CHAPTER XVI

Aircraft Gas Turbines in the United States

GAS turbines were proposed as power plants for aircraft in the United States, as in Europe, long before anything was done which led or could lead to practical results. It would be a waste of time to list all these empty claims, which go back at least as far as a patent of 1919. It is more interesting to inquire why actual development of gas turbines was not begun in the United States by engineers who were working during this period on the development of machines which were very closely related to the gas turbine in principle and in the nature of the problems which they presented.

DISCUSSION DURING THE 1930'S

Throughout the period between the two wars one close relative of the gas turbine was continuously under development in the United States. This was the turbosupercharger, which is essentially a gas turbine with the combustion chamber replaced by a reciprocating engine: the compressor of the turbo delivers air to the engine, and the exhaust of the engine supplies the hot gases which drive the turbine. Until about the middle of the 1930's, however, the developers of the turbo (General Electric and the Army) had all that they could do to solve the problems of that device, which were much easier than those of a gas turbine. The chief obstacle to a successful turbosupercharger was the difficulty of making turbine buckets which could withstand the high temperature of the exhaust gases of the reciprocating engine; this problem was finally solved about the middle of the 1930's, as will be shown (below, p. 494 f), and beginning at just about this time engineers at both Wright Field and at General Electric did in fact seriously consider from time to time the possibility of going on to develop a true gas turbine.

Each time that such a study was made it led, however, to the conclusion that basic knowledge had not yet progressed far enough to make such an engine possible. There were two principal reasons: (1) the low efficiencies of current compressors and turbine wheels, and (2) failure to evaluate what was probably the chief competitive merit of the turbine engine, its lower weight.

The turbosupercharger of the latter half of the 1930's had a compressor and a turbine of very low efficiency (60% to 65% for the former and 65% to 70% for the latter). A true gas turbine was completely out of the question unless very considerable improvement could be made in both elements, but the turbosupercharger would not have profited at all by improvement in turbine efficiency, and only slightly by improvement in compressor efficiency, since there was more than enough energy in the exhaust of the reciprocating engine to supply all the supercharging desired even at existing efficiencies. Consequently very little effort was spent on making such improvements; and this omission is not to be blamed, since the resources available to the Army for the development of the turbo were far from adequate, and it was only natural that they should be used only for the tasks most necessary for the development of the turbo itself.

One line of development which was seriously considered by Wright Field throughout the 1930's, and which might have served as an intermediate step on the way from the turbosupercharger to the gas turbine, was the compound engine. In this type of engine the turbine wheel of a turbosupercharger is not only connected to the compressor but is geared to the crankshaft, so that if the turbine is able to extract from the exhaust more than enough energy to drive the compressor this excess is fed back to the crankshaft of the engine itself. As soon as this arrangement is used, the efficiency of the turbine wheel and the compressor are no longer matters of indifference, since every gain is reflected in the net output of the engine. Colonel E. R. Page, the chief of the power plant branch at Wright Field during the 1930's was an eager advocate of the compound engine throughout this decade, but although one such engine was built in 1934, higher authorities in the Army were very little interested, and after incomplete tests of this engine had been made no further compound engines were built.[1] Studies of compounding were made on a theoretical basis during the latter half of the 1930's, and actual development of a special two-stage turbine wheel was begun in 1939, but before these developments had led to anything the development of gas turbines had begun as a result of impulses received from completely different directions.

During the 1930's in the United States engineers were interested in turbine engines for their simplicity and lack of vibration, but the memoranda and reports on the subject at Wright Field and at the General Electric Company usually do not even mention the probable weight of such an engine, and give the general impression that it was assumed (tacitly rather than explicitly) that it would be about the same as that of a conventional power plant. This being true, it was only natural that it was also assumed that there was no sense in developing a gas turbine unless its fuel consumption could be fully competitive with that of a conventional engine, and this in turn led to the calculation of such extremely high values for the required component efficiencies and blade temperatures that successful development seemed to be utterly hopeless. In the middle of the 1930's, when a material was being adopted for the buckets of turbosuperchargers which permitted operation at temperatures as high as those used in any gas turbine developed in any country by the end of the Second World War (up to 1,400° F) (cf. below, p. 494-495), Wright Field was convinced that it was no use even starting the development of a gas turbine until bucket materials were available which could withstand temperatures of 2,500° F.[2]

The development of industrial gas turbines in the United States as in other countries definitely lagged behind Swiss

[1]The engine built in 1934 was an R-1820-29 Wright Cyclone, essentially an ordinary Cyclone with the impeller of its integral gear-driven supercharger coupled directly to a standard turbosupercharger turbine wheel so that no special gearing need be developed. The engine was unsuccessful when tested, but the failure was due rather to the intercoolers (one for each cylinder) than to the compounding as such. The engine was not even tested at Wright Field.

[2]So little thought was given to turbines that it did not even occur to Wright Field engineers that the temperature of the products of combustion could be reduced by the use of excess air, although the literature since before 1910 was full of discussion of dilution by air and by steam as well.

development in the 1930's: it was in Switzerland, specifically in the firm of Brown-Boveri et Cie, that the Velox boiler was developed at the beginning of the decade and the Houdry-process turbine in the middle of the decade. The first practical industrial gas turbines in the United States were built under Brown-Boveri license: these were Houdry-process turbines built by the Allis-Chalmers Manufacturing Company beginning in 1938.[3] It was only at the very end of the decade that various American engineers began to write and speak of the possibility that gas turbines might be used as industrial prime movers.

In 1939, as a result of the inspection of foreign gas turbines by a Navy officer, the Bureau of Ships requested the National Academy of Sciences to investigate the possibility of the use of gas turbines for ship propulsion. A special committee was set up in 1940 and reported in January 1941[3a] that the promise of gas turbines for ship propulsion was very good indeed and that development should be begun at once. The report added, however, that gas turbines were completely out of the question for aircraft, since they would weigh at least 13 pounds per horsepower, against little over one pound for conventional aircraft engines. The error was due largely to the fact that no member of the committee had any knowledge of aircraft-engine practice, either as regards lightweight construction or as regards the reduced durability which is acceptable in that field.

This background of universally pessimistic opinion accounts in part for the fact that the one attempt made in the United States in the 1930's to develop a gas turbine for aircraft was dropped without receiving any financial support or even any encouragement whatever from the military services. R. E. Lasley, who had formerly been a steam-turbine engineer for Allis-Chalmers, had obtained a number of patents dealing with gas turbines beginning in 1925, and early in the 1930's set up the Lasley Turbine Motor Company in Waukegan, Illinois, to develop a gas turbine for aircraft. In July 1934 Lasley

[3]One reason for the pre-eminence of Brown-Boveri in the gas-turbine field was undoubtedly that Brown-Boveri had led in the development of axial compressors, which finally gave efficiencies high enough (of the order of 85%) to make possible the construction of turbines with positive efficiency despite the use of the very low blade temperatures required for economical life.

[3a]See Chapter XII, p. 327, n. 6a.

showed movies of his engine running, and claimed that it operated with an efficiency of 11.6%.[4]

The financial resources of the Lasley company were insufficient to prosecute the development rapidly, and in 1934 Lasley approached the Navy to request financial support. He was unwilling, however, to grant the rights which the government demanded under its development contracts, and these negotiations came to nothing. Lasley then applied to the Army, and representatives of Wright Field visited his shop in August 1934. They reported that the efficiency of the Lasley engine was hopelessly low, and after consultation with Moss of General Electric issued the memorandum containing the opinion mentioned above, that there was no hope of satisfactory efficiency until the turbine blades could be run at temperatures of at least 2,500° F.

What eventually became of the Lasley turbine is not known, but it is probably true that it had no chance of success in any case. Lasley was working toward the same unsound objective toward which other engineers were convinced that work should be directed: efficiency fully competitive with the reciprocating engine, with no regard for the possibility and utility of a less efficient but much lighter engine. As a result, to judge from Lasley's patents, he had made his engine very complex in order to raise the over-all efficiency in spite of low component efficiencies. In the light of hindsight, it is clear that the only course which could lead to success was to keep the engine as simple as possible, and to improve efficiency by refinement of the design of simple elements, not by gadgetry.

Finally, virtually all the discussion of gas turbines for aircraft in the United States until the end of the 1930's was in terms of a turbine used for mechanical power, i.e., for driving a propeller, rather than of jet propulsion. This idea also was logical enough until airplane speeds of at least 500 mph were envisaged, since up to that speed and even perhaps somewhat above it a propeller is a more efficient means of propulsion than a jet, whatever the type of engine under consideration. In 1923 the National Advisory Committee for Aeronautics had published a study of jet propulsion made by Edgar Buckingham of the Bureau of

[4]Conventional aircraft engines had an efficiency of the order of 30% to 35%.

Standards in response to a request by McCook Field. This study concluded (correctly) that at 250 mph the fuel consumption of the most efficient jet engine possible (with a reciprocating compressor of 85% efficiency driven by a reciprocating engine) would be at least four times as great as that of a reciprocating engine driving a propeller. Buckingham had suggested that thrust augmenters of the ejector (Mélot) type might possibly improve this poor efficiency, and about ten years later, in 1932, the action of these devices was studied by both the Bureau of Standards and the NACA itself. The results, published by the NACA, showed definitively that the benefit to be derived from ejector augmentation was too slight to alter Buckingham's results appreciably: under the most favorable conditions the thrust was increased by only 37%.

