, could do no harm. This type of construction brought a serious decrease in the efficiency of the turbine, but this inefficiency did not matter because in spite of it there was more energy available in the exhaust than was required for the amount of supercharging desired. In a gas turbine engine, however, this loss of efficiency was intolerable: the turbine wheel was put inside a casing, and in order to have tolerable efficiency it was necessary to have a minimum of clearance between the bucket tips and the casing. Thus the most important single criterion of the merit of a material became the amount it would creep in given time under a given temperature and stress. Such tests were perfectly well known and had been widely used on materials for other applications since the early 1920's,[17] and the DVL in Germany had already begun creep testing in connection with its work on turbosuperchargers in 1936, but in the United States such tests of materials for turbo or gas turbine buckets were very rare until the development of gas turbines actually began in 1941. The tests actually made before that time were in general incomplete and intended only to make comparisons of various materials under certain conditions rather than to obtain complete design data.

[17]The stress-rupture test was actually devised much later than the creep test in order to get results more rapidly.

Compressor Efficiency

Second only to metallurgy as an obstacle believed in the 1930's to preclude the building of successful gas turbines was the low pressure ratio and efficiency then achieved by rotary compressors. The centrifugal compressors used in the United States in 1930 in gear-driven superchargers, the only superchargers in actual production and service at that time, were limited to pressure ratios of about 1.2:1; the efficiency was not over 70%[18] exclusive of losses due to installation in the airplane even at this low ratio and became much lower at higher ratios. In 1935 the situation was only a little better: 70% efficiency could be maintained to about 1½:1, but fell off to well under 65% even at 2:1. The efficiency of these compressors was certainly too low to give a turbine engine of acceptable performance. Even in the case of a turbojet, which does not demand nearly so high compressor performance as a turboprop, a usable engine could be built only if the compressor gave at least 3:1 pressure ratio at about 80% efficiency as in the early German engines or 4:1 at 75% as in the early British engines. A propeller-driving turbine has to have a pressure ratio of at least 5:1 with at least 80% efficiency to be of any use whatever.

After 1935, however, progress in the art of centrifugal superchargers became more rapid. Until that date, although a centrifugal supercharger had for years been a part of virtually every high-power aircraft engine developed or produced in the United States, there was only a single source for these superchargers, the General Electric Company. This company had been the first to manufacture centrifugal industrial blowers in the United States, beginning in 1907, and for many years had been the only important manufacturer thereof. As a natural result GE became the sole supplier of centrifugal compressors to the aircraft-engine industry when geared superchargers became standard on radial engines with the appearance of the Wasp in 1926. Not only was the business too small for GE to do extensive development at its own expense, but except for such obvious necessities as designing a supercharger for a new engine model, GE made little effort to persuade the engine builders to pay for further development.

This lack of interest in supercharger development was very largely due to a general failure to realize what was to be gained by it, and this in turn was due to a rather astonishing lack of detailed

[18]Really accurate figures on compressor efficiency are impossible to obtain for any date in the 1930's since a standard method of measuring efficiency was not established until 1941 (see text below).

information about what existing superchargers were actually doing. It was known theoretically, for example, that the flow capacity of the supercharger had to be matched to the requirements of the engine if optimum efficiency was to be secured, but it was not until after the middle of the 1930's that it was realized that existing matches were often if not usually extremely poor, with very great losses of efficiency resulting. In part this was certainly due to the truly pernicious system whereby only the impeller and diffuser were built by GE, while the inlet and the collector or casing were designed and built by the engine builder. Both the inlet and the collector have an extremely important effect on the over-all performance of the compressor, and it was simply impossible to develop the compressor rationally under this system of divided responsibility. GE made recommendations concerning the design of these components, but in order to reduce the size of the engine they were often disregarded by the engine builders, who made no independent tests of the complete supercharger, let alone of their inlets and collectors. General Electric, on the other hand, was very secretive about its part of the work; it issued no information about the efficiency or any other characteristics of the superchargers it supplied, the only figure it released being an approximate one for the maximum power required to drive the impeller, which the engine builders needed in order to design the drive. Thus it was not even known what the efficiency of existing superchargers was.

