CHAPTER XIII

British Aircraft Gas Turbines

The First Proposals and the Period of Neglect: 1926-1936

Early Studies by the RAE (1926-1930)

During[1] the first half of the 1920's A. A. Griffith of the Royal Aircraft Establishment, developed a theory of axial-flow compressors and turbines based on the relatively new science of airfoils. On the basis of the new theory, which among other things indicated that the blading should be of the free-vortex type, Griffith believed that he could design a compressor of efficiency high enough to make a gas turbine a practical engine for driving a propeller, and in 1926 he proposed that an axial-turbine be developed for use as an aircraft prime mover. The Aeronautical Research Committee (hereafter, ARC) unanimously approved the carrying out of "preliminary experiments to verify the theory".

The first step was to design a small single-stage axial compressor and single-stage axial turbine (with free-vortex blading) on a common shaft; tests of aerodynamic efficiency could be made by forcing air through this set, although it had no combustion system and thus was not a complete engine. In order to get data for the design of this unit, wind-tunnel tests were carried out in 1927 on cascades of airfoils representing turbine and compressor blading. After the results were in, the single-stage compressor-turbine unit was built and tested in 1929. These tests showed the very encouraging efficiency of 90% per stage.

In November 1929 Griffith argued in his report that an aircraft turbine could be built which would not only be lighter

[1]Hayne Constant, "The Early History of the Axial Type of Gas Turbine Engine," Institute of Mechanical Engineers, London, *Proceedings* 153, 1945, pp. 411-426.

and smaller than current reciprocating engines but more efficient as well, and he specifically proposed to build a counter-rotating counterflow engine. This report was considered by a special panel of the ARC. The panel, although it recommended against immediate construction of a complete engine, did recommend in April 1930 that further experiments be carried out directed toward that ultimate objective, including both further experiments with turbocompressors and experiments on combustion.

In 1930, however, Griffith was assigned to the Air Ministry laboratory at South Kensington, where there were no facilities for this sort of work. Before he returned to the RAE at Farnborough in 1931, appropriations had been cut because of the depression, and the general belief was that there were more immediately pressing uses for the available funds, in particular work on supercharging, fuel injection, and compression ignition. The result was that from 1929 to 1936 no further work at all was done by the RAE toward a gas turbine.

Whittle's Original Proposals (1928-1930)

In 1930 Flying Officer Frank Whittle[2] was seeking support for a turbine engine that differed from the one proposed by Griffith in two important respects: the engine was simpler mechanically,[3] and the useful power was to be taken in the form of an exhaust jet rather than as a propeller drive.

Whittle's first training in aircraft engines had been three years of study as an apprentice in the Royal Air Force. He then became a cadet in the RAF college at Cranwell, where a thesis on a scientific subject was part of each term's work, and in his fourth term, in 1928, Whittle wrote on the future development of aircraft. B. M. Jones had just published a paper on "The Importance of Streamlining" in which he argued[4] that at top speed in level flight two-thirds of the power of a commer-

[2]Air Commodore F. Whittle, "The Early History of the Whittle Jet Propulsion Gas Turbine" (The First James Clayton Lecture), Institute of Mechanical Engineers, London, *Proceedings* 152, 1945, pp. 419-435.

[3]This scheme called for a single-stage turbine and a three-stage (two axial and one centrifugal) compressor.

[4]*The Importance of "Streamlining" in Relation to Performance* (Aeronautical Research Committee, "Reports and Memoranda," No. 1115) (London: His Majesty's Stationery Office, 1927), pp. 425-426.

cial transport and half the power even of a racer were used in overcoming drag due to turbulence which could be largely eliminated by better design of the airframe. Whittle drew the obvious conclusion that if anything like this amount of drag could be eliminated speeds could be very greatly increased, and of course these higher speeds would make reaction propulsion very much more efficient relative to a propeller than it was at existing speeds: from the beginning Whittle thought in terms of speeds of the order of 500 mph and very high altitudes. In his thesis, accordingly, Whittle considered the possibility of rocket propulsion.[5]

From the RAF college Whittle was sent, after a year of other duties, to an Instructors' Course at the Central Flying School in Wittering. Here he continued to study propulsion, and after considering a scheme where a reciprocating engine drove a compressor to produce a jet he hit on the combination of the gas turbine with jet propulsion to make a turbojet engine. He applied for a patent on this engine (British 347,206) in January 1930, and it was granted, although exactly the same basic type of engine had been patented by the Frenchman Guillaume nine years before[6] (cf. above, p. 324).

Whittle knew that general opinion held the gas turbine impractical because of low permissible temperatures and poor component efficiencies, and he knew nothing of the RAE's recent work which indicated means of improving the latter. He believed, nevertheless, that the turbojet was a practical engine at the time for reasons of three different sorts. First, he believed that neither compressors nor turbines had yet been really scientifically designed, and that careful application of available knowledge of aerodynamics would result in vastly better efficiencies. Second, he considered that an aircraft turbine was essentially an easier job than a stationary turbine, both because the low temperature of the atmosphere at high altitude would improve thermal efficiency, and because the

[5]In the same paper he discussed gas turbines for propeller drive, although he did not suggest that they be used for jet propulsion; he was interested in turbines at this time only because of the advantages of high power, simplicity, and absence of vibration which were the usual bases of interest in gas turbines for all applications at this time.

[6]Whittle was completely ignorant of Guillaume's work.

ram effect of the forward motion of the airplane assisted in compression and reduced the pressure rise required of the compressor. Third, he thought that for aircraft the turbojet was easier to develop than the propeller-driving turbine usually considered for that application because the useful part of the power would not suffer losses in the turbine and because the additional weight and complication of gears and other parts were eliminated.

With these arguments and a notebook full of sketches and calculations, Whittle, who was then only 23 years old, asked the Air Ministry in 1930 to back the development of an engine which he proposed to design. The Air Ministry refused. While willing to support a long-range program of research by the RAE directed at ultimately acquiring the basic knowledge required to construct a successful gas turbine, the Ministry shared the generally accepted view that in the present state of metallurgy and the art of component design[7] such engines could not succeed. Whittle's case suffered very considerably from his youth and lack of presence, as well as his lack of technical training and experience, all of which made it impossible to overcome an opinion universally accepted by the leading engineers in the field.

After his failure to obtain Air Ministry support, Whittle attempted to sell his idea to private industry, and approached both manufacturers of steam turbines and makers of aircraft engines. One of the engine builders, and probably others as well, made a careful review of Whittle's proposals, but concluded that while in principle the scheme was sound, it could not become practical for ten years at least: existing metals would not permit sufficiently high temperatures and stresses, existing compressors were too inefficient, and — most important of all — airplane speeds were not high enough to make jet propulsion desirable. Since in the existing state of the industry anything ten years off might as well be indefinitely far off, this engine firm decided to do nothing about the scheme; its logic was probably the same as that of the others.

[7]In the light of the RAE's experience with supercharger compressors the extremely high compressor tip speeds proposed by Whittle seemed fantastic to the Air Ministry.

Thus there ensued a period of about six years in which gas-turbine studies were at an almost complete stop in England. Fortunately, however, the Royal Air Force, following its usual practice with its most promising engineering candidates, assigned Whittle in 1934 to take the Tripos in Mechanical Sciences at Cambridge, in which he received first-class honors in 1936.[8] During the time he was at Cambridge, Whittle continued to work occasionally on the turbine, although he had almost no hope of its realization and let the basic patent of 1930 expire rather than pay a renewal fee. What was more important, he acquired a thorough knowledge of the science of aerodynamics, including the most recent advances.

The Financial History of Power Jets, Ltd

While Whittle was at Cambridge he was approached by two former officers of the RAF, R. D. Williams, who was acquainted with Whittle and knew of his turbine proposals, and J. C. B. Tinling, who was Williams's partner in a light engineering business. These two men quickly became convinced that the turbojet would soon replace the piston engine, at least for high-altitude operation. An agreement was made between them and Whittle whereby, in return for half of any eventual profits, they would attempt to obtain capital on reasonable terms for development of the engine, act as managers of the enterprise and as Whittle's agent, and pay all the interim expenses. Whittle estimated that the total cost of developing the engine to the point of having a prototype suitable for flight would be about £50,000 ($250,000), and Williams and Tinling believed that if this capital could be found, a usable engine could be developed within five to seven years.

Whittle's basic patent had lapsed, as has been told, but without patents it would have been virtually impossible to raise capital for the development of the engine, not only because of the protection they could give but because they were

[8] A certain amount of specialization was required of all RAF officers, and Whittle had elected engineering. This choice did not mean, however, that he would become a purely engineering officer like the Engineering Duty Only officers of the American Navy; the ordinary career and ordinary advancement of the RAF remained open to him.

really the sole substantial assets which could represent the capital, at least during the first phase of the development. Fortunately Whittle was able to obtain new patents on various particular features of his engine, but even with these patents he felt that he was nearly defenseless against any large company which might wish to take his ideas, since he had not the financial resources which would have been necessary for a legal action. For this reason it was decided that the turbine should not at that time be offered to any aircraft-engine maker.