A turbojet was discussed by some of the members of the General Electric turbosupercharger team before the middle of the 1930's, but the head of the group, Moss, believed that all gas turbines were impractical at this time. It was not until 1939 that a careful analysis was made at General Electric leading to the conclusion that a turbojet would be superior to a turboprop as a way of utilizing the gas turbine.[5] The actual history of the development of gas turbines both in the United States and abroad has shown, of course, that the obstacles to a successful turboprop were so great that even with all the resources devoted to development of this type of engine during the war none was in service as late as mid-1949.

Failure to consider the turbojet in the United States in the 1930's was due principally to the fact that power plant engineers tended to consider the airplane as given, both in its design and its speed, and to study the power plant in terms of its performance at this given speed. It was not until late in the 1930's that air speeds of even 400 mph began to be considered seriously, at the time of the design of the P-38 Lightning and the P-39 Airacobra fighters, and it was only a year or two later that the General Electric study was made which pointed out the superiority of jet propulsion at speeds somewhat greater than this.

[5]The assumptions underlying this conclusion were: efficiency of single-stage turbine not over 75%, efficiency of centrifugal compressor not over 70%, blade temperature not over 1,500° F; a propeller efficiency 85% at 400 mph, 78% at 500 mph, and 65% at 600 mph.

The Beginnings of Gas Turbine Development: 1939-1941

Proposals from Builders of Airplanes: the Northrop Turboprop and Lockheed Turbojet

The earliest complete designs and serious proposals for the development of aircraft gas turbines in the United States, aside from Lasley's abortive attempt, came not from builders of engines of any sort, but from builders of airplanes. This fact is of considerable significance: the two earliest gas turbine projects in Germany likewise came from builders of airplanes.

The first of these designs originated in Northrop Aircraft, Inc. One of the original employees of this company, which was founded in March 1939, was a Czech engineer, Vladimir H. Pavlecka, who had acquired considerable enthusiasm for the gas turbine during his work in the aircraft industry abroad. Pavlecka considered the gas turbine a superior replacement for the reciprocating engine in driving a propeller, and convinced the head of the company, J. K. Northrop, that such an engine should be developed, chiefly on the grounds that it was simpler than a reciprocating engine and required less complication of accessories, but in part also because it would be freer of vibration and somewhat lighter.

Since Northrop intended to develop a turbine which could compete with reciprocating engines on their own ground, he had to develop one with nearly as high efficiency as a reciprocating engine, regardless of the difficulties which this entailed. He hoped to attain a specific fuel consumption of only 0.55 lb per hp/hr, or less than a third higher than the cruising consumption of average conventional engines at that time, by the use of the very high pressure ratio of 10.5:1 and by the development of a compressor and a turbine with efficiencies of 85%. The achievement of this efficiency from the turbine was not thought to be exceptionally difficult in the existing state of the art, and it was believed that enough had been learned about axial compressors to make it possible to obtain 85% efficiency from a compressor of that type.[6]

[6]Since about 1936 Brown-Boveri had been building and selling axial compressors with efficiencies of 85% or better, but this did not mean that all the problems were solved for Northrop in advance; problems of accurate machining and small clearances were much simpler on large industrial compressors than in the small size required for an aircraft engine.

Northrop assigned about half a dozen engineers to the study of the new engine, which he named the Turbodyne, and let them work for about six months on the preparation of preliminary designs and analyses before going to the Army and Navy with a request for a development contract. The private investment up to this point was only about $25,000, but in the company's opinion it was impossible to proceed much further at private risk. Northrop estimated that well over $1 million would be required before an engine could be put in successful operation; the net worth of his company was only between $3 and $4 million, and he thought it out of the question to risk a large fraction of this in the development of a device as far off, as uncertain, and as far removed from the company's principal line of business as the Turbodyne.

The Army and Navy showed very little interest in the Turbodyne for several months after Northrop first approached them in 1940. Finally on June 30, 1941, a joint Army-Navy development contract under Navy supervision was given to Northrop, under which he was to prepare detailed designs and analyses of a 2,500-hp engine and to build an experimental compressor for it. The contract was of the cost-plus-fixed-fee type: the size of the estimated cost of this first phase, $483,600, in relation to the resources of the company, made this the only sort of financial arrangement possible. No arrangement was made for the provision of test facilities, most of which were ultimately borrowed by the company from the services, and this lack meant that at least a year was lost in the first four years of work.[7] The whole nature of the original contract seems to have been rather poorly thought out, since it should have been obvious from the beginning that there would be no facilities capable of testing the compressor of a 2,500-hp engine other than a complete engine itself. The lack of these facilities

[7]The total value of special facilities acquired or borrowed by the company during the first four years of the development was only some $250,000, but even this amount was too much in the company's opinion to risk in a development of this sort, even though it would have readily risked considerably more on the development of a new airplane for which it saw good prospects of sale in a reasonably near future.

made it necessary to amend the contract in 1943 to call for the construction of complete engines rather than compressors alone.

Only a few months after the first studies of the Turbodyne were begun by Northrop, studies of another aircraft turbine were begun by the Lockheed Aircraft Corporation. This project, called the L-1000, was different from Northrop's in an extremely important respect: the turbine was to be used for jet propulsion, not for propeller drives. Begun in 1940, Lockheed's project was the first serious American work on a turbojet by a margin of at least a year.

The designer of the Lockheed L-1000, Nathan C. Price, had started as a steam turbine engineer. About 1930 he had gone to work for Doble Steam Motors, a small firm specializing in high-pressure steam engines, which made him project engineer on development of a small reciprocating steam engine intended primarily for railroad switch engines and for busses. To obtain the necessary output in as small a space as possible, Price designed a combustion system in which air was forced by a blower past atomizer burners, roughly the same arrangement that was later used for the combustion system of gas turbines. As an advertising device this engine was installed in place of an OX-5 as the power plant of a Travelair biplane and was first flown on April 12, 1933. Although the purpose of this experiment was purely to create publicity for the engine and aid in its sale for ordinary installations, the flight was so successful and the comments so favorable that Price joined with several members of the Boeing School of Aeronautics in a common venture to study a steam-powered airplane.

During the fall of 1933 and early 1934 Price designed a steam turbine specifically for aircraft. The turbine which drove the propeller was also coupled to a centrifugal compressor which supplied the air for the combustion chamber, and the products of combustion were expelled through a nozzle designed to produce jet thrust. The engine thus resembled the turboprop of today both in the combustion system and in the use of jet exhaust. Price's calculations of the performance of such an engine convinced him that its efficiency and weight could be at least as good as those of an ordinary aircraft engine at low altitude, and that the power could be maintained at higher

altitudes by the use of a higher blower ratio without running into any of the very serious problems involved in the altitude supercharging of an internal-combustion engine. Attempts were made to have the design developed, first by trying to interest a manufacturer of aircraft engines or of steam turbines, then by trying to get support from the Army, but all of them failed, and the project was dropped about 1936.

Between 1935 and 1940 Price continued to work on the application of turbines to aircraft and obtained various patents covering, for example, a steam turbine for propeller drive with jet thrust from the condenser, a Velox-type boiler, which is essentially a gas turbine engine used as a source of heat for generating steam rather than as a source of mechanical energy, and in 1939 a scheme for pure jet propulsion at high speed by the exhaust of a reciprocating engine equipped with a folding propeller for use in take-off and at low speed (U.S. 2,233,031).

Toward the end of 1940, the Lockheed Aircraft Corporation, for which Price was then working, decided that the whole power-plant situation needed a fundamentally new attack, with the purpose of attaining radically higher speed and altitude than could be achieved with any existing engine. This, of course, was exactly the approach of Whittle and of all the Germans who advocated turbojets in 1936 and later. Price was set to work on the problem, and after six or eight months he had made preliminary plans and analyses of a gas-turbine jet-propulsion engine. He did not think of this as an invention, but simply as the only logical type of engine for the purpose in the light of existing thought and knowledge.

After the preliminary work had been done by Price, more personnel were assigned to the project and detailed layouts were made both of the L-1000 engine and of a plane, the L-133, intended to utilize it. The aims of the designers were high: the plane was intended to go 625 mph at 50,000 feet altitude (0.94 Mach). This was probably the first time in the United States that a plane and engine were designed as an integral whole, and in many respects the design was novel: it proposed to use the jet principle not only for propulsion but for control (by means of jets in the wing tips), and boundary-layer control was to be combined with propulsion. But in addition to these features which were unessential as far as the engine was concerned, there was one really important and — at least in the short run — most unfortunate difference from the early foreign jet-engine designs: the L-1000 was intended to have actually a higher efficiency than contemporary reciprocating engines, and therefore was designed with a very high pressure ratio (achieved by an axial followed by a reciprocating compressor),[8] and a great deal of intercooling. Ease and quickness of development were thus sacrificed in trying for much more general utility than that of a pure interceptor fighter.