In 1934-1935 Wright Aeronautical Corporation became the first of the American engine builders to undertake the study and development of its own superchargers. Wright's reason for undertaking supercharger research was simply that satisfactory performance could not be obtained from the supercharger supplied to it by General Electric for use on a new model of the Cyclone with a two-speed supercharger drive which the company had recently begun to develop. With a two-speed drive a poor match of the supercharger to the engine could and did cause much more serious trouble than with a single-speed drive. When General Electric maintained that the supercharger used on the single-speed Cyclone was perfectly suited to the two-speed model, Wright decided that the only solution was to let someone on its own staff become thoroughly familiar with the working of superchargers, and assigned the job to Kenneth Campbell.

Wright's first test equipment for supercharger studies consisted of a 150-hp dynamometer with the rear end of a Cyclone engine used for the gearing. Testing of superchargers on this rig began in 1935. Until 1941 tests were run of complete superchargers only,

with the regular engine inlet elbow in place, not because the company was unaware that it would be desirable to test the components of the supercharger independently, but because the inlet elbow was a part of the supercharger casting and it would have been too expensive to build a new casting with an axial inlet. For the same reason most of the work done during the first two years consisted of testing slight modifications of existing superchargers, since it would have been too expensive to build radically different designs.

One of the most important results of this early work by Wright was the gradual acquisition of an understanding of the design principles of the vaned diffuser. Until not long before 1935 all American diffusers had been of the vaneless type, which does not have to be designed to match exactly the desired characteristics of the supercharger, but when the vaned diffuser was introduced in order to improve the performance of the supercharger, proper matching of that component became the most critical part of supercharger design. Wright's work led to the rejection of the idea of a throat in the diffuser passages, on which the previous design procedure had been based, and to the establishment of a completely new design procedure. The work of these first two years also resulted in very considerable modifications of the design of the impeller, most important of which were a considerable decrease in the width of the air passages at the tip and alteration of the wall contours to create a more nearly constant cross section in the inducer or entrance portion of the impeller.

By 1937, after about two years of work, Wright's newly created supercharger staff had acquired a working knowledge of the main principles of supercharger design: this knowledge was only elementary in most respects, but it was sufficient to give a design method and a basis for independent development of new superchargers. Wright's staff then set out independently to design completely new superchargers for the new G-200 model of the Cyclone[19] and for the new R-2600 and R-3350 engines. In March 1938 Wright management definitely decided to use its own rather than a GE super-

[19]Wright's head start in developing its own superchargers meant that it was the only American firm to have an engine in production early in the war with a supercharger as good as (actually slightly better than) that on the Rolls Royce Merlin XX, which was put in production in 1940. The supercharger of the G-200 Cyclone, put in production in 1939 for use on the B-17, had an efficiency of 70% at a pressure ratio of 2.3:1, while the supercharger of the Merlin XX as tested by Wright Field had an efficiency of 68% at the same pressure ratio (both efficiencies include inlet losses). The chief features which distinguished the Merlin XX supercharger from other American superchargers were present in the G-200: improved inducer design, narrow impeller tips, and a small number of vanes in the diffuser.

charger for the R-3350, and from this time on, all Wright's superchargers were designed by its own staff, although for economy of production the impellers continued to be manufactured by GE. After 1937 research was directed toward further refinement of the elements already studied, and a beginning was made of studying the effect of the inlet and carburetor on the performance of the supercharger. In 1939 a new 500-hp rig was acquired, although the total cost was still limited to $10,000.

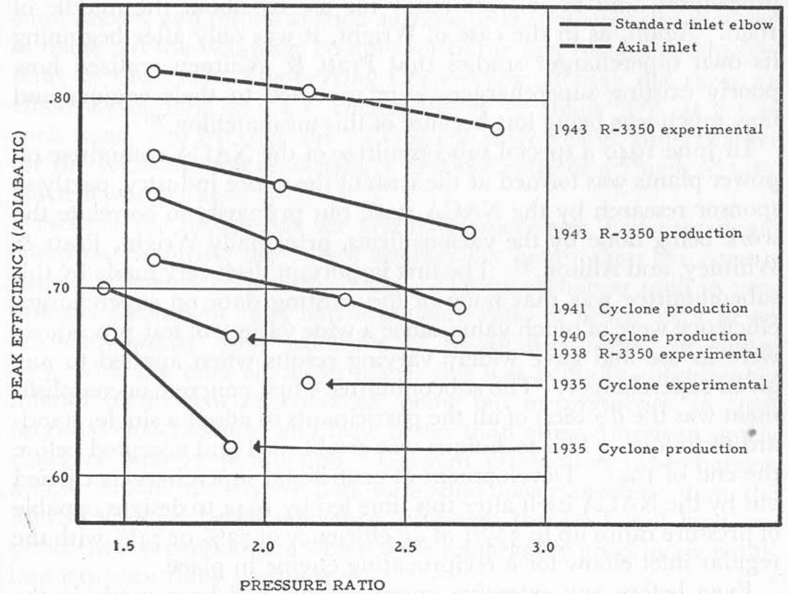
In 1941 Wright very greatly expanded the scale of its supercharger development and research, engine production being now great enough to bear the cost. A 1,000-hp steam-driven rig was acquired and was run on a two-shift basis by a much enlarged staff. Much more shop work could be done, and for the first time superchargers were tested with axial inlets. It was realized for the first time that the inlet elbow had been costing a great deal in over-all supercharger efficiency: 7½% on the R-3350, for example. By the end of the war a new elbow had been developed which gave an efficiency only 1% lower than could be obtained with an axial inlet. Testing with an axial inlet also facilitated the improvement of the rest of the supercharger, where the effects of changes in design had previously been masked by the disturbances created in the elbow; this was largely responsible for the considerably greater rapidity with which detailed information was acquired after 1941. A completely new inducer was now developed.