For a number of months Williams and Tinling were unsuccessful in their attempts to raise capital to support the venture. Finally, in October 1935, they met M. L. Bramson, a well-known independent aeronautical consulting engineer, who introduced them to Sir Maurice Bonham-Carter and L. L. Whyte of O. T. Falk and Partners. This firm was associated with the investment-banking firm, O. T. Falk and Company, Ltd, of which O. T. Falk and Sir Maurice Bonham-Carter were managing directors. O. T. Falk and Partners handled business which was not suitable for the company, both making certain investments in its own name and also securing additional capital for the projects in which it was interested by promoting direct investment by outside capital. The partners were conscious that there was a real national problem growing up because of the increasing tendency of investors to seek security above all in their investments, and Whyte had previously proposed the creation of a large development corporation in order to obtain venture capital by spreading the risk over a large number of projects and a large number of investors. Whyte himself was unusually well equipped to take an interest in a new technical idea and appreciate its importance, since he had taken a degree in physics at Cambridge. Thus Falk and Partners, although by no means specialists in the financing of new technical developments, were peculiarly receptive to such ideas, and had already financed a few other projects of this sort, such as a cipher machine and the Scophony television system.

Whyte was much impressed by Whittle as soon as he met him, in particular by the fact that although Whittle said frankly that the chances were probably fifty to one against success, nevertheless he was sure that because of his thorough knowledge of theoretical aerodynamics he could make very great improvements in the efficiency of compressors over the existing state of the art, which was based almost entirely on empirical design; this would, of course, remove one of the two great objections universally advanced against gas turbines at this time. Bramson, a practicing consulting engineer in whose opinion the firm had great confidence, was himself so much interested in the idea that in order to be free to make a disinterested report on its feasibility he voluntarily gave up the claim to a share in any profits which he would have had by virtue of his having presented the idea to Falk and Partners. His report was made in the fall of 1935, and concluded that Whittle's proposals were definitely sound and practical; this commitment of his reputation was undoubtedly an act of considerable courage in view of the almost universal disbelief at that time in the feasibility of gas turbines.

Even if technically sound, Whittle's engine was an extremely uncertain commercial venture in 1935. Granting that the engine could be developed to have the performance predicted by Whittle, there was no assured or calculable market for such an engine. It was not and could not be in any sense a superior replacement for existing engines in existing airplanes, owing to the inherent characteristics of jet propulsion. Whittle had, of course, realized this from the beginning, and had always thought of the engine as being used in a plane going at a very high speed at a very high altitude, where jet propulsion was theoretically superior to a conventional engine and propeller; but as for the economic utility of such speeds and such altitudes he simply assumed that it would be found to exist. It is particularly surprising at first glance that military uses were not those in mind at the beginning, but the current notion of fighter tactics placed such emphasis on continued operation at full speed at medium altitude that Whittle believed that the jet engine was not suitable.[9]

[9]When military uses were first considered, Whittle's first idea was that the engine was more suitable for a bomber than for a fighter, since he believed that future bombers would operate at much higher average altitudes than fighters. This notion was only revised in 1939-1940, largely because it began to be realized that extremely high speeds would be of utility in fighters even if range was very short.

Whittle's only concrete suggestion for an immediate use was in a long-distance mail plane. This was certainly a thing of at least dubious economic practicality, although the fact that transatlantic commercial aviation was virtually impossible with the conventional equipment of 1935 gave a certain reality to a proposal for a high-speed long-range mail plane which such a notion would not have today. But actually neither Whittle nor his sponsors were particularly concerned about the market for the engine; all assumed that if an engine could be developed with the predicted characteristics, uses would certainly be found for it and a new industry would be created.[10]

The result of Whyte's favorable impression and Bramson's report was that before the end of 1935 Falk and Partners agreed to back the development of the Whittle engine. Since Whittle was on active duty as an officer of the RAF, his rights in his inventions were subject to a decision of the Air Ministry. The standard British practice since about 1926 in the case of inventions by government employees was that if secrecy was necessary the government retained all the rights, but if it was not, then the government retained the right of free use while the inventor was given the commercial and foreign rights subject to the payment of a certain fraction of the royalties to the government. The Air Ministry examined Whittle's proposals and declared that it was unlikely that the engine would ever be of military use and that there was no need to impose secrecy; it accordingly granted the commercial and foreign rights in the patents to Whittle, who transferred them to the new company. Since Whittle received stock instead of royalties for the inventions, the government agreed to take a quarter[11] of Whittle's stock in lieu of its regular share in commercial and foreign royalties. The Ministry also gave Whittle permission to devote six hours a week to the affairs of the new company.

[10]Thus Whittle was already thinking of long-range passenger-carrying transports with pressurized cabins; it was known that American airplane builders were already working on the development of such cabins.

[11]In June 1936, when Whittle requested commercial and foreign rights in additional patents, it was agreed that the government's share in his stock should be increased to 35%, but the change was not made until 1940, when the share actually assigned, at Whittle's suggestion, was 43%, the increase being justified by the much more extensive support the government was then giving to the company.

Late in 1935 a four-party agreement to create a new company to be called Power Jets, Ltd, was signed by Whittle, Williams and Tinling, Falk and Partners, and the President of the Air Council of the Air Ministry. The company was to have two classes of stock. The class A stock was to consist of a total of 98 shares; until £50,000 of B shares had been issued the A shares were to have 49% of the voting power, of the profits, and of the proceeds of an eventual liquidation, as well as the entire reversionary rights in the patents in case of liquidation. Of the 98 A shares, Whittle received 42, Williams and Tinling 21 each, and the Crown 14.[12]

The class B stock, with a value of £1 per share, was to have 51% of the voting power, profits, and proceeds of liquidation, until the total amount issued should amount to at least 50,000 shares, when it was anticipated that the company would be reorganized to permit further expansion.[13] Falk and Partners were to subscribe £2,000 ($10,000) at once, and within a year were to subscribe a very much larger additional sum or lose the voting rights of the shares which it already held.[14] The holders of the A and B stock were to elect three directors respectively; Falk and Partners had the right of naming the chairman and managing director.[15]

This agreement was obviously exceptionally favorable to the inventor, Whittle. Falk and Partners were willing to agree to such an arrangement because Whittle's contribution to the whole undertaking was unusually great; not only was he the original "inventor", but he was to serve as Chief Engineer of the new company without salary, since he was an officer on active duty and his services were contributed to the company by the government. Thus the company was able to operate on a capital which would have been completely insufficient had it

[12]After the change made in 1940 Whittle held 32 shares and the Crown 24.

[13]The two classes of stock would receive rights in the reorganized company in proportion to the share of profits assigned to each in the original organization.

[14]In addition to shares received for cash, Falk and Partners were eventually given 1,400 B shares in all in return for organization and management services at the foundation of the company.

[15]Falk and Partners' control of the company was protected by the fact that since this was a "private company" they could prevent the sale of B shares to anyone of whom they disapproved as long as they controlled the board of directors, i.e., as long as they fulfilled their obligations under the agreement.

had to pay ordinary salaries. In addition, it was realized by Falk and Partners from the beginning that the entire undertaking would ultimately have to be a partnership with the state, and the extensive rights granted to Whittle were granted to him in large part as a representative of the state.

Late in 1935 Whittle began design of an engine to serve for the original bench tests, although not for flight. In March 1936 the new firm of Power Jets, Ltd, was legally incorporated, with L. L. Whyte as chairman and managing director, a position which he continued to hold until June 1941. Although the company would have liked to proceed by constructing and testing each component of the engine individually, it was realized that this procedure would be too slow and expensive for its resources, and that in any case test apparatus adequate for the separate testing of the turbine and compressor did not exist and could not possibly be constructed with the funds available. Consequently an order for the construction of the entire engine was given in June 1936 to the British Thomson-Houston Company (hereafter, BTH), on the basis of cost plus a percentage of cost. Whittle was given completely free access to the BTH steam turbine plant and could consult freely with its engineers; he also had access to all the financial records dealing with his engine, and checked the details of the costs himself.

In July the Air Ministry assigned Whittle to a postgraduate year at Cambridge and extended the arrangement under which he was permitted to devote six hours a week to his work as Chief Engineer of Power Jets. In October the company applied to the Air Ministry for financial support in the form of a research contract, but the Deputy Director of Scientific Research in charge of engines, David R. Pye, refused, stating that it was not likely that Whittle would succeed where so many better equipped people had failed. Whittle also presented his case directly to Henry T. Tizard, chairman of the ARC since 1933 and of its engine subcommittee since some years earlier. Tizard wrote in October 1936 to say that he was very glad to hear that something of this sort was at last being tried, and that Whittle's engine was completely sound in principle. Although Tizard's support brought no government funds until over a year later, this encouragement from so respected an authority was largely responsible for the continuance of Falk and Partners' support, since by this time it was being realized that it would be very difficult to raise funds outside the firm itself. There were two principal reasons for this difficulty: first, the general belief among all investors that any new idea of this kind ought naturally to be supported by the Air Ministry and not by private investors; and second, the fact that the secrecy which was required to protect the competitive position of a small company made it undesirable to reveal any details of the scheme to those who would have been most likely to support it if they had known the details. The informal prospectuses shown only to carefully chosen investors by Falk and Partners described the engine and progress made to date only in the most general terms.