By 1941 the designs of the engine and the plane were ready for actual development to begin, and after H. P. Hibbard, Lockheed's vice president of engineering, was convinced that the regular engine companies would not undertake the development of an engine of this type, it was decided that Lockheed itself should proceed with the development of both the airframe and the engine. The plans were informally discussed with various Army officers in 1941 and were formally submitted to the Army in 1942, but discussions continued for about a year before Lockheed was allowed to know in May 1943 that, as we shall see, other companies had been working since 1941 on jet engines of both American and British design.

The NACA's Development of the Campini Ducted Fan

From the beginning of the 1930's the Italian engineer Secondo Campini had created a good deal of attention by advocating a type of aircraft engine which is halfway between a conventional engine with a propeller and a true jet engine. The engine proposed by Campini was to consist of an ordinary reciprocating engine driving a many-bladed propeller or fan of small diameter situated within a closed air passage or duct. At cruising power it would function in much the same way as an engine with an ordinary propeller, but the location of the fan within a duct made it possible to obtain additional thrust for combat or similar purposes by burning additional fuel within the duct behind the fan. The original publication of this idea had been made in 1930.[9]

[8]Later by two axial compressors in series.
[9]*Aerotecnica* nos. 8-12 (Rome, 1930), and Italian patents 383,188 (1931) and 394,184 (1932).

In 1936 Eastman N. Jacobs of the NACA went to an international aeronautical congress in Italy and became very much interested in the Campini scheme. This interest increased further when Campini in 1938 published[10] computations of the performance of this sort of power plant based on experimental work which he had done with the components. In 1939 Jacobs began the theoretical study of this type of engine, and eventually persuaded the NACA that experimental investigation should be undertaken.

Construction of an experimental engine was begun by the NACA apparently during the course of 1940. The engine consisted of a 600-hp R-1340 Wasp driving a single-stage axial-flow fan located within a duct.[11] The first experiments, carried out probably late in 1940, showed that very great difficulties were involved both in maintaining this combustion and in keeping it within the duct, and no stable combustion had yet been secured by the end of 1941.

The Major Engine Builders: Pratt & Whitney and Wright

In neither Britain nor Germany did any of the established aircraft-engine companies propose to build a turbine engine until they were convinced of its practicality by either an outsider or a government agency. In the United States the same thing is true with one exception, the Pratt & Whitney PT-1, and even this exception was an engine quite different both in design and in purpose from those which were successfully developed by the end of the war.

For some time before 1940 L. S. Hobbs of Pratt & Whitney had been interested in the possibility of a turbine power plant, largely because of its inherent freedom from vibration, but on the basis of general current opinion had rejected the simple form of turbine engine, with a rotary compressor, as hopelessly inefficient in competition with the reciprocating engine as a source of power for a propeller. About 1940 Hobbs had a study made of this type of engine used for jet propulsion, but

[10]*Aerotecnica* 18, January 1938, pp. 18-63; published in translation as "Analytical Theory of the Campini Propulsion System," NACA, *Technical Memorandum*, No. 1010 (Washington: 1942).
[11]"NACA Investigation of a Jet-Propulsion System," NACA *Advance Confidential Report* L4D26, April 1944.

rejected this too as impractical, since the fuel consumption came out much greater than that of a conventional power plant at the airplane speeds which he was considering, while he assumed that the weight of the turbojet engine per pound of thrust at this speed would be as great as that of the conventional power plant.

At about this same time Andrew Kalitinsky of the Massachusetts Institute of Technology proposed to Pratt & Whitney a more efficient type of gas turbine, with which he had already had experience in Switzerland and which had been proposed even earlier in Sweden, where it became known as the Götaverken system.[12] Various versions of this system had been proposed and tried; Kalitinsky's was essentially halfway between a compound engine and a pure turbine engine. The turbine wheel was driven by the exhaust of a two-stroke Diesel as in a compound engine, but only enough power was taken from the Diesel engine itself to drive the compressor, most of the net useful power coming from the turbine and the rest from the jet exhaust. Provision was made for burning additional fuel between the exhaust of the Diesel and the inlet to the turbine in order to provide additional although uneconomic power for short-period use. The fact that a two-stroke Diesel uses a large amount of excess air and the fact that the gases were expanded in the Diesel engine before delivery to the turbine meant that their temperature at the turbine was so low that there would be no serious difficulties with turbine blades: the turbine inlet temperature was expected to be about 1,200°F normally, and only 1,400°F with afterburning. The combined Diesel engine and reciprocating compressor were of the opposed-free-piston type,[13] which is inherently in perfect balance and thus free of vibration; this was also a combination of the most efficient internal combustion cycle with the most efficient compressor. Thus it was hoped not only that this engine would be smoother in operation than the conventional reciprocating engine, but that it would be even more economical of fuel.

[12]See article by H. G. Hammar and E. Johansson, Institute of Marine Engineers, London, *Transactions* 51, 1939, pp. 139-154; *Sulzer Technical Review* (Winterthur, Switzerland) Special Number, December 31, 1941.

[13]This type of engine had been sold in the United States before the war by the Frenchman Pescara as an economical form of industrial air compressor.

Nothing came of Kalitinsky's original contact with Pratt & Whitney, but in the fall of 1940, when Hobbs was discussing the general problem of turbines with J. C. Hunsaker of MIT, Hunsaker suggested that Kalitinsky's scheme might well prove superior to the ordinary turbine engine with a rotary compressor driven by the turbine itself. Hobbs then had Kalitinsky make preliminary calculations of probable performance which showed that even on the most unfavorable assumptions such an engine would have a cruising fuel consumption (without afterburning) of 0.34 lb/hp hr, while the most favorable assumptions gave 0.27, compared with about 0.42 for the best current reciprocating engines. This calculated performance was of very great interest in connection with the Army's current emphasis on long-range strategic bombing: plans for a very heavy bomber[14] called for 130,000 lb of fuel to carry 10,000 lb of bombs to the required distance; if fuel consumption could be reduced from 0.42 to 0.31, the fuel would be reduced to 96,000 lb; and if this was done with no increase in the weight of the power plant, the bomb load could be more than quadrupled by an increase from 10,000 to 44,000 lb.

On the basis of these calculations Pratt & Whitney immediately determined to go ahead with further investigations. After Kalitinsky's calculations had been checked by Pratt & Whitney's own research department, the company in May 1941 began making a preliminary engine and installation layout. These indicated that a 4,000- or 5,000-hp engine of this type would probably weigh 50% more than a conventional engine, but that the total installed weight of the power plant would be about the same, owing to savings in the weight of the accessories. Experimental investigation of the components was begun at once, as a purely private venture of the company.

The other major American engine builder, the Wright Aeronautical Corporation, made no studies or designs of its own for a gas turbine. About 1940, however, this company learned of the Power Jets development in Britain, and in 1941 entered into negotiations for an American license for the manufacture of the Whittle engine. These negotiations failed when authority to develop and build the engine in the United States was se-

[14]These plans were the genesis of the B-36.

cured by a direct deal between the American Army and the British government, and the Army contracted for the work to be done by another company, as will be told below.

The Navy and the Turbo Engineering Corporation Study

The first government support for a systematic theoretical investigation of all the possibilities involved in aircraft gas turbines came from the Navy in the form of a contract with the Turbo Engineering Corporation. The contract was signed in June 1941, but the go-ahead was given earlier, in January.

The Turbo Engineering Corporation consisted principally of Rudolph Birmann, an engineer of Swiss origin. Birmann had become interested in gas turbines at the time of his studies under Professor A. Stodola in Zurich, and as his thesis in 1922 had submitted the design and calculations of a gas turbine[15] which he considered to be practicable with the compressor and turbine performance possible at that time and the materials then available. Birmann suggested the use of a turbine wheel of the centripetal type,[16] believing that it would show a better efficiency than the ordinary axial-flow turbine, be capable of handling larger pressure ratios, and operate at higher speed for a given flow, thus exposing less blade surface to heating by high-temperature gases and simplifying the cooling of the wheel, which was necessary with the materials then available. In addition, the centripetal turbine was free from all problems of attaching the blades to the disk, since the blade and disk could be machined out of a solid forging.

Birmann did not believe that the time was ripe in the 1920's for the actual development of a gas turbine, but after he came to the United States he did design and build at his own expense a small turbosupercharger using both the centripetal turbine and another component of novel design: a compressor of the mixed or diagonal-flow type. Birmann believed that this type of compressor would be capable of producing as high a pressure

[15] The gas generator for the engine of this study was a reciprocating combination engine and compressor, one side of the piston being exposed to combustion pressure and the other serving as compressor. The engine was thus the same in basic lines as the Götaverken system or the Pratt & Whitney PT-1.