All this work resulted by 1943 in a supercharger which with an axial inlet had a peak efficiency of 81% at a pressure ratio of 2:1, about 80% at 2½:1, and 75% at 3:1. The gradual improvement in efficiency as a function of pressure ratio from the time that Wright started work in 1935 to the testing of this new supercharger in 1943 is shown in the chart on the opposite page.

As the power of existing engines was increased after 1935, and as new types were brought out with more cylinders but no greater over-all diameter, it became necessary for the supercharger to compress more air per minute without being greatly increased in diameter. The work done by Wright after 1935 was as much directed at improving the flow coefficient of the supercharger as at improving its efficiency and pressure ratio, and did in fact produce a steady increase in the flow coefficient which was as important as the steady rise in efficiency and pressure ratio already described.

The other major engine manufacturer, Pratt & Whitney, did nothing with the development of superchargers until 1938, when like Wright in 1935 it was virtually forced into the field. In this case the cause was high-altitude surging encountered in the first

SUPERCHARGER PERFORMANCE, 1935-1943: WRIGHT AERONAUTICAL CORPORATION



SOURCE: Wright Aeronautical Corporation.

two-stage R-1830. After GE failed to cure the trouble and Pratt & Whitney failed in its attempt to get another firm to work on the problem, the latter company decided it would have to go into supercharger development itself. Attempts were first made to eliminate the surging by cut-and-try methods applied to the diffuser; an inlet and diffuser were produced which succeeded in this respect and were adopted for the R-1830C5 (-76) put in production in October 1939, even though they gave lower efficiency than the original design, but the principal scientific result of this early work was the full realization of how little the company understood the basic phenomena of supercharger operation. It was during this work that Pratt & Whitney for the first time actually measured the power being used to drive one of its superchargers.

About September 1939 the company decided that real progress could be made only if instruments were developed to observe and measure the air flow at various points within the supercharger, and to make possible the isolation of the effects of changes made in the separate components (inlet, impeller, diffuser, and collector). Contracts were given to Harvard and the Massachusetts Institute of Technology for the development of instrumentation and test procedures, and these were ready for use by about the middle of 1940. Again, as in the case of Wright, it was only after beginning its own supercharger studies that Pratt & Whitney realized how poorly existing superchargers were matched to their engines and how much was being lost because of this mismatching.[20]

In June 1940 a special subcommittee of the NACA committee on power plants was formed at the wish of the entire industry, partly to sponsor research by the NACA staff, but primarily to correlate the work being done by the various firms, principally Wright, Pratt & Whitney, and Allison.[21] The first important discovery made by this subcommittee was that none of the existing data on supercharger efficiency were of much value, since a wide variety of test procedures were in use and gave widely varying results when applied to any given supercharger. The subcommittee's first concrete accomplishment was the decision of all the participants to adopt a single, standard technique. This technique was established and accepted before the end of 1941. Development of centrifugal superchargers carried out by the NACA itself after this time led by 1944 to designs capable of pressure ratios up to 3½:1 at an efficiency of 73% or 74% with the regular inlet elbow for a reciprocating engine in place.