The £2,000 ($10,000) originally subscribed in cash by Falk and Partners and an additional £725 ($3,600) placed by them in July 1936, a month after the order was given to BTH, did not suffice for the completion of the first engine. In December 1936 it became clear that considerably larger capital was required. The original agreement had provided that Falk and Partners had the option of raising a large additional sum within a year after the formation of the company or losing the voting rights on the shares which they already held, but in view of the difficulties encountered in obtaining outside investment, and because the firm believed that a smaller sum would suffice at this stage, Falk and Partners decided not to take up their option. They did, however, especially after Tizard's encouragement, wish to continue the work at a more moderate pace, and in April 1937 a new agreement was reached. In return for finding a part of the additional funds immediately needed, Falk and Partners retained voting rights on the B shares they actually held, but the right of naming the chairman and thus control of the board of directors was given to the holders of the A stock, who with their friends subscribed the rest of the funds required in return for B shares. The voting rights of these B shares, added to the 49% voting rights of the A shares, gave the A shareholders complete control of the company. The bills for the construction of the first engine were just met by these

means, and Laidlaw, Drew, and Company accepted B shares instead of cash for its work on the combustion system. By the end of April 1937 the total subscriptions for cash and material services amounted to £5,965 ($30,000).

The engine was put on test in April 1937. The fact that it ran, even though with much lower performance than Whittle had hoped, was naturally extremely encouraging for everyone concerned. On June 22, 1937, two months after the testing began, Tizard wrote Whyte saying that the engine was sound in principle, that gas turbines would become necessary in order to get high enough output for future airplanes, that the possibility of burning heavy oil was very attractive, and that although success could not be considered certain Whittle had shown very great ability. He also pointed out that success was not going to be achieved cheaply in any case; it was essential to obtain funds in much larger quantity than had been obtained hitherto.

Power Jets then made a serious attempt to raise funds in considerably larger quantity than they had been available before, and looked to both private investment and government support as sources. Within the government the company's proposals were supported by Tizard, the Chairman of the ARC, and also by Hayne Constant of the RAE, but Pye, who was then Director of Scientific Research, still believed that Power Jets was wrong in trying to go ahead rapidly with development instead of doing scientific research on the basic problems involved. The actual running of the engine in the spring of 1937 had, however, made him less completely skeptical than he had been in the fall of 1936, and in August 1937 the Ministry finally promised support, although only to the extent of £1,000 ($5,000) for reports on the work up to July 31, 1937 (which as we have seen had cost about £6,000 or $30,000), plus £4,000 ($20,000) for 20 hours of running of a reconstructed version of the engine. The first payment was not made until May 1938, however, so that the Ministry aid was of no assistance whatever in the reconstruction of the engine which the agreement called for.

In addition to seeking Ministry support, the company in July 1937 hoped to raise from private sources an additional

£18,000 ($90,000). The agreement by which government support was undertaken in August meant, however, that the entire project was under the official rules of military secrecy. This made it still more difficult to raise money, and in addition certainly did nothing to lessen the conviction of most investors that the proper source for all the financing was the government. The result was that only one important sale of B shares could be made for cash; this was £3,000 ($15,000) subscribed in November 1937 by the engineering firm of G. and J. Weir.[16] BTH agreed, however, to accept £2,500 ($12,500) of shares in part payment for reconstruction of the engine, and the rest of the cost of the reconstruction which was carried out in 1937-1938 was met by the sale in the early months of 1938 of a number of very small lots of B shares totaling £775 ($4,000). The total value of B shares issued for cash and material (nonmanagement) services from May 1937 through April 1938, the second year of the company's history, was £6,425 ($32,000), making a total of £12,390 ($62,000) in the first two years and a month.

The reconstructed engine was run in April and May 1938 for about 4½ hours before it was partially destroyed by a turbine failure. In May 1938 the government paid the £1,000 quoted in the first contract (March 18, 1938) for reports on work to July 31, 1937, but payment could not be made for the 4½ hours of running which had been completed before the rebuilt engine failed in May, because the contract called for 20 hours running and did not provide for progress payments. Thus the second reconstruction of the engine, carried out in the summer of 1938 at a cost of about £2,400 ($12,000), had to be financed from the £1,000 paid by the Ministry in May 1938 and from the small remainder in the Power Jets treasury. The engine was once more ready for test in October 1938.

Whyte, the chairman and managing director, was then convinced that it was absolutely necessary to speed up the rate of development; expenses which had been at the rate of under £7,000 ($35,000) per year should be at least doubled if the

[16] The head of this firm, Lord Weir, had played an important role in aeronautical procurement in the First World War and had been Secretary of State for Air in 1918.

work was to be done adequately. On November 1, 1938, the Ministry amended its contract of March 18, 1938, to pay £900 ($4,500) for the running already done in the spring of 1938 and to add £1,340 ($6,700) for the second reconstruction of the engine and £4,000 ($20,000) for additional running. Whyte hoped to raise an additional £10,000 ($50,000) privately, but the best that could be done was to secure an additional £2,000 ($10,000) in May 1939 from G. and J. Weir, and at the same time to persuade BTH to take shares in return for an additional £2,000 ($10,000) of work. In January 1939 the Air Ministry paid the £900 for the running done in April and May 1938, and the £1,340 for the reconstruction carried out in summer and fall 1938. These sums largely financed the modifications, experimental running, and combustion research done in the winter and spring of 1938-1939.

During the period from May 1938 through May 1939 the company had issued £4,250 ($21,000) of B shares for cash and material (nonmanagement) services, and had received £3,240 ($16,000) from the government, making a total of £7,490 ($37,000). As of July 1, 1939, the total receipts (including material services) since the foundation of the company in March 1936 had been £19,880 ($99,000), of which £16,640 or 84% came from private sources and £3,240 or 16% from the Air Ministry. The government had also contributed the services of Whittle, who received no salary from Power Jets. These services were limited to six hours a week at the beginning, but after July 1937 Whittle had been assigned to the development full time.

By July 1939 enough progress had been made with the engine to convince the Director of Scientific Research that the Whittle engine might well prove to be a practical device and that the development should be appreciably accelerated. The government accordingly undertook to cover the cost of all future work of Power Jets. The rapid growth of the firm's activities with government finance is shown by the following table compiled by the company. At about the same time the government agreed to supply working capital by purchasing for £7,600 ($38,000) the original bench engine and leaving it with the company for development. The first payment under these

USE OF GOVERNMENT FUNDS BY POWER JETS, LIMITED

Year	*Revenue Utilized for Other than Capital Expense*	*Machinery*	*Buildings*	*Total*	*Total of Employees at End of Each Year*
1939	£ 12,000	...	...	£ 12,000	15
1940	72,000	£ 1,500	...	73,500	134
1941	160,000	21,000	£ 10,000	191,000	329
1942	270,000	93,000	160,000	523,000	562
1943	370,000	98,000	30,000	498,000	983
Total	£884,000	£213,500	£200,000	£1,297,500	

agreements was not made until February 1940, but the company was tided over the latter half of 1939 by the payment in August of £4,000 ($20,000) for running of the second reconstruction of the bench engine. In addition, £3,830 of B shares were issued privately after July 1, 1939, mostly to people who had already invested in the earlier days, and various pieces of work done before July 1939 were paid for by the government from time to time.

Even, so, the scale of activities increased so rapidly in 1940 that the company was unable to finance itself with normal progress payments. Since the absolute secrecy then imposed and the wartime restriction on new capital issues made it impossible to obtain additional working capital from private sources, the government agreed in January 1941 to put the work on a pay-as-you-go basis, and to pay up at once in full all expenses incurred since July 1, 1939, and not yet paid for by the government.

In return for this unusual support, the government asked for more extensive rights in any developments resulting from the work thus financed than it possessed in the results of the earlier work done largely at private expense. The company refused this request, and no agreement was reached, but the lack of one was not allowed to delay the progress of the work. In June 1941 L. L. Whyte resigned as managing director of the company and was replaced by Williams and Tinling, who remained in charge for the rest of the existence of Power Jets as a private company.

Early in 1944 the Ministry of Aircraft Production decided, for reasons discussed below (pp. 369 ff), that Power Jets should be

nationalized. It was announced that the facilities already built for Power Jets at a cost to the government of some £350,000 ($1,400,000)[16a] would be incorporated in a new national center for gas-turbine research, and that the government would under its war powers direct the technical staff of the company to work for this new research center. The government was willing to buy the company's assets, but the best offer that it would make was to pay £3.2s.6d. for each £1 B share, while the A shareholders would receive a total payment in the ratio of £49 to every £51 total paid to the B shares, as provided by the original Articles of Association.