[16] This type of turbine was later studied experimentally in Germany, and was used by von Ohain in the early Heinkel centrifugal gas turbines.

ratio in a single stage as the centrifugal compressor and that it would be more efficient because it eliminated the losses due to the two right angles around which the air had to flow in the centrifugal type. He demonstrated his supercharger to the Army about 1929, but the Army was unwilling to support its development. Results were just beginning to be obtained from the General Electric turbo, and the Army — probably very wisely — did not wish to divide the very limited funds which it had for this sort of work between two companies. Birmann then demonstrated his turbosupercharger to the Navy, which was interested but had no available funds and in any case was unwilling to give development contracts to an individual person. Since the DeLaval Steam Turbine Company, for which Birmann worked, was not interested in developing a device this far out of its ordinary line of business, the turbosupercharger was put on the shelf for a number of years. DeLaval did, however, build a 500-hp centripetal turbine for use in a steam compressor in 1935 and another, identical machine for independent testing in 1937. This unit was found to be only slightly more efficient than the axial type, but the diameter and weight of the centripetal turbine were much lower and it was capable of handling in two stages a total pressure ratio for which three axial stages would have been required.

About 1937 an independent investor who had earlier backed the development of small high-pressure steam engines became interested in Birmann's turbosupercharger, and with financial backing from this investor and also from DeLaval, which now became interested in the proposal, the Turbo Engineering Corporation (hereafter, TEC) was formed to exploit Birmann's patents in other than steam applications. The intention was to start with turbosuperchargers and then to go on with any other applications which might seem interesting. Birmann believed at this time that his compressor could give a maximum pressure ratio in a single stage of 3:1 at an efficiency of about 76% or 77%, or an efficiency of 80% at a pressure ratio of 2:1. This would be a marked improvement over the efficiency of American centrifugal compressors being used currently in both gear-driven and turbosuperchargers, which had an efficiency of under 70% at a maximum pressure ratio of about 2:1.

After its incorporation in 1937, TEC proceeded at its own expense to build an experimental turbosupercharger with a two-stage compressor, at a time when General Electric had only single-stage turbos available. It was tested on the bench by DeLaval and then delivered early in 1939 to the Navy, which confirmed that it was capable of maintaining sea-level power to 25,000 feet altitude. It had an additional advantage over the GE turbos in that whereas the latter exhausted to the side and thus created drag-producing turbulence in the air stream, the TEC turbo exhausted to the rear and thus produced a certain amount of jet thrust. Its demonstration led very soon to a Navy contract for four two-stage, 25,000-foot turbos for larger engines, the R-2800 and the R-3350.

Part of the bench testing of the original TEC turbo by DeLaval had consisted in rigging it up as an independent turbine engine, leading the compressed air through a combustion chamber where fuel was burned and thence to the turbine wheel. When so rigged up it had proved capable of running very well under its own power, and this fact together with the growing general interest in gas turbines for aircraft propulsion had led to discussions of gas turbines between TEC and the Navy during 1940. In December 1940 TEC submitted to the Navy a proposal for a general theoretical study of all the problems involved in the design of a turboprop — turbojets were mentioned, but the obviously high fuel consumption led to their rejection — and about January 1941 the Navy instructed TEC to go ahead with the study. Reports on the results of this study were delivered to the Navy in instalments, the first dated September 1941 and the last June 1943.

Late in 1941 the first of the four turbosuperchargers ordered by the Navy from TEC was tested on the bench by DeLaval and was then delivered to the Navy which installed it on an R-2600 in a Grumman TBF and showed that it was capable of maintaining sea-level power to 40,000 feet.[17] All four of these turbos were rigged up with combustion chambers and tested by DeLaval in 1942 and 1943 in the same way as the original

[17]The compressor of this turbo was tested separately by the NACA in 1942 and showed efficiencies of 82% at a pressure ratio of 2:1, 81% at 2½:1, and 78% at 3:1. Tests by the NAF with −30° F intake air showed efficiencies of 70% at 4:1 and 65% at 5:1.

smaller machine, and all of them not only ran but produced a certain amount of excess power which was simply rejected in the form of compressed and heated air. One of them eventually accumulated 1,000 hours of running time with an inlet temperature of 1,800°F; the turbine wheels and buckets were forged of a single piece of ATV-3, with the buckets internally cooled by air taken in at atmospheric pressure, passing through holes drilled in the wheel, and leaving the blades in a torque-producing direction.

By 1942 the Navy was anxious as a result of these tests both for actual quantity production of the TEC turbosupercharger and for experimental work on other TEC designs, including an actual gas turbine. Since TEC had no manufacturing facilities and DeLaval, which had previously done all TEC's experimental shop work and testing, was by now too busy with production of its regular line of steam equipment to continue in this function, the Navy arranged for TEC to be given a plant by the Defense Plant Corporation.

Although the Navy continued until 1943 to believe that because of its short range and poor take-off a turbojet would be useless as a primary power plant, it had before the end of 1941 come to believe that a turbojet booster engine might be very desirable as a means of obtaining short bursts of very high speed in combat, and the theoretical studies by TEC had shown that such an engine would be far easier to develop than a turboprop. Consequently the first gas turbine which the Navy contracted with TEC actually to construct was not a turboprop but a small booster turbojet, aimed at 1,100 lb of sea-level static thrust. This contract was dated October 19, 1942.

The Army and the Durand Committee

Although the services were little interested in turbojets in 1940, they had already by 1938 become very much interested in reaction propulsion by rockets. The Army had asked the National Academy of Sciences to make an investigation of rockets in 1938, and later in the year the Navy had joined the Army in sponsoring a study of booster rockets by the California Institute of Technology. Early in 1941 intelligence reports from Germany moved the Army to further action: although there were no accurate reports of German turbojets, the Air Corps did know by the beginning of 1941 that the Germans were investigating rockets as primary power plants for aircraft, and at this date the nontechnical man probably made little distinction between rockets and jets.[18]

Shortly after this information on German developments was received, General H. H. Arnold, Chief of the Air Corps, wrote on February 25, 1941, to Vannevar Bush, Chairman of the NACA, saying that reports from abroad showed that rockets were being investigated both as boosters and as primary power plants, and that since the California Institute of Technology rocket program could produce nothing usable for at least a year or two, it would be desirable for the NACA to study the subject.

In March 1941 Bush responded to General Arnold's request by setting up a special committee under W. R. Durand known as the Special Committee on Jet Propulsion; it is to be recalled that in the United States at this time the term jet propulsion not only included but ordinarily referred principally to rockets. Bush was aware, however, of the general discussion of other types of unorthodox engines, and the membership of the committee seems a clear indication that rockets were intended to make up only a small part of its activities: in addition to representatives from the staff of the NACA and from the Air Forces, the Bureau of Aeronautics, the Bureau of Standards, Johns-Hopkins University, and the Massachusetts Institute of Technology, it included industrial representatives only from manufacturers of turbines: Westinghouse, Allis-Chalmers, and the Schenectady steam turbine division of General Electric. The regular aircraft-engine companies were intentionally excluded at the request of General Arnold, who feared for some reason that they might be opposed to any unorthodox developments in the field of power plants. The reason for the exclusion seems to have changed later on, after the United States had entered the war, to a desire to prevent the diversion of any of the engine companies' resources from the development and production of the conventional engines on which the Army depended for

[18]There was a good deal of confusion in the intelligence reports. Early in 1941 a report on the jet-propelled Heinkel 280 said that it used jet-assisted take-off, but apparently thought its main power was conventional.

fighting the war. Whatever the reasons, the companies received no official information whatever about the development of gas turbines at any time before 1945.

At the first meeting of the committee, Kalitinsky of the Massachusetts Institute of Technology presented an analysis of his project for a turbine with a free-piston gas generator (cf. above, p. 452 ff), and Jacobs of the NACA reported on the calculations he had made concerning a ducted fan (cf. above, p. 450 ff). Before the second meeting of the committee was held, Pratt & Whitney had decided to develop Kalitinsky's engine, and it was withdrawn from the agenda.

The three industrial-turbine companies, however, all preferred engines of what has become the standard type, with a rotary compressor driven by a turbine wheel, to the types of engine discussed by Jacobs and Kalitinsky. As we have seen, gas turbines were becoming generally accepted by 1940 as suitable for certain industrial purposes, and a committee of the National Academy of Sciences had recommended in January 1941 that they be developed for marine propulsion. Allis-Chalmers had been given a Navy contract for a marine gas turbine as a result of this report, and the two other firms were actively studying the problem. Westinghouse and GE took Navy contracts for marine gas turbines not long after Allis-Chalmers, and GE had accepted orders in 1940 for turboblowers for the Kellogg Hydroforming process which were generally similar to the Houdry machines. Two if not all three of the companies were actively studying the possibility of gas turbines for locomotives since Brown-Boveri had built one in 1939.

Although the committee of the National Academy had rejected gas turbines as impractical for aircraft, asserting that they would weigh at least 13 lb/hp, the companies were willing to restudy the problem, and a special subcommittee was set up to deal particularly with this type of engine. This subcommittee quickly decided to proceed by having each of the three turbine builders make preliminary studies of whatever type of engine seemed most promising to it, and by July the three outlines had been brought in.

All three of the engines accorded in the use of axial rather than centrifugal compressors. This was certainly due at least in part to the fact that the NACA had begun development of this type of compressor in 1938 and was showing considerably higher efficiency than could be obtained with centrifugal compressors.[19] In addition, Allis-Chalmers had had experience since 1938 with axial compressors in the Houdry turbines which it built on Brown-Boveri license, and its experience was certainly reported to the committee.