Even before any extensive improvements had been made in the pure centrifugal compressor, Rudolph Birmann had argued for some time that very considerably better performance could be obtained from a modified centrifugal compressor with the curvature of the impeller passages distributed along their whole length instead of occurring abruptly at the entrance. Later this idea was extended to produce the mixed-flow impeller, which discharges the air partly to the rear. Whether this type of compressor is actually more efficient than the ordinary centrifugal type when both are equally well developed is a disputed question, but it does seem to be true that the mixed-flow type has one definite advantage when used in a gas turbine: that of discharging the air in the desired direction without the need of a right-angle turn after the impeller. Birmann was already confident by the middle of the 1930's that a compressor of this type would give a pressure ratio of 3:1 at 76% or 77% efficiency.

[20] It was also only now realized that the reason for the surging of the R-1830C2 was that the supercharger was too large.

[21] It was only shortly before this that a general change had been made in the NACA committees, admitting representatives from industry and making the NACA directly aware for the first time of the problems which the industry considered most pressing.

Considerable difficulty was encountered in machining experimental compressors, and results as good as those predicted were not obtained at once, but the two-stage compressor of the first turbosupercharger built by the Turbo Engineering Corporation in 1937 did show an efficiency of 76% at 3.4:1, corresponding to about 78% at 2:1 in each stage, and by 1944 the TEC single-stage geared supercharger for the R-2800E was delivering a pressure ratio of 4:1 with 67½% efficiency or 5:1 at 66½%.

Neither the British nor the Germans, moreover, had centrifugal compressors during the 1930's appreciably better than the Americans in efficiency or pressure ratio. The supercharger used in production Merlins in 1939 had a pressure ratio of about 2.3:1 at an efficiency under 70% exclusive of installation losses, or under 65% with the inlet elbow in place; this was actually considerably inferior to the new supercharger being put in production in 1939 on the G-200 Cyclone, and little better than other American superchargers then in production. German production superchargers at the end of the 1930's had somewhat lower pressure than the Merlin with no better efficiency, although the DVL did have experimental superchargers which were remarkably good in air handling capacity (flow coefficient).

The fact was that development of gas turbines with centrifugal compressors was begun abroad, not on the basis of what had been already attained in compressor performance, but on the basis of what it was hoped to attain. Whittle believed that he could obtain 80% efficiency at a pressure ratio of 4:1 from a centrifugal compressor, and while he greatly overestimated his ability to achieve this improvement single-handed and in a short time, the goal itself was reasonable as is shown by the fact that it was ultimately attained in the Rolls Royce Derwent V in 1945. About 75% at 4:1, which was enough for a very useful engine, the Rolls Royce Welland, was already obtained by Power Jets by the end of 1941 or early 1942. While even this was some five or six years after Whittle started his experimental work, it must be remembered that during this entire period (up to the beginning of 1942) he was completely unable because of lack of a dynamometer to test any compressor separately. Thus he could improve the design of the compressor only on the basis of running his complete engine, and because of failures or the need to alter other components the engine could be run only a very small part of the time.

The less well-known axial type of compressor was the choice of the British RAE for gas turbines before 1930, of the Junkers Airplane Company in 1936, and of the German aircraft-engine firms in 1939. The German engine firms based their choice on the 1938 announcement by the AVA research institute of a compressor with an efficiency of 80% at a pressure ratio of over 2:1, and the RAE obtained this same efficiency and pressure ratio in 1939. Owing to an earlier start both the British and Germans were definitely ahead of the United States in axial-compressor design between about 1936 and about 1940: this type of compressor was completely neglected in the United States until 1938, when the NACA began to develop an eight-stage unit. Even with this late start, however, the NACA compressor, which was a remarkably advanced design by E. N. Jacobs, soon surpassed the early German compressors by giving a pressure ratio of 3.4:1 at 87% efficiency. In 1941 this work was taken as the basis of the compressors of the Westinghouse turbojet and the General Electric TG-100 turboprop. The NACA's own work on this compressor was virtually stopped very soon after the formation of the supercharger subcommittee in 1940, since the military services believed that it was more important to devote all available efforts to the improvement of the type of supercharger actually in use on service engines.

The lateness of the dates at which appreciable improvements began to be made in the centrifugal compressor in the United States and at which the development of the axial type was begun cannot be explained as due to previous lack of sufficient basic knowledge. It would appear that none of the compressor development depended on any advances made in basic knowledge since 1930 at the latest. The results obtained were entirely due to development of the compressor as such, and might have been obtained much earlier if the development had been started earlier. The decisive factor in the beginning of the development was simply the realization of the importance of the supercharger in the over-all performance of the reciprocating engine. If development of gas turbines had been begun in the United States in the mid-1930's, all this compressor development could have been begun at once.