The company's position was very weak, since its only certain assets were the commercial and foreign rights in patents acquired before the outbreak of war, its claims to any rights at all in the work done entirely at government expense since that time being very poor. Accordingly the company decided that the only course was to sell, rather than to go into cold storage until the end of the war and then be faced with the necessity of constructing new facilities and acquiring new personnel. The holders of the B shares received £67,875 ($272,000) in return for investments of £20,320 in cash and material services and £1,400 of management services. Whittle, as a service officer, had voluntarily surrendered to the government both his A shares and his reversionary rights in the patents. In return for the services represented by the A stock not in the hands of the government, i.e., for that of Williams and Tinling, the government paid net £27,948 12s. 10d. ($112,000), plus £18,838 each, or a total of £37,676 ($150,000), for their share of the reversionary rights. Whittle was given a tax-free interim grant of £10,000 ($40,000) at this time, and in 1948 a final grant of £90,000 ($360,000).

This arrangement, carried out in April 1944, meant that the total net purchase price, aside from the grants to Whittle, was just under £133,500 ($534,000). This was 6.4 times the cash and material services invested in the company, but the actual investors of cash and material services received only a little over £3 for each £1 invested, despite the fact that the uncertainty of success in the beginning had been so great that the

[16a] The pound was devalued in September 1939 from about $5 to about $4.

government had refused to invest anything whatever in the scheme.

The government's chief argument in driving so hard a bargain was that without the government financing after July 1, 1939, which amounted by January 1, 1944, to about £1,300,000, or over 60 times the private investment, the company could not possibly have succeeded in producing a usable product and must necessarily have been liquidated. It must be observed, however, that to all practical purposes the company was completely financed by private means until the middle of 1939 (cf. above, p. 345) despite the difficulties due to the secrecy imposed by the government after 1937, and that it is not at all improbable that in the state of development reached by 1939 it would have been possible, if the company had been free of government restrictions, to raise a very much greater amount of private capital.

British Gas Turbine Development: 1936-1945

The First Power Jets Engine (1936-1937)

The first engine designed by Whittle for Power Jets, the WU, was intended as a bench engine, not as a flight prototype; it was to produce a rather arbitrarily chosen figure of about 1,400 lb sea-level static thrust. The compressor chosen was of the double-sided centrifugal type, centrifugal because it was easier to develop and lighter than the axial, double-sided in order both to reduce the diameter and thus the drag of the engine and to reduce internal friction losses. The engine had a single combustion chamber.

Whittle expected that he could achieve extraordinary performance from his components, particularly the compressor, from which he expected a pressure ratio of 4:1 at an efficiency of 80%, when the best that had been achieved to date was a pressure ratio of about 2.5:1 with an efficiency of perhaps 70%. The only part of the design which really worried Whittle was the combustion system, which had to achieve an intensity of combustion far above that existing in any other device. To get help in the design of this component Whittle visited the British Industries Fair, and although most of the manufacturers of oil-

burning equipment turned down his request as impossible the job was undertaken by Laidlaw, Drew, and Company.

The order for the actual construction of the first engine, apart from the combustion system, was given to the British Thomson-Houston Company in June 1936, and the engine was ready for test in April 1937. The tests lasted until August of that year. They revealed that the performance of the compressor was far below expectations, both in the pressure ratio and in the efficiency, which was well under 70%, that the efficiency of the turbine was also below that assumed in the design, and that there were extremely serious problems with combustion. The mere fact that so unorthodox an engine actually ran on its first attempt was, however, extremely encouraging to all concerned.

The Beginning of Government Interest (1937)

All this work of Power Jets was done, as has been told, entirely at private expense and private risk, but it was promptly reported to the government. Meanwhile the RAE was studying gas turbines with renewed interest. Griffith, stimulated by a junior engineer of the RAE, Hayne Constant, had decided in 1936 to revive the turbine program, putting Constant in immediate charge. Early in 1937, at almost the same time that the first runs of Whittle's engines were being made, Constant submitted to the ARC a paper in which he argued, as Griffith had done in 1929, that a turboprop with an axial compressor could be lighter and smaller than existing reciprocating engines and just as efficient except for cruising at low altitudes. Finally, the British learned in 1936 that the Swiss firm of Brown-Boveri was building successful stationary gas turbines (see above, pp. 326-327), and Griffith was sent in 1937 to inspect and report on these engines.

In May 1937 the Engine Subcommittee of the ARC considered Constant's paper and Whittle's experimental results together, and made a report recommending government support for development of gas turbines. The Directorate of Scientific Research, influenced in part by this report but even more by the information that Brown-Boveri was offering for sale gas turbines with guaranteed performance, decided to support research on gas turbines as a matter of great scientific interest, even though it still believed that they would have no practical application for a long time to come. The RAE was authorized to begin design of a gas turbine for propeller drive[17], and sufficient funds were allocated to support the work at the rate which the RAE thought proper. This meant that the first RAE compressor was not actually built and on test until 1938, and the first bench engine not until October 1940, although funds for research became reasonably plentiful by the end of 1937.

Progress of the Whittle Engine (1937-1940)

Power Jets held the opposite view, that it had a practical engine which was only in need of development like any other engine, but, as we have seen, the Directorate of Scientific Research was not convinced, and the total actual payments of the Ministry to the company up to mid-1939 were only £3,240 ($16,000). Fortunately Power Jets was able to pay from private capital over 80% of the total cost of its work up to that date.

After testing of the first WU engine was finished in August 1937, BTH was given an order for its complete reconstruction. The principal changes were an improved diffuser for the compressor, a completely new combustion system, and alteration of the blading of the turbine to conform to the free-vortex principle.[18] The assumptions of the design were considerably altered, in particular the assumed efficiency of the compressor being lowered to 70%.

[17]In July 1936 the Ministry had already permitted the RAE to proceed with the design and construction of a small eight-stage axial compressor as a first step toward the ultimate development of a turbine engine.

[18]Whittle had from the beginning believed in the desirability of this type of blading, but he had assumed that its advantages were so obvious that it must be the general practice in the turbine industry, and hence had not bothered to give specific instructions to BTH, which had designed the first turbine according to the usual practice. The compressor and turbine theory developed by A. A. Griffith of the RAE had already led Griffith in 1926 to conclude that free-vortex blading was desirable, and such blading was used on the turbine-compressor unit designed by the RAE in 1926-1927 and tested in 1929 (cf. above, p. 332), but Griffith's work was not public and was unknown to Whittle. Whittle later obtained a patent on free-vortex blading.

The second version of the engine was tested in April and May 1938. Its most important result was perhaps the demonstration that the turbine as designed by Whittle had an efficiency of about 84%.[19] The performance of the compressor, although somewhat improved, was still far from satisfactory, but by far the most serious defect was still in the combustion system.

The second version of the engine failed after only four and a half hours running, and a third was designed. The major change here was in the combustion system: instead of a single chamber, 10 individual chambers were used for the same total flow, with the result that far more satisfactory tests of an individual chamber could be carried out without exceeding the capacity of the blowers available at the BTH plant. Testing of this third version of the engine began at the end of October 1938 and continued for two and a half years.

From 1938 to 1940 by far the greater part of the work centered on combustion.[20] Experiments were made on a combustion system which vaporized the fuel before injection, and it was with a system of this sort that most of the work was done until the middle of 1940, but it was never really satisfactory. Finally, in October 1940 a satisfactory atomizer burner and flame tube were designed by I. Lubbock of the Asiatic Petroleum Company, which had been supplying special fuels for the vaporizing burners, and were proved on the third version of the original bench engine. While this of course did not put an end to an urgent need for further combustion-system development, it did provide a working solution which made possible a great deal of progress in the development of the engine as a whole.

[19]This is the "total-to-total" efficiency, which is apparently the standard method of comparing turbines today. Whittle used total-to-static efficiency, on which basis this turbine attained at least 90%.

[20]One of the most serious difficulties in the way of any work on the combustion system independently of the engine as a whole was that while there was an adequate air supply as far as quantity was concerned, the pressure at which the air was supplied was little more than atmospheric, whereas in the engine the air entered at nearly four atmospheres of pressure. This difficulty was not eliminated until November 1940, when as will be seen the Ministry of Aircraft Production gave the company access to a blower at Dartford which had been built to supply air for a new tunnel under the Thames.

The Government Decision to Hasten Development; Origin of the W-1 and W-2 (1939-1940)

Until 1939 the Air Ministry continued to regard all work on gas turbines as long-range research rather than as development of practical engines, but this attitude began to change shortly after the middle of 1939, when the results of the tests of the second reconstruction of the original Power Jets bench engine were showing fairly clearly that the turbojet was a perfectly practical engine in principle. Since the utility of such an engine could only be shown by actual flights in an airframe specially designed for it, the government decided to proceed with the construction of a flight engine and of a special air-frame. In July 1939 Power Jets was promised a contract paying the full cost of the construction of an engine designed for actual flight, which became the W-1, and in August the Gloster Aircraft Company, Ltd, was promised a contract for the design and construction of two examples of an airframe, the E 28/39, intended primarily as experimental vehicles for flight-testing the engine, but with the design based as far as was practical on the requirements of an interceptor fighter. Late in 1939, moreover, even though the construction of the W-1 was just beginning, the government promised to pay for the development of a much more ambitious flight engine, the W-2.