It was apparently owing in large part to Durand, who was an exceptionally energetic chairman, that jet propulsion was very seriously considered by the committee, and that the engines proposed by both Westinghouse and Allis-Chalmers used the turbine for jet propulsion: the former proposed a pure turbojet, the latter, one of the ducted-fan type. Only GE proposed a turboprop. This is really quite remarkable in view of the fact that until this time almost no one in the United States — Price of Lockheed and a few people in the Lynn turbosupercharger group (not the Schenectady steam turbine division) of GE seem to be the only exceptions — had believed that jet propulsion was practical. Engineers, generally, as we have seen, had previously tended to think of the gas turbine purely as a substitute for the reciprocating engine in driving a propeller.

In July 1941 it was decided that each of the three turbine companies should go ahead with a detailed study of an engine of the type it preferred; after the preliminary studies had been made it would be decided whether one or more should be actually developed. In September the committee recommended that contracts should be given for the development of all three engines. In October the NACA relinquished all supervision over these three projects, although a smaller committee with revised membership continued to meet occasionally for about a year at a place where the three manufacturers and interested experts could exchange ideas and information.

In accordance with the recommendations of the committee, the Navy invited proposals from Allis-Chalmers in October 1941, and a contract was awarded in February 1942 for a detailed design study. Westinghouse was given a Navy letter of

[19]In 1938 E. N. Jacobs and E. W. Wasielewski of the NACA had begun an investigation of axial-flow compressors on the basis of airfoil theory. Eventually an eight-stage axial compressor was built with an efficiency of 87% at a pressure ratio of 3.4:1.

intent covering construction as well as design of a small booster turbojet known as the 19A on December 8, 1941.[20] GE received an Army contract for its turboprop, known as the TG-100 and later as the T-31.[21]

The Importation of the Whittle Engine

Early in 1941 the General Electric Company had sent D. R. Shoults to England as its technical service representative for the turbosuperchargers of the B-17's then being delivered abroad. Quite soon Shoults picked up from various sources enough information to conclude that turbojet engines were being developed. He informed Colonel A. J. Lyon, the technical liaison officer of the Air Corps in Britain, and the two men were soon permitted by the Ministry of Aircraft Production to inspect the whole turbojet development. When the Chief of the Air Corps, General H. H. Arnold, made a visit to England in the spring of 1941,[22] they informed him to his great astonishment that gas turbines were not simply projected but had been built and were on the point of being flown. Although engineers at Wright Field had long been aware of English publications and patents concerning gas turbines, this was the first occasion on which top officials of the Air Corps had realized that they were actually being built and could really be used for jet propulsion.

When Arnold returned to the United States in April 1941 he began to arrange for the manufacture of the Whittle engine there, and his efforts were much increased after the first flight of the E28/39, on May 15. Discussions between Army representatives and the British Ministry of Aircraft Production were begun in July, and at the same time Major D. J. Keirn was sent from Wright Field to England for the sole purpose of investigat-

[20]The reason for this difference in date is unknown, but may be the fact that the Navy at this date was firmly convinced that unorthodox power plants were of use on carrier-based fighters only as boosters, while the Westinghouse axial turbojet was the only engine of the three suited for use as a booster.

[21]This assignment of the contracts was made despite the fact that it was the Navy which was the more interested in the propeller turbine and the Army in jet propulsion because the Army already had close relations with GE while the Navy had similar relations with the other two companies.

[22]Shortly after writing the letter of February 25, 1941, which led to the creation of the Durand committee; cf. above, p. 458.

ing the gas turbine work. In September 1941 the necessary arrangements were concluded with the British, and in the same month the Army contracted with GE to build an experimental quantity of engines to Whittle's design, and with Bell to build a suitable airplane. The turbosupercharger group at Lynn which developed the Whittle engine was completely separate in its organization from the group in the steam turbine division at Schenectady which was developing the TG-100, and was chosen for this work by the Army because its experience with turbosuperchargers gave it an incomparable background. GE was sufficiently impressed by the fact that the E28/39 had actually flown to undertake the development of a jet engine without hesitation. The Power Jets W-1X bench engine, virtually the same as the W-1 which had flown in the E28/39 on May 15, and a set of drawings for the W-2B, which Power Jets intended as its service model, were flown from England to the United States on October 1, 1941.

The Development of the Whittle Turbojet in the United States: 1941-1943

The Power Jets W-1X experimental engine and drawings of the W-2B which the British planned at this time to have produced in quantity by Rover as a service engine arrived at the Lynn plant of the General Electric Company on October 4, 1941. When the drawings were inspected they were found to be incomplete in some important respects, particularly the lack of an automatic control system, and in a few instances to follow practices which the experience of GE had shown to be hazardous. The Army authorized GE to make original designs for the missing control system and other parts, and also to alter any mechanical details which in the company's opinion were capable of being improved, as well as to redraw the engine completely to conform to American and company production practice, but GE was not to make any changes having a material effect on performance.

Before even the first engine was built GE accordingly made a large number of mechanical changes. An automatic control system was designed. The impeller of the compressor was

strengthened by the use of the buttress vane which GE had developed in its earlier work on centrifugal compressors, and which was ultimately adopted in modified form on the British versions of the Whittle engine. Finally, GE adopted a new material for the turbine buckets, the Haynes Stellite Company's alloy, Hastelloy B. GE had carried out extensive experiments with various materials for turbosupercharger buckets in the summer of 1941, and had concluded at that time that Hastelloy B was the most promising material for this use that it had yet found.[23]

When the first GE engine, known as the I, was tested beginning on March 18, 1942, it was found to run excessively hot, but it was relatively free of one of the two chief troubles encountered in the first British W-2B's, breakage of the turbine buckets. The superior reliability of the buckets was due simply to the very great superiority of Hastelloy B over Rex 78 as a material, since the buckets were made to almost exactly the same design. The first GE engine, like the British W-2B's, surged well below full speed, but whereas this difficulty was not cured in the British production version of the W-2B until 1943, GE cured it immediately by using thicker vanes in the diffuser and thus reducing its cross-sectional area.[24]

The excessive temperature of the gases passing through the turbine wheel was due to two factors: the failure of the compressor to come up to the design efficiency, and unequal distribution of the air among the various combustion chambers. The aerodynamic design of the impeller of the W-2B compressor was considered by GE to mark a considerable advance in the art, since it gave good performance at a tip speed of about 1,550 ft/sec, corresponding to a pressure ratio of about 4:1, whereas

[23]Cast buckets of Stellite alloy No. 21 (Vitallium) had been tried at this same time but were not liked nearly so well as the forged Hastelloy B by the group at Lynn. Vitallium was used on the first TG-100 by the GE Schenectady group, but this choice was due at least in part to the fact that the TG-100 buckets required more machining than those of the I-series engines while Hastelloy B is more difficult to machine than Vitallium. Nimonic 80 was tried by GE, but the company neither liked its performance as well as that of Vitallium or Hastelloy B nor wanted to use a material which had to be machined to size.

[24]GE built no engine with the very bad 80-vane diffuser of the original W-2B; the first American engines had the 10-vane diffuser first tested by Power Jets in November 1941. The British production model, the W-2B/23, used a 20-vane diffuser designed by Rover.

until this time GE had considered 3:1 a very high ratio for a single-stage compressor. The hot running convinced GE, however, that something was wrong with Power Jets' diffuser and blower casing, and GE set to work immediately (May 1942) to design a new one of its own, with completely separate air passages from the impeller rim all the way to each combustion chamber. While waiting for design and development of the new blower casing to be completed, various stop-gap measures were tried in order to permit longer development running of the original engine at full power. The one finally used was suggested by Whittle, who visited GE in June 1942; he informed GE that the British were obtaining completely separate passages through the casing to each combustion chamber by simply inserting partitions in the existing blower casing. With this change made, the I-A engine could be run at a thrust of about 1,300 lb without serious overheating; the British Rover W-2B/23 could deliver only about 1,000 lb thrust without surging at this time, and it was not until November 1942 that it passed a 25-hour test at 1,250 lb.

The I-A engines were flown for the first time in a Bell P-59A on October 2, 1942, eight months before the British W-2B was flown. Owing to the existence of what was virtually a limitless runway at Muroc, there was not the danger in taking off with engines of deficient thrust which there would have been in Britain. The fact that the GE engine was flown eight months before the Rolls Royce engine, plus the fact that the light wing loading of the P-59A made it easier to fly at high altitude than the Meteor, meant that GE ran into trouble with surging at altitude and eliminated it well before the British first encountered it in mid-1943.

While the I-A was being flown,[25] GE was going ahead with the design of its own new blower casing and diffuser. The completely separate passages from the impeller to each combustion chamber were made rectangular in cross section, and the turn from the radial to the rearward direction was made in a right angle, around which the gases were led by internal vanes. It is very interesting that at about this same time Power

[25] Flight tests of the P-59A with the I-A lasted about a year. The highest speed recorded was 404 mph at 35,000 feet.