Early in 1940 the Director General of Research and Development, Air Vice-Marshal Arthur W. Tedder, began to take a strong personal interest in the development of the Whittle engine after seeing a run of the bench engine in January. The engine had been considered so far as purely a research project which did not enter into the regular planning of RAF procurement. Ordinarily this status would have lasted at least until the engine had flown, demonstrated its merits, and led to a decision by regular engine manufacturers to develop their own versions of the engine, for which development contracts would have been given. Beginning in 1940, however, the Whittle engine was pushed somewhat ahead of this normal procedure.

The most striking evidence of this changed attitude was in the authorization given to Gloster very early in 1940 to proceed

with the design of an actual fighter based on the W-2 engine as soon as the design of the E 28/39 based on the W-1 was completed, and without waiting, as would have been normal, for the experimental airplane and engine to be flight tested. The resulting fighter, ultimately known as the Meteor, was intended for a speed of about 400 mph at sea level, or some 100 mph more than the conventional fighters currently in production. Gloster calculated that this could be obtained by an airplane with two engines mounted in the wings, the thrust promised by Power Jets for the W-2 being 1,600 lb. It is interesting to compare this specification with that of the German Messerschmitt Me 262, design of which had been begun toward the end of 1938, about a year and a half before. The Me 262 was intended to have a speed of 528 mph at sea level, this being believed to be the limit which could be attained without serious troubles from compressibility; and it was believed that this speed could be obtained with two wing-mounted axial-flow engines each developing 1,320 lb thrust. The drag of the Messerschmitt was considerably lower than that of the Meteor, enabling it to make a considerably higher speed with considerably lower thrust, but very little or none of this difference seems to have been due to the larger diameter of the centrifugal engines of the Meteor.[21] The major factors seem to have been the higher wing loading of the German airplane[22] and its generally cleaner design.

In the middle of 1940 the administration of aeronautical development in general and of turbine development in particular was reorganized. In May the materiel functions of the Air Ministry were taken away and put under a newly created Ministry of Aircraft Production (hereafter, MAP). In June a single Deputy Director of Scientific Research was given authority over all aspects of gas turbines; the man chosen to fill this post was H. Roxbee Cox, who had previously been Superin-

[21]The maximum nacelle diameter of the first production version of the Whittle engine, the Rolls Royce Welland, was 43 in., while that of the Jumo 004 of the Me 262 was only 34 in., so that the frontal area of the Welland nacelle was 1.6 times that of the 004 nacelle. In a study by the RAE the conclusion was reached, however, that the drag of the nacelles of the Meteor was actually slightly less than that of the Me 262's nacelles.

[22]55.0 lb/sq ft against 25.2 lb/sq ft for the Meteor.

tendent of Scientific Research in the RAE. It should be remarked, however, as illustrative of the official attitude toward turbines at this time, that they were not Cox's only concern; for the next two years he had a number of others as well.

The somewhat more favorable attitude toward the immediate practicality of turbine development which began to appear early in 1940 resulted in a somewhat more liberal government policy on research facilities, although it was still nothing which might be called generous. Whittle had requested in 1940 that the government should construct a test plant with facilities for the separate testing of compressors and turbines, the lack of which was seriously hindering the progress of the work. This request was turned down, but in November 1940 the government did make available to Power Jets a blower which had been built for a road tunnel, work on which had been suspended because of the war. This for the first time made possible the testing of combustion chambers at pressures corresponding to those prevailing in service.

The W-1 Engine and the First Flight of the E 28/39 (1939-1941)

As soon as the government decided in July 1939 to pay the cost of developing an engine suitable for flight, Whittle set out to design the W-1. It was intended to yield a little under 1,200 lb thrust, which was believed to be enough to produce a speed of 380 mph in the E 28/39 experimental airplane being built simultaneously. The aerodynamic design of the W-1 was very close to that of the contemporary third version of the WU bench engine. The one important step forward introduced at this point was the use of the new Brown-Firth alloy Rex 78 for turbine blades instead of the same company's Stayblade which had been and was still being used on the WU. Before the W-1 was completed the Lubbock burner passed its first tests on the WU bench engine and was immediately incorporated in the W-1.

The first W-1, called the W-1X, was put on test in December 1940, and the experience gained from its running was used to make further modifications in the final W-1, which was put on test in April 1941. On May 15, 1941, the W-1 was flown in the E 28/39; at that time it was cleared for flight at a thrust of

850 lb for an installed weight of 623 lb. Thrusts of a little over 1,000 lb had been obtained on the stand.[23] The two E 28/39 airplanes continued to be used through 1941 for testing of the W-1.

Acceleration of Turbojet Development after the Flight of the E 28/39; the RAE F-2 and the deHavilland Goblin

The first flights of the E 28/39 immediately created much greater enthusiasm for and confidence in turbojets in general and in the Whittle engine in particular. The plane attained 338 mph at 20,000 feet and 334 mph at 5,000 feet. The low-altitude speed was faster than that of the best conventional fighters currently in service, and although it was obvious that nothing was really proved by this comparison between service airplanes with full equipment and a purely experimental prototype, and although the airplane carried only 96 U.S. gallons of fuel and weighed only 3,690 lb when making these speeds, still it was natural that such performance from a completely novel type of engine should make a radical change in the attitude of nearly everyone concerned. Rolls Royce, which had been working on a gas turbine of its own since 1939 as a long-range project,[24] now began to assign really important resources to its development. In June 1941 Bristol undertook a survey of the entire field of gas turbines, and by the spring of 1942 had completed the design of what became the Theseus turboprop,

[23]It is interesting to compare this performance with that of the Heinkel He S 3b with which the first German turbojet-powered flight had been made on August 27, 1939 (Chapter XIV, below). The Heinkel engine developed 1,100 lb thrust against the 850 of the W-1, but it weighed 795 lb instead of 623, so that the specific weights were almost identical: 0.74 for the He S 3b and 0.73 for the W-1. The specific fuel consumption of the German engine was about 1.6, that of the W-1 a little under 1.4.

[24]Rolls Royce had become interested in gas turbines some time before 1939, but although it was convinced that the engine of the ultimate future would be of this type, it had no one on its staff available for studies of gas turbines until it hired A. A. Griffith from the RAE in 1939. Griffith then resumed studies of his counter-rotating counterflow engine. The intention then was to use it for a ducted fan, although the basic unit was capable of being used as the basis of either a turbojet or a turboprop just as well. The time from the middle of 1939, when Griffith came to Rolls Royce, to the beginning of 1941 had been used for preliminary calculations and a limited amount of combustion testing; the number of men assigned to the project had been extremely small. Beginning in the spring of 1941, however, the project was for a time assigned extremely high priority by the company, and the engine was run on compressed air in October 1941, although lack of a suitable combustion system prevented its running under its own power until 1943.

although nothing was done in the way of actual development because of the pressure of work on its regular engines.

Two turbojet developments other than Power Jets' began at this time to be pursued with all available resources. The first was an axial-flow turbojet which had been sketched by the RAE in December 1939 and was developed by Metropolitan Vickers after July 1940. In 1940 the RAE had finally put on test its first complete experimental unit of an axial propeller-driving gas turbine.[25] This unit, known as the B-10, was the high-pressure portion of a compound bench engine. At the same time a later design, for a noncompounded axial turboprop known as the D-11, was under construction by Metrovick, to which the designs had been delivered by the RAE in the latter part of 1939. The D-11, like the B-10, was a bench engine, not a flight prototype, and both these turboprops had always been regarded by the RAE as long-term research. Immediately upon the outbreak of war, the RAE had set about the design of an axial turbojet based on the D-11, originally intending to develop it in collaboration with Power Jets. In July 1940 actual detailed design and development of this engine had been entrusted to Metrovick after Power Jets had been obliged to withdraw because of the pressure of its work on its own engine. In the early part of 1941 the RAE and Metrovick were instructed to devote all available energies to the development of this F-2 jet engine, and the turboprops were completely abandoned.

A completely new line of turbojet development, accompanied by a new line of airframe development, was begun in 1941 by Major F. B. Halford and the deHavilland Aircraft Company, Ltd.[26] In January 1941, Tizard, who was then Technical Adviser to the Minister of Aircraft Production and the effective head of all aeronautical research and development, invited Halford and deHavilland to design a new jet-powered interceptor and a new engine. No specifications were set by the government for either the performance or the design of the new engine or airplane, but all the drawings and information con-

[25]The compressor had been tested in December 1939.

[26]Halford at first acted as an independent engineer in his dealings with the government on this engine, but he had for a long time been in charge of deHavilland's conventional engine development, and eventually his engine work was consolidated with that company's by the formation of the deHavilland Engine Company.

cerning the work already done by Power Jets and Gloster were made available. DeHavilland decided that a single-engine airplane was preferable for ease of production, and that for this reason an engine would be required with very considerably greater thrust than any being currently developed from the original Whittle design: the figure was eventually set at 3,000 lb. This was the origin of the DH-100 airplane, later known as the Vampire, and of the H-1 engine, which became the Goblin.[27] The basic design of the H-1 differed from that of the Whittle engine in two important respects: the use of a single-sided instead of a double-sided centrifugal compressor, and the use of straight-through instead of reverse-flow combustion. The basic decisions concerning the design of the Goblin were reached in April 1941, and design began immediately, soon supported by a government contract.

Plans for Quantity Production of the Whittle W-2B and the Meteor (1941)

One of the most important results of the successful flight of the W-1 Power Jets engine in the E 28/39 in May 1941 was that the government almost immediately began to lay definite plans for quantity production in the near future of the latest Power Jets design, the W-2B, and of the Meteor fighter in which it was to be used.

The government had first faced the problem of ultimate quantity production of the Whittle engine a year before, in 1940. The ideal solution would, of course, have been to give it to an experienced aircraft-engine firm, but this was completely out of the question in view of the absolute necessity for such firms to concentrate every effort on the engines being currently used in the war. The possibility of financing the construction of production facilities by Power Jets was considered but rejected. The government believed that Power Jets, being completely inexperienced in quantity production, would be less capable of organizing it than a firm with experience of that sort, while Power Jets, although it believed that it was perfectly capable of designing a product suitable for quantity production,

[27]E. S. Moult, "The Development of the Goblin Engine," *Journal of the Royal Aeronautical Society* 51, 1947, pp. 655-685.

had so small a staff that it did not care to try to organize the production itself. Early in 1940, the Rover Company, Ltd, a manufacturer of automobiles, was definitely committed to production of the Whittle engine.

Drawings of the W-2 (above, p. 352), which was then intended to be the prototype for the first production engine, were delivered to Rover in April 1940 with a government order for the production of a small number of experimental engines and for the beginning of production planning. Only a month later Whittle had convinced himself by further calculations that this design was extremely liable to complete failure, and had started to produce the revised design known as the W-2B. The revised design was not completed until early in 1941 and thus could profit from what had been learned from the running of the W-1X. Although no W-2B had yet been built when the E 28/39 flew in May 1941,[28] the success of the W-1 in that airplane was so encouraging that without waiting for a prototype to be tested the government almost immediately gave Rover an order for a small number of W-2B's with instructions to prepare for quantity production. By the fall of 1941 Rover was almost ready to begin quantity production of the W-2B, and in order to gain production experience the special factory set up for this purpose in Barnoldswick actually began to produce those parts of the W-2B of which the design was believed to be final. At about the same time Gloster reached the verge of quantity production of the Meteor airframe.

Difficulties with the Development of the W-2B (1941)

Not many months after the successful flight of the W-1, however, serious difficulties began to appear in the development of the W-2B. These difficulties were of two sorts: straight technical problems, and problems in the relationship between Power Jets, which was designing and developing the engine, and Rover, which was to produce it in quantity.

As for the technical situation, the first W-2B's, which were delivered in October 1941, surged badly at outputs over about

[28]An example of the original W-2 delivered by Rover in April 1941 had proved a complete failure, but since this had been discounted in advance it did little to detract from the great enthusiasm and confidence created by the flight of the W-1 in May.

1,000 lb thrust, a little over half their design thrust, and in addition suffered from frequent failure of the turbine blades, which were made of Rex 78.

The problem of the relations between Power Jets and Rover was at least equally serious. From the beginning of Rover's connection with the program in April 1940, the two firms had never had the same idea concerning the extent of Rover's authority to modify Power Jets' designs. Rover was given authority to make any mechanical changes which would facilitate production without affecting performance, but this apparently simple arrangement led to two sorts of difficulties: Power Jets alleged first, that most of Rover's changes did affect performance, and second, that they did not facilitate production.[29] There was also uncertainty as to whether Rover had the right to do genuine development of the engine. The earliest differences between the two firms were primarily over "productionization" changes, since Rover's staff was too small and too inexperienced to do extensive development.[30] Very early, however, Rover employed Lucas and Company, Ltd, not only to produce but to develop the combustion system, a move which was strongly criticized by Power Jets; and as Rover acquired additional staff it entered directly into design and development questions. Relations between Power Jets and Rover had accordingly become more and more strained as time went on.

The Gas Turbine Collaboration Committee

As a general measure to speed up gas turbine development in these difficult circumstances, the Ministry, at Cox's initiative, in October 1941 invited all the firms then in the field to form a Gas Turbine Collaboration Committee, of which the Admiralty, the RAE, and the National Physical Laboratory also

[29]Power Jets denied in general that its designs were in need of "productionizing" by anyone. Although the original staff of the company were without experience in quantity production, they had hired a production engineer to go over every part of the W-2B engine as it was designed, and had also consulted specialists in the manufacture of all parts such as castings which were to be made outside.

[30]Rover's automobile design and development had been done with a staff consisting approximately of a chief engineer (Maurice Wilks), an assistant chief engineer, a development engineer, a chief draftsman, and six draftsmen.

became members. Regular meetings were held frequently, beginning in November 1941, and under wartime conditions the engineers attending gave completely full and frank reports of the problems they had encountered and of the measures taken to solve them.

Assistance by Rolls Royce in the Development of the W-2B Compressor (1941-1942)

Rolls Royce, as has been told, was interested in gas turbines as a long-range project before the war, and its interest had been greatly increased by the flight of the E 28/39 in May 1941. At that time, however, the firm had been under the greatest pressure to improve the Merlin rapidly enough to meet the improvements in German aircraft as they appeared, and although Griffith and a small group had accelerated their work on the counterrotating, counterflow turboprop, Rolls Royce could scarcely divert any additional engineers to gas turbines. By the end of 1941, the worst of the crisis in the Merlin development had been surmounted, and Rolls Royce was able to devote a certain amount of time to the development of turbojets in addition to continuing work on the Griffith project.

The first phase of turbojet development in which Rolls Royce lent a hand was the development of the W-2B compressor, which as we have seen was giving very serious trouble with surging at the end of 1941. Whittle had made great contributions to compressor design on the basis of pure theory, but neither he nor anyone on the staff of Power Jets or Rover had had any previous experience with compressor development. Their work was additionally handicapped by the lack of any facilities whatever for testing a compressor otherwise than as a part of a complete engine. Rolls Royce, which had had great experience and great success in the development of compressors as superchargers for reciprocating engines (cf. above, Chap. VIII, pp. 225-231), was frequently consulted beginning late in 1941 by both Power Jets and Rover for advice on the compressor of the W-2B. At the suggestion of S. G. Hooker of Rolls Royce, the latter firm in December 1941 built a compressor test rig powered by a Rolls Royce Vulture engine which was continuously used from then on for testing

experimental compressors and parts thereof designed by Power Jets and Rover.

Rover Given Authority to Develop Its Own Engines: the W-2B/23 (1941-1942)

In order to hasten the development of the W-2B engine, which was being counted on as a power plant for the Meteor, the government decided in the fall of 1941 to deprive Power Jets of such authority as it had over the design of the production engine and limit that company to the conduct of research and development, the results of which were to be made available to all those interested in gas turbines. Hitherto all changes introduced by Rover had been subject to government approval, which was given only after consultation and argument with Power Jets; now Rover was given full authority to make such changes in the Power Jets designs as it believed necessary.

Rover's small development staff under Maurice Wilks at Clitheroe were obliged to spend by far the larger part of their time in attempts to eliminate the surging of the compressor of the W-2B/23, as their version of Whittle's original W-2B was known. They designed and tested a considerable number of modified impellers and diffusers during the latter part of 1941 and all of 1942, and eventually developed a 20-vane diffuser (first tested in January 1942) which was a considerable improvement over Whittle's 80-vane design. Even in the middle of 1942, however, a thrust of about 1,000 lb was all that could be got without surging. W-2B/23's were installed in a Meteor in July and used for taxiing trials, but the thrust was too low for take-off with runways of the length available, and the engines were still extremely unreliable.

In the first part of 1942, J. P. Herriot, who had come to Rover from the Department of Aeronautical Inspection in 1941 and was the only member of the Rover staff with experience in the development of high-power engines, had suggested that the exclusive concentration on compressor development was preventing the general mechanical development of the B/23 engine. As a result a second development group was set up under Herriot in August 1942 in the turbine production plant which Rover had established at Barnoldswick, and endurance running was begun at once. In July 1942 the American General Electric Company, which was developing engines derived from the W-2B, gave Rover several sets of turbine blades made of Hastelloy B. These blades were very distinctly superior to the blades of Rex 78, and for the first time permitted reliable turbine life of 25 hours and more. A little later the new British alloy Nimonic 80 became available, and by the end of 1942 was preferred by the British to Hastelloy B, even though the blades made of Nimonic 80 had to be machined all over and could not be simply forged to size like those of Hastelloy B. In November 1942 Rover succeeded in putting a B/23 through a 25-hour special-category test at 1,250 lb thrust, and flight tests in a Wellington flying test bed were carried out. Two months later a similar test was passed at 1,400 lb. The engine was flown for the first time under its own power, although at a lower rating, in an E 28/39 on March 1, 1943. After the turbine blades had been skewed 5°, a special-category test was completed later in March at 1,600 lb thrust, the original design rating of the engine.