Jets independently began the development of exactly the same sort of diffuser and casing, which it called the type-16.[26]

The new casing was one of the two most important new features in the new I-14 engine, aimed at 1,400 lb thrust. The other most important new feature was an improved turbine wheel, copied from the Power Jets W-2/500 experimental engine, which had been tested in Britain in September 1942. The chief feature of this turbine was the use of fewer, broader, and longer turbine buckets, which both lessened trouble with breakage and, in conjunction with an increase in the area of the nozzle diaphragm, increased thrust by increasing the mass flow through the engine. The I-14 had one additional significant feature, although of less importance than the two just mentioned: this was a new combustion liner, the principle of which had been developed by A. J. Nerad of GE's Schenectady Research Laboratory, the designer of the combustion system of the TG-100.

The I-14 performed very well indeed when it was tested, giving the full 1,400 lb design thrust soon after it was first run in February 1943, one month after the Rover B/23 had passed a 25-hour test at this thrust. The I-14 was taken as the basis of a new model, the I-16, aimed at 1,600 lb thrust, which differed from the I-14 only in details. Design of the I-16 was begun in January 1943, and the engine was run on the bench in April. This was the first American model to deliver the thrust aimed at in the original W-2B; it had a guaranteed thrust of 1,600 lb and averaged about 1,650 lb for a weight of 825 lb and a guaranteed fuel consumption of 1.23 per hour. It was in March 1943 that the Rover B/23 first passed a 25-hour test at 1,600 lb thrust, and in April that the engine (now the Rolls Royce Welland) passed a 100-hour test under type-test conditions at that rating. Flight testing of the I-16 in the P-59A showed that even this engine surged at altitude, but the difficulty was quickly corrected at the cost of a small reduction in the excess of actual sea-level thrust over the guaranteed 1,600 lb by the simple device of milling less material from the dif-

[26] Cf. Chap. XIII, p. 368. The type-16 casing was not tested, however, or at least showed no very good performance, until January 1944. When GE engineers showed designs of their new casing to Whittle in June 1942, he gave no indication that Power Jets was working along similar lines.

fuser casting and thus reducing the area of the air passages by about 5%. In July 1943 a fully-armed P-59A was flown with these modified I-16's at 46,700 feet. The Welland had first flown in the Meteor in June 1943, and was still having trouble with surging at about 25,000 feet.

Development of the Original American Designs to the Middle of 1943

By the latter part of 1942, work was proceeding in the United States on the imported Whittle turbojet and on seven gas turbines or jet-propulsion engines of native design: the Northrop, Pratt & Whitney, and GE turboprops, the Allis-Chalmers turbine-driven ducted fan, the NACA piston-driven ducted fan, and the Westinghouse and TEC turbojets. All these developments except the Pratt & Whitney engine were being carried out at government expense. The preliminary designs of an eighth engine, the Lockheed turbojet, were complete, but development was awaiting government financial support.

The Question of Collaboration

In the late summer of 1942 Major Donald J. Keirn inspected the British jet and turbine developments and reported in October that the British were far ahead in four respects: the development of the engines themselves, research on the possible applications of the engines, the study of the design and possible performance of turbine-driven planes, and the coordination of the development of the planes and the engines. The report also described the operation of the British Gas Turbine Collaboration Committee, which comprised representatives of all manufacturers and government agencies in the field, and where all phases of the program were discussed and information was freely exchanged. Five days after this report was submitted Brigadier General Benjamin W. Chidlaw wrote a memorandum to the authorities at Wright Field, informing them that the British were far ahead of us and requesting them among other things to present to the Chief of Staff a plan for cooperation

with other groups working on jet propulsion in the United States and in allied countries.

The question of collaboration was then discussed by the Army, the Navy, and the NACA at a meeting held in Washington on November 20, 1942. Here it was agreed that not only the original engines as of 1941 but later projects of various plane and engine manufacturers which had recently entered the field were being developed with almost no knowledge of what others were doing.[27] Nevertheless, despite the fact that all the American manufacturers of conventional aircraft engines had been exchanging every sort of information wholeheartedly and without any reservation whatever since the beginning of the emergency in 1940, those present at this meeting alleged that "basic differences in national laws" made anything like the British collaboration on gas turbines impossible.[28] As far as collaboration with foreigners was concerned, Hunsaker of the NACA assured those present that Americans working independently would very shortly overtake the British. The Navy's policy seems to have been particularly secretive at this time: a year before this the Navy had specifically instructed Westinghouse to develop the 19A turbojet without trying to learn anything about what anyone else was doing; for at least a year after the TEC turbine study began no information concerning it was given to the Army; and now the Navy agreed with the NACA that any appreciable amount of collaboration would be "more trouble than it was worth".

It did not take long to show the complete unsoundness of this belief that individual firms with no outside help could quickly

[27]American manufacturers except GE had no real knowledge of English turbines, and GE knew only of the Whittle engine until 1943, when first a British delegation visited the United States and then an American delegation went to England. Even the NACA committee on jet propulsion was left ignorant of the Whittle engine for a long time, and the GE Schenectady group working on the TG-100 was given no information about the I engines by Lynn. Secrecy concerning the Whittle engine was, however, one of the conditions imposed by the British when they consented to have it licensed in the United States.

[28]Collaboration between the industrial turbine companies and the aircraft engine companies was particularly desirable and would almost certainly have occurred if it had been permitted, since the engine companies were becoming anxious to obtain information on gas turbines and the turbine companies were anxious for general aircraft-engine background. At least one of the turbine companies and one of the engine companies actually made arrangements to exchange information which had to be cancelled because of requirements of military secrecy imposed on the turbine manufacturer.

equal the results of work which had started years before they entered the field and to which a number of British firms and laboratories and one American firm were continually contributing all their current results.

The Ducted Fans and the Turboprops

Two of the engines of purely American design under development in 1942 were ducted fans: the NACA power plant, driven by a reciprocating engine, and the Allis-Chalmers engine, which was driven by a gas turbine.

After the original NACA engine designed by Jacobs had failed to give stable combustion in its original tests in 1941, the power-plant group at Langley Field was called upon in December to redesign the burner. This group substituted a burner which injected solid fuel for the original vaporizing type. This burner made it possible for the first time to get a thrust with afterburning stable enough to measure; the early tests, begun in January 1942, showed 600 lb thrust with afterburning of about 1 lb of fuel per second against 300 lb thrust from the fan alone.

Reports of the successful maintaining of afterburning and of the fairly good ratio of additional thrust to additional fuel consumption[29] made a considerable impression on the NACA Special Committee on Jet Propulsion, and Dr. Durand, the chairman of the committee, recommended strongly that the NACA try to develop an engine suitable for experimental flight. The 600-hp R-1340 used hitherto was replaced by an 825-hp R-1535, and a further improved burner was designed. The changes were completed in July 1942, new tests were conducted, and in October a report was made to the committee. By that time the engine was delivering 900 lb static thrust as a pure ducted fan, or 2,110 lb with afterburning of 2.3 lb of fuel per second.

The Allis-Chalmers turbine-driven ducted fan, on the contrary, had progressed very slowly indeed: even by the middle of 1943 the design studies were not complete, and construction had not yet begun.

[29] Although 1 lb of fuel per second for 300 lb additional thrust is a specific consumption of 12 lb per lb thrust per hour.

Three of the engines of purely American origin under development at the beginning of 1942 were turboprops. Two of these, the Northrop Turbodyne and the General Electric steam turbine division's TG-100 were gas turbines of the ordinary type, with a rotating compressor driven directly by the turbine wheel. The other was the Pratt & Whitney PT-1, with a free-piston reciprocating Diesel compressor and a turbine wheel geared only to the propeller.

The original Army-Navy contract given to Northrop had called for a detailed design and analysis of a complete engine but for actual construction of only the compressor, since this was believed to be the most critical part of the design. About the middle of 1943 it was realized that equipment was nowhere available to test a compressor for a 2,500-hp engine otherwise than as a part of the engine, and that no progress at all could be made without constructing a complete engine.

Pratt & Whitney's work on the PT-1 was not even aimed at a flight engine at this time, but was purely of the nature of research into the design of the components. These components were built in forms and of materials suitable for bench testing, and were to be completely redesigned when the time came to build a flight engine. In 1943 little more than a start had been made in solving the basic problems of this novel type of engine.

Of all the turboprops, GE's TG-100 made the most rapid progress, but all that had been accomplished even with this engine by May 1943 was to get it running on the stand without a propeller. This accomplishment was creditable, but it was now clear that a great deal more work remained to be done before it could be run delivering power to a propeller, let alone be flown.

The Turbojets of American Origin

Of all the turbines of American design under development by the end of 1942, only two were turbojets: the Westinghouse 19A and the Turbo Engineering Corporation engine. Designs were already complete for the Lockheed L-1000, but construction was awaiting financial support from the government. Although the Army — largely owing to reports of German activity and actual observation of British activity — had been interested in turbojets as primary power plants since about the middle of 1941, the Navy had always maintained that jet propulsion was impractical because it involved both shorter range and longer take-off run. As a result, the two jet engines, both of which were sponsored by the Navy, were intended for use as boosters only and were accordingly quite small: the Westinghouse engine was designed to suit the Navy's request for 450 lb thrust at 500 mph at 25,000 feet, corresponding to roughly 1,000 lb sea-level static thrust, and the TEC engine was designed for 1,100 lb sea-level static thrust; Whittle had designed his W-2B engine in 1940 to produce 1,600 lb.

The Westinghouse 19A axial-flow engine, for which the Navy letter of intent had been issued in December 1941, made very good progress. The designs were completed in the very reasonable space of ten months and the engine was run on the bench on March 19, 1943. Even so, it could not hope to catch up with the great head start of the Whittle engine; it was not flown until after the end of 1943, and even then developed only some 1,200 lb thrust, which was very good for its size, but was small compared with the 1,600 lb of the GE I-16.

The design of the TEC turbojet, for which the Navy contract was signed in October 1942, was completed quite rapidly, but construction was held up. The company did not move into the Defense Plant Corporation plant obtained for it by the Navy until the spring of 1942, and it was long after this before some of the most essential tools were obtained. In the midst of this confusion the first task of the company was getting its turbosupercharger into production; and as experimental projects it had a very large turbo for the R-4360 and a gear-driven supercharger for the R-2800 in addition to the turbojet. The result was that construction of the turbojet, for which the Navy contract had been signed in October 1942, was only beginning in the middle of 1943.

Gas Turbines from 1943 to the End of the War

The Attitude of the Services in 1943

The Army had begun flying jet-propelled aircraft in October 1942, and in July 1943 the P-59A with I-16 engines was flying at well over 400 mph and above 45,000 feet of altitude. In

Britain the Meteor had been flown with de Havilland Goblin engines in March 1943, and systematic testing with the Rolls Royce Welland version of the Whittle engine began in June. The turbojet by this time was no longer in the class of a somewhat dubious experiment but in that of a military engine requiring only a certain amount of additional development before it would go into service.

At the same time that the turbojet was establishing itself as an engine type of probable utility, interest in turboprops and ducted fans, at least as engines to be used in the near future, had very much diminished. In part this lack of interest was because the much greater difficulties involved in developing turboprops and ducted fans were by now apparent, and in part because it was now realized that there was no apparent application at hand where they would have any great superiority over conventional engines even if successfully developed, whereas it was clear that no other engine could compete with a turbojet in producing maximum speed in a fighter.

Thus by mid-1943 it was becoming generally admitted that despite the fact that jet-powered fighters would be very much inferior in both take-off and range, there was no use in good take-off and range if the fighter possessing them was to be outperformed in combat by jet-powered enemy fighters. Even the Navy was finally convinced, and in 1943 gave its first contract for an airplane with jet propulsion as primary power, the McDonnell FD-1 (later designated FH-1).[30] But although the jet engine had proved itself in principle in this country by the performance of the P-59A with the General Electric engines, the speed of the P-59A even with the 1,600-lb I-16's installed in July 1943 was only 414 mph, which was scarcely superior to the speeds being attained at that time by experimental fighters with reciprocating engines and propellers, and both the Army and the Navy were anxious to have much more powerful turbojets than even the 1,600-lb I-16, let alone the 1,200-lb 19A.[31]

[30]The first airplane designed for the Navy around a jet engine also had a conventional power plant in the nose; this plane was the Ryan FR-1, the contract for which was given late in 1942.

[31]The speed of the P-59A was almost exactly the same as the speed of the British Meteor with its two 1,600-lb Rolls Royce Wellands, but the conclusions drawn in the two countries were opposite. Where Rolls Royce continued to develop engines

(*Footnote continued on next page*)

Development of the other types of engines, on the other hand — ducted fans and turboprops — could be either dropped or definitely treated as a long-range project with low priority on engineering resources.

Development of Turbojets for Use in the War; the General Electric I-40

Development of the existing small turbojets was not completely stopped in the middle of 1943, despite the desire for larger engines. General Electric continued with the development of the original size of I engine, testing an 1,800-lb I-18 in January 1944 and a 2,000-lb I-20 in April 1944, and the I-18 was even flight-tested in the P-59A beginning in November 1944. Westinghouse continued its work on its 19A engine, which became the only one of all the original American designs existing in 1942 to fly before the end of the war. The original 19A was flown on an FG-1 Corsair on January 21, 1944, in its original function as a booster, developing about 1,200-lb thrust. Two of the improved 19B's (J-30's), developing 1,365-lb thrust, flew as sole power of a McDonnell FD-1 (FH-1) on January 1, 1945. Work was also continued on the TEC turbojet, but even by September 1944 this engine was not yet complete, although the compressor had been shipped to the NACA for tests, and since the company was still far behind schedule on production of its turbosupercharger it was decided that the only possible course was to drop all other work, including the turbojet, and concentrate on the turbosupercharger and the geared supercharger for the R-2800.

The chief characteristic of the turbojet development program in the United States beginning in 1943 is, however, the development of much larger units. Two projects were begun with the intention of obtaining engines as quickly as possible, perhaps in time to be of use in the war, and two more as longer range projects aimed at engines of greater efficiency. The short-range projects were the production in this country of another British engine, the de Havilland Goblin, and the development of a new General Electric design, the I-40, based on the company's experience with the I-16 but incorporating many new features. The longer range projects were the Lockheed L-1000, development of which was finally authorized and subsidized by the government at this time, and a second GE engine, the TG-180, an axial turbojet based on its experience with the TG-100 turboprop.

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of higher performance but the same dimensions as the Welland so that they could fit in the Meteor airframe, the American Army now reclassified the P-59A as a trainer, and set out to obtain larger engines at once.

The de Havilland Goblin or H-1 had been designed in 1941 to produce 3,000-lb thrust, enough to power the single-engine de Havilland Vampire fighter (above, p. 357). It had already momentarily produced 3,010 lb of thrust in a bench run in June 1942, and had been cleared for flight at 2,000 lb before the end of the year; the first flight, in a Meteor, was actually made in March 1943. Both the Army and the Navy were anxious by early 1943 to have this engine built in the United States, and since Allis-Chalmers' ducted fan seemed to have no promise of short-run utility, the Navy development contract was cancelled in mid-1943 to free its facilities, which were the only ones available, for the production of the Goblin.[32] Before Allis-Chalmers was in production, however, an engine was available which gave very much more thrust, and plans for production of the Goblin were eventually dropped.

This more powerful engine was the General Electric I-40. Early in 1943 the Army had asked GE to study the possibility of a turbojet to produce 4,000-lb thrust instead of the 1,600 lb for which its current engines were designed but which was not achieved until the middle of the year. GE responded with two different design studies: the TG-180 (later designated J-35) with an axial flow compressor, designed by the Schenectady group which had been developing the axial TG-100 turboprop, and the I-40 (later designated J-33) with a centrifugal compressor, designed at Lynn.[33] For some time General Electric was uncertain which of the two engines it should develop, but it was ultimately decided that, since the axial engine was the more promising in the long run while the centrifugal was the

[32] At this same time the Army contracted with Lockheed to build the single-engine XP-80 fighter around the Goblin. Design began in July 1943, and the airplane was flown on January 9, 1944, with a British-built Goblin, then rated at 2,300-lb thrust. It made a speed of about 475 mph.

[33] The original studies of the centrifugal engine were based on a thrust of 3,000 lb, but by the middle of 1943 the aim had been raised to 4,000 lb.

more likely to be of use before the end of the war, both should be developed. Designing of both engines was accordingly begun in June 1943.

The compressor and turbine of the I-40 were derived from the I-16 without any essential changes except in the method of manufacture. The combustion system, however, was of the straight-through type rather than the reverse-flow used in the original British W-2B and the earlier American I-series engines. Like the right-angle blower casing first used on the I-16, this change was developed independently by GE at about the same time that a similar change was being made in Britain.[34] GE's primary reason was to simplify assembly and service; the reverse-flow system on the I-16 was not excessively unreliable or difficult to manufacture.

The combustion system of the I-40 was made of Inconel sheet (80% nickel, 14% chromium, 6% iron). The turbine nozzles were precision-cast of Stellite alloy No. 21. The turbine buckets of the first experimental engines were forged of Hastelloy B, as in the earlier I engines, and it was originally intended to make all production buckets in the same way, but as plans were made for large quantity production of the I-40 it became doubtful whether sufficient forging capacity could be created. Precision casting of Stellite alloy No. 21 had solved the production problem for turbosuperchargers, and although it was quite a different problem to cast buckets for the I-40, which were 35 times as large as those of the turbo, experiments were made. Half the engines built at Lynn were equipped with cast buckets of Stellite alloy No. 21, and by 1945 considerable progress had been made toward a satisfactory production technique.