As a result of the delays in the production of Whittle-type engines with adequate thrust, the first flights of a Meteor were made, not with the engines for which it was designed, but with the Halford Goblin. In September 1942 Goblins had already been cleared for flight at 2,000 lb thrust,[31] and since the Vampire airplane designed for them was not yet ready[32] it was decided to modify a Meteor to take two Goblins; the first flight of this special Meteor was made on March 3, 1943.

Power Jets and the W-2/500 (1942)

While Rover went ahead during the latter part of 1941 and all of 1942 in its attempt to get its B/23 version of the W-2B in a state where production could begin, Power Jets continued with its independent development of the same basic design. By December 1941 it had put on test the W-2B Mark II, which incorporated two principal changes: a new 10-vane diffuser, designed after consultation with Rolls Royce, which it was hoped would cure the troubles with surging, and a new turbine

[31]The design thrust of 3,000 lb was obtained briefly on the test bed in June 1942.
[32]The Vampire first flew in September 1943.

with fewer and broader blades, which it was hoped would cure the troubles with blade failures. This engine attained a thrust of 1,510 lb without surging, but the turbine blades were still excessively short-lived and unreliable.

In March 1942 Power Jets designed a new engine, the W-2/500, in which more extensive modifications were made, since Power Jets was no longer obliged to consider the possibility of putting into immediate production the changes which it introduced. This engine retained the new diffuser of the W-2B Mark II, and in addition introduced a new blower casing and a new turbine with blades which not only were still broader than those of the preceding design but were also longer, in order to increase the flow of air through the engine. On its first run, in September 1942, the W-2/500 reached and surpassed the original design thrust of the W-2B, giving 1,755 lb without surging. The broader blades of the W-2/500 brought a considerable improvement in reliability, although the best material and the best method of fabrication had not yet been combined.[33]

Gas Turbines Transferred from Research to Development (1942-1943)

The expansion of turbine development during 1941-1942 finally led the MAP to consider the administration of this work a full-time job. At the same time it was decided that it had now reached the stage where it should be formally transferred from the Research to the Development Directorate within the Ministry. Accordingly, toward the end of 1942 Cox was relieved of all his duties other than those connected with turbines, was given charge of both research and development in the field of turbines, and received the title of Deputy Director, Research and Development, Engines (T). A few months later, early in 1943, the importance of the turbine development was recog-

[33]The W-2/500 had two sets of blades, one machined of the old and unsatisfactory material Rex 78, and a second forged to size of the new material Nimonic 80, which appeared in July 1942. Forging to size was tried because the methods of machining in use up to this time were so slow that delays in obtaining new sets of blades had been a real hindrance in turbine development, but Nimonic 80 was not suited to this method of fabrication. Power Jets had hired T. A. Kestell in 1941 to produce a machine for the automatic machining of blades, but this machine did not run until 1943, and production was insufficient until a battery of four machines was created about the end of that year.

nized as being so great that Cox was given a rank parallel with that of the Director of Scientific Research and the Director of Technical Development, with the title of Director of Special Projects. Development of jet-propelled airframes as well as engines was then put under this single authority.

One important result of the changed attitude was that early in 1943 the government also began to make available for the first time really adequate test facilities: a steam turbine in a power plant at Northampton was lent for use in compressor testing by deHavilland, Metrovick, and Armstrong Siddeley, and a beginning was made of setting up special facilities for Power Jets at Whetstone designed specifically for the testing of turbine-engine components. The Whetstone rig, with 6,000 hp available, was first operated in April 1944.

Rover Replaced by Rolls Royce as the Producer of Whittle-Type Engines; The Welland (1943-1944)

In January 1942 Rolls Royce had begun to design and develop a turbojet of its own, on a subcontract from Power Jets awarded after discussions among that company and Rolls Royce and the Ministry. The engine, known as the WR-1, was designed in close collaboration between Rolls Royce and Power Jets.[34] It was intended primarily as a means whereby Rolls Royce could gain experience with the new type of engine, but it was designed as a flight prototype and the design specifications were chosen with that in mind. Its chief distinguishing characteristic from other turbojets of that time was its very low, 2.6:1 pressure ratio, which was chosen on the basis of rather pessimistic predictions of compressor efficiency. Two engines were built and tested before the end of 1942, but by this time great progress was being made with the 4:1 blower of the W-2B; the WR-1 was outmoded and was abandoned in favor of the direct assumption of responsibility by Rolls Royce for the W-2B production engine.

[34]Rolls Royce was not obliged to follow the Whittle design in any respect, but the WR-1 did resemble the Whittle engines in its leading features: use of a two-sided centrifugal compressor, reverse-flow combustion, and a single-stage axial turbine. In many details, however, the WR-1 differed from the W-2B, the most important being the aerodynamic design of the compressor, which was based entirely on Rolls Royce's own experience with supercharger development.

This decision that Rolls Royce should assume responsibility for and control of the development of the W-2B as a production engine was reached after discussions with Rover held late in 1942 with the approval of the government. Both Rover and the government then realized that Rover lacked sufficient background and technical staff for adequate development on its own, while the original idea of having development done by Power Jets with Rover doing nothing but production had had to be more or less modified from the very beginning and completely abandoned in the fall of 1941. Technical direction of the Rover staff and workshops began to pass to Rolls Royce toward the end of 1942, although formal responsibility for the organization was not assumed by the latter firm until April 1, 1943. The number of development engineers transferred to the turbine work by Rolls Royce was small, amounting to about a dozen; roughly another dozen engineers, or half the Rover staff, elected to remain with Rolls Royce. Rolls Royce immediately stopped almost all work on its other turbine projects, although the counterrotating counterflow engine was not completely dropped until October 1944.

Rolls Royce was unable to introduce into the W-2B/23 much of what had been learned during 1942 from its own experience with the WR-1 and from Power Jets' with the W-2/500, since production tooling was then fully set up and stocks of certain parts existed. In particular, the existence of already manufactured blower casings in quantity made it impossible to make the alterations in that component which as a result of experience with the W-2/500 seemed to be one of the most desirable changes, nor was it possible to change to a turbine wheel with fewer and stronger blades. Rolls Royce did, however, succeed in putting an end to the blade failures on the existing B/23 turbine by standardizing early in 1943 on the use of Nimonic 80 machined to size and then intensely developing the technique of production.

Rover, as has been told, had put the B/23 through a 25-hour test at the design rating of 1,600 lb thrust, in March 1943, and in April Rolls Royce put the Welland, as the engine then became known, through a full 100-hour test under type-test conditions at this same output. It was not until June 12, 1943, however, that the Meteor was actually flown with Wellands, which were cleared for 1,400 lb thrust in the first flight and 1,600 lb thereafter. In the early tests in the Meteor it was discovered that the engine surged at about 25,000 feet and above, and further development was done, although this fault was never completely eliminated in the Welland.

The Welland was put in production in October 1943 and deliveries began in May 1944; the production engines were rated at 1,600 lb thrust, weighed 850 lb, and had a specific fuel consumption of 1.12/hr. With this engine the production Meteor I had a speed at sea level of about 410 mph. The first production Meteors were delivered to the squadrons in July 1944, and were used against flying bombs beginning in August. For this use a thrust of 1,700 lb was obtained by the use of an exhaust nozzle of restricted size, which was satisfactory at the altitude of about 5,000 feet at which the bombs flew although it would have aggravated the difficulties with surging at high altitudes. Production Messerschmitt Me 262's were going into service at about this same time with a speed of 520 mph at sea level or 526 mph at 3,300 feet.

The Derwent I (1943-1944)

As early as the fall of 1941 Rover had begun to claim that the reverse-flow combustion system of the Power Jets W-2B engine was excessively hard to produce and warped excessively in service, and that it should be replaced by a straight-through system.[35] Power Jets had objected strongly to undertaking any major alteration in design at that time, since it was feared that this situation would delay the production of a serviceable engine, but as soon as Rover was authorized in the fall of 1941 to do development on its own, studies of a straight-through engine were begun. An experimental unit built from parts

[35]There was no established production technique at that time for sheet-metal combustion systems, but subsequent experience has shown that Power Jets was right in claiming that one could be developed just as well for the reverse-flow as for a straight-through system, and it seems to be true that, whatever difficulties Rover had with warpage in service, the systems built by Power Jets were perfectly satisfactory. Later on, however, Rolls Royce went over to straight-through combustion because of service difficulties, and American experience has shown that although the reverse-flow system is not unduly difficult to produce it is harder to assemble and more difficult to maintain in the field.

made for Rover's reverse-flow B/23 was run in March 1942, and the design of the new W-2B/26 was begun almost immediately thereafter.[36] The first B/26 was run in November 1942.