The I-40 was first tested on January 13, 1944; in February it momentarily developed a thrust of 4,200 lb on the bench, and it

[34]This combustion system was due to A. J. Nerad of GE's Schenectady staff, who had designed the combustion system for the TG-100. It was late in 1942 that the Lynn Division first called on Nerad to develop a new system for the I-series engines, which until then had followed the British design in every detail, the Lynn group having had no experience whatever with combustion of this intensity. Power Jets had sketched straight-through engines in 1940, but these sketches seem not to have been known to other firms either in Britain or in the United States. Rover had put together a straight-through "lash-up" and run it in March 1942, and had then designed the straight-through W-2B/26, which was first run in November 1942.

was soon developed to an average thrust of about 4,000 lb, with a guarantee of 3,750 lb. On June 10, 1944, it was flown in a specially modified version of the new Lockheed single-engine jet fighter built originally for the de Havilland Goblin. This new version, designated the XP-80A, naturally gave much better speed — over 500 mph — with the 4,000-lb I-40 than the XP-80 did with the 2,300-lb Goblin, and plans for production of the latter were dropped.

The P-80A Shooting Star and the I-40 (J-33) were the first jet fighter and the first jet engine suitable in the Army's opinion for fighter use to be put into quantity production in the United States, and the only ones to reach this stage before the end of the war. Production at Lynn was experimental and service-test only, and only a few dozen engines were built there before the end of the war, but the Syracuse works of the General Electric Company, which were to do the quantity production, were within a month of attaining the full scheduled production rate at the end of the war. Even these fighters came off the lines too late to see actual combat, but although the P-80A and I-40 were not in service as soon as the British Meteor and Welland, which were used from August 1944 against V-1 flying bombs in England and which were sent in very small numbers to Europe in January 1945, the reason was not because development lagged in the United States. The Welland had exactly the same 1,600-lb thrust rating as the I-16 and attained it at the same time, and the Bell P-59A had almost exactly the same speed with two I-16's as the Meteor had with two Wellands. The P-59A would probably have been the better fighter of the two, since despite the fact that it attained the same speed with the same thrust its wing loading was lighter (28 lb/sq ft against 31.5), and this meant that it was more maneuverable at altitude[35] and had a shorter take-off run. The reason why the P-59A was not used as a service fighter while the original Meteor was so used lies in differing military requirements, not in inferior performance.

At the end of the war, however, the British were definitely ahead. The I-40 engines shipped by Lynn had an average

[35]The light wing loading of the P-59A was the result of the Army's original specification, which called for maneuverability at altitude.

rating of 4,000 lb thrust for a weight of 1,820 lb; their maximum over-all diameter was 48 inches. The guaranteed specific fuel consumption was 1.185 per hour.[36] The Rolls Royce Nene, design of which was begun in March 1944 (ten months after the I-40), had in 1946 obtained a rating of 5,000 lb thrust for a weight of 1,580 lb,[37] a maximum diameter of 49½ in. and a specific fuel consumption of 1.06 per hour. The chief factor in the lower fuel consumption of the Nene seems to be in the aerodynamic design of the compressor, which has an efficiency of about 79% at a pressure ratio of 4:1 compared with about 74% for the compressor of the I-40 at the same pressure ratio. The difference in weight is unexplained. Since GE stopped development of the I-40 immediately after the end of the war, it is not possible to say whether it could have developed the engine to equal the 1946 performance of the Nene.

The Long-Range Projects

By the middle of 1943 it was generally recognized that the only gas turbines which could possibly be ready before the end of the war were the two small turbojets begun in 1941 (the General Electric I-16 and the Westinghouse 19A) and two of the new large turbojets, the imported de Havilland Goblin and the General Electric centrifugal I-40. From this time on all other projects were either abandoned or considered as long-term development for use after the war.

Both the ducted fans which had been under development up to this time were completely abandoned by the middle of 1943. We have already seen that the Allis-Chalmers turbine-driven fan was still in the design stage when it was dropped to free the facilities for production of the de Havilland Goblin. The NACA engine, driven by an R-1535, had, it is true, shown experimental results which were up to the original expectations, and by April 1943 it was calculated that with the latest model of the R-1535 the engine could deliver 2,030 lb thrust at a speed of 550 mph and an altitude of 10,000 feet. The specific fuel consumption was 2.14/hr, however, and the engine was much

[36]Combustion pressure drop 3.18 psi. Turbine inlet temperature 1,492°F; bucket temperature 1,200°F-1,350°F.

[37]Both weights include engine accessories, but it is uncertain whether the same accessories are counted as engine accessories in both cases.

heavier and larger in cross section than a turbojet. By 1943 the services were convinced that straight turbojets were much more promising. The development of the NACA engine was accordingly stopped in April 1943, and it was never flown.[38]

None of the three turboprops under development in 1942 was abandoned before the end of the war, but all three were by 1943 considered as long-range projects which would certainly not be used in the war. Work on the General Electric Schenectady steam turbine division's TG-100 axial-flow turboprop was very much slowed down by the new TG-180 turbojet (see below), and although it was the most advanced of the three engines in 1943, it was not run with a propeller until May 1945 and not flown until December 1945.[39]

A new contract was given to Northrop on July 1, 1943, calling for the construction of two complete engines, now intended to deliver 3,800 hp, at an estimated price of $1,505,854. Even the first of these two engines, although it was the first American turboprop to run with a propeller, was not run on the stand until December 1944, and it had not flown by the end of the war. As has been said, development was slowed down by perhaps a year owing to the lack of adequate experimental facilities, but the chief reason for the slowness of this development was certainly nothing but the inherently enormous difficulty of developing an engine of the very high efficiency aimed at in the Turbodyne.[40]

The Pratt & Whitney PT-1 turboprop was, as has been said, the only one of all these engines which was a private venture, and the changing attitude of the services had no effect on its status, which had been one of long-range applied research from the beginning. The PT-1 remained in this status throughout the war, although about 25 engineers were eventually

[38]On the Campini-Caproni airplane as actually built in Italy, see F. E. Pickles, *Caproni-Campini Aircraft and Allied Development in Italy* (Combined Intelligence Objectives Subcommittee, Item No. 5, File No. XII-24) (London: His Majesty's Stationery Office). This airplane was powered by a ducted fan with afterburning driven by a 900-hp Isotta-Fraschini engine. The first flight was made in August 1940, and in December 1941 a flight was made from Milan to Rome which was widely publicized at once. The performance of the airplane was extremely poor (about 200 mph), but this was not generally known until after the war.

[39]At that time it developed 2,200 shaft hp plus 600 lb exhaust thrust.

[40]This engine used an 18-stage compressor and a four-stage turbine.

assigned to it, and it had cost some $3.3 million of the company's money by the end of the war. The greatest share of the work was put on the least well-known part, the free-piston Diesel compressor, and this component proved in fact to present the most serious problems; it was eventually made to work fairly well at part speed, but it was never got up to design speed. There were also serious difficulties with combustion in the afterburner. On the other hand the turbine wheel itself presented no serious problems: the first model had an efficiency of 85%, credit being given for exhaust thrust, and the high-temperature problems of ordinary gas turbines were largely absent because of the low gas temperature.[41]

Finally, two of the new turbojets undertaken in the middle of 1943 were themselves long-range projects, intended to secure better performance and in particular lower fuel consumption at the cost of a longer development period. These were the Lockheed L-1000 and the General Electric TG-180, neither of which was ready for flight at the end of the war.

Design of the General Electric TG-180 or J-35 turbojet was begun at the same time as the I-40, in mid-1943. The TG-180 was an axial-flow engine with an 11-stage compressor. It was first run on April 23, 1944, only three months after the I-40, but progress from this point was much slower, as was to be expected because of the greater difficulty of developing an axial compressor. The TG-180 was first flown (in an XP-84) in February 1946, at which time experimental engines had an average rating of 4,000-lb thrust, with a guarantee of 3,750 lb, both figures just equal to those for the I-40 20 months earlier. The 11-stage axial compressor gave a smaller diameter (37½ in. against 48 in.) but greater weight (2,300 lb against 1,820 lb); its higher efficiency at the same 4:1 pressure ratio gave a lower fuel consumption (1.075 instead of 1.185 per hour).

[41]On June 30, 1945, a Navy contract was received covering virtually the entire costs of future work, and a complete engine actually designed for flight was laid out and built. By the time this was done, however, it was realized that it would be a number of years before all the novel features of the engine had been sufficiently developed for service, while the pressing need from both the national and the company's point of view was for the rapid development of orthodox turbines. Orthodox turboprops now promised to give the 5,000 hp of the PT-1 with far less development and for a third the weight, while by the addition of regeneration they promised almost as low fuel consumption. The PT-1 was accordingly laid aside.

The preliminary design of the Lockheed L-1000, later given the official designation XJ-37, had been completed by 1941 and formally submitted to the Army in 1942, but it was not until the middle of 1943 that the Army decided to support its development as a long-range project.[42] Its design promised smaller diameter and much lower fuel consumption for given thrust than any other turbojet yet under development, although the complexity which was to secure the good fuel economy meant that development would necessarily be slow. Lockheed developed the XJ-37 for about two years and then, in October 1945, turned it over with the staff headed by Price to the Menasco Manufacturing Company.

[42]The Army refused, however, to permit the development of the L-133 airframe which had been designed in intimate association with the engine. In part this was because the Army disapproved in principle of developing an airframe too closely tied with one specific engine, and in part because it wanted Lockheed to use its facilities to develop the XP-80 airframe for the de Havilland Goblin, which was to be manufactured by Allis-Chalmers.