As soon as Rolls Royce took over Rover's work early in 1943 it decided that like Rover it much preferred the straight-through system because of the troubles with warping of the reverse-flow system in service. The reverse-flow Welland could not be simply dropped, since the straight-through engine would not fit in the Meteor I and II airframes which were then in production, but Rolls Royce limited its work on the Welland to what was strictly necessary to get a serviceable engine in production, and its forward-looking development was entirely centered on the straight-through type.

Even before Rolls Royce took formal control of the Rover development on April 1, 1943, Rover and Rolls Royce engineers had decided, on the basis of the performance of Merlin superchargers, that it ought to be possible to obtain 40% greater air flow and proportionally greater thrust from a compressor of the size of the one taken unchanged from the Welland for use in Rover's straight-through B/26. No change was made in the Welland, for the reason already given, but during 1943 the B/26 design was modified into the B/37, which was then developed into what became known as the Rolls Royce Derwent I. It was decided to hasten production of the new engine by using the blower casings already produced for the Welland, and for this reason the increase in thrust over the Welland was limited to 25%, to be achieved by the use of a new impeller adopted with modifications from one developed by Power Jets in 1943 for the W-2/500 (cf. below, p. 368), a new diffuser developed by Rolls Royce, and a scaled-up turbine.

The Derwent I was first tested in July 1943. It passed a 100-hour test under type-test conditions at 2,000 lb thrust in November 1943 and was flown at that thrust in March 1944. When production engines began coming off the line in November 1944, they were at first rated at only 1,800 lb, but a new

[36]Whittle had himself designed two straight-through engines, the W-2X and W-3Y, in the spring of 1940 but had preferred to concentrate Power Jets' resources on the development of the reverse-flow W-2B. Rover's design of the B/26 was made without any knowledge of either these Whittle designs or the Halford Goblin, which also had straight-through combustion.

diffuser developed during 1944 was soon substituted to raise the service rating to 2,000 lb for 960 lb weight. The efficiency of the engine was, however, somewhat lower than that of the Welland: the specific fuel consumption was 1.18/hr instead of 1.12. About 500 Derwent I's were produced altogether.

The Derwent I was used in the Meteor III, which had a speed of about 460 mph or 50 mph more than the Welland-powered Meteor I. Even this speed was seriously inferior to the 520 mph of the German Me 262,[37] although the thrust of the Jumo 004 engines of the Me 262 was slightly less than that of the Derwent I, and although their reliability, life and fuel consumption were vastly inferior.

The W-2/700 and the Derwent II and IV (1943-1944)

Beginning with 1943 the course of Power Jets' work began to diverge definitively from that of Rolls Royce. While Rolls Royce's work on the original reverse-flow engine was restricted to those modifications absolutely necessary in order to put the Welland into service, and its real forward-looking development had been turned to the straight-through Derwent, Power Jets continued to concentrate on development of the original type. After the W-2/500 of 1942, Power Jets built the W-2/700, first tested in July 1943, with further increases in air flow and corresponding increases in thrust produced by further lengthening of the turbine blades. The impeller was of a new design which had first been introduced on the W-2/500 in mid-1943. During the development of the W-2/700 another important change was made in the compressor, the introduction of a completely new diffuser and blower casing, first tested on the engine in January 1944. This new design, the so-called type-16 diffuser, had an abrupt 90° turn into the combustion chambers; there was not even a rudimentary volute, and all the diffusion was accomplished in straight-line passages located after the turns.

With the type-16 diffuser the W-2/700 compressor at last nearly achieved Whittle's original aim of 80% efficiency at

[37]Early in 1944 the deHavilland Vampire was flown at over 500 mph with a Goblin engine which had been cleared for experimental flight at 2,500 lb thrust, but the engine and airplane were both experimental and quite a way from quantity production.

4:1 pressure ratio: it had an efficiency of 78% to 82% over most of the range between ratios of 2.5 and 3.8:1. The new impeller proved, however, to have serious mechanical weakness. A W-2/500 exploded in flight in November 1943 because of a failure of this impeller, and in April 1944 the same thing happened to a W-2/700. American General Electric I-16 impellers with buttress ribs were then installed and solved the problem of mechanical strength, but some thrust was lost until Power Jets developed them to have the same aerodynamic performance as the original design.

During 1944, after the design of the Derwent I had been virtually fixed, Rolls Royce proceeded to design and develop improved models of the Derwent with considerably more freedom, incorporating the new type-16 blower casing developed by Power Jets on the W-2/700.[38] Design of the Derwent II was begun on January 14, 1944, and the engine was first run on June 29; about a half dozen of the engines were built. The Derwent III was designed for boundary-layer control and did not involve any changes in the basic engine design, but further improvements were made in the Derwent IV, which developed about 2,350 lb of thrust on its first tests, in February 1945.

Before the end of 1944, however, another line of development had shown Rolls Royce that by making a completely fresh start an engine of the same dimensions as the Derwents I through IV could be built with vastly more thrust than the most that could be hoped for by continued development of the original design, and all further development of the latter was dropped. The new line was that which had led to the Nene and which soon produced the Derwent V; the development of both these engines will be described below.

The Nationalization of Power Jets, Ltd; Gas Turbines Considered as Standard Service Types

Early in 1944 two major changes were made to put the development of aircraft gas turbines in the same status as that of conventional engines. The first of these changes was the abolition of the peculiar status of Power Jets, Ltd, which was a

[38]Rolls Royce somewhat improved the performance of the vaned right-angle turn by redesigning it to contract while turning.

private company but operated entirely on government funds, and which was neither a true engine-producing establishment nor yet a regular research establishment. The government decided to combine the government-owned portion (virtually all) of the facilities and personnel of the RAE in a national, government-owned and directed gas-turbine research center. In order, however, to prevent the loss of those members of the staff who would not have been willing to work as civil servants, the government did not organize the nationalized concern in the usual way, but created a new stock company, Power Jets (Research and Development), Ltd. All the shares of the new company were owned by the government, but the company's activities were free of the regulations applying to an ordinary government department.[39]

There seem to have been two principal reasons for making this move at this time. The first was the inability of the government to reach an agreement with the company concerning the extent of their respective rights in the results of the work done since 1940, when the government had undertaken to pay 100% of the company's expenses (cf. above, p. 345). The second was that the government had long had difficulty in getting Power Jets to do the sort of technical work that the government wanted and nothing else, and straight government operation cut a number of Gordian knots in personal relationships. The fundamental point at issue was the proper scope for Power Jets' activities. Especially after the great advances made as soon as Rolls Royce entered the field in full force, the government was convinced that Power Jets could never succeed in competing with the established engine firms in the development of service engines and wanted the company to restrict itself to general-purpose research, the results of which could be used by those firms. Power Jets, however, continued to be eager to develop its own engines, and its desire to develop its new W-2/500 and W-2/700 designs rather than concentrate on work which would make the W-2B serviceable with the least possible delay in production had led to a low point in cooperation between Power Jets and Rolls Royce in the latter half of 1943, even though personal relations between the two concerns remained excellent and were never marred by tension of the sort which arose between Power Jets and Rover. Cooperation with the firms did in fact improve after Power Jets was nationalized.

[39]When its scientific functions were taken from Power Jets (R & D), Ltd, in 1947 and given to the National Gas Turbine Research Establishment (a civil-service organization parallel to the RAE), most of the best scientific personnel did in fact leave.

The new publicly-owned corporation, Power Jets (Research and Development), Ltd, was set up in April 1944, and at the same time the organization of the Ministry of Aircraft Production was altered in the second of the two steps which put the development of turbines in the same status as that of conventional engines. The Directorate of Special Projects (cf. above, p. 364) was abolished, and the Director, H. Roxbee Cox, was made Chairman and Managing Director of the new Power Jets. Control of turbine development in the Ministry was combined with control of piston-engine development (the importance and burden of which were now rapidly decreasing) in the hands of the Director of Engine Development. This post had been held since the beginning of 1944 by a reserve officer, Air Commodore F. R. Banks, who had previously been Director General of Engine Production. Complete control of research as well as development was in his hands, and it was his responsibility to fit turbines into the general long-range program for the research, development, procurement, and service use of all types of aircraft engines. Later on his title was changed to Director of Engine Research and Development, but the combination of research and development had existed in fact ever since the beginning of 1944 or even earlier. This shift marks the final complete acceptance of gas turbines as normal service aircraft engines.

The Rolls Royce Nene and Derwent V (1944-1945)

On March 17, 1944, Rolls Royce started work on a completely new engine intended to produce about twice the power of the Derwent I. The origin of the engine was a government request for a turbojet to produce 4,200 lb of thrust. The government's request may have been influenced to some extent by the fact that General Electric in the United States already had the I-40 running on the bench in January 1944, and in February had obtained as much as 4,200 lb thrust, but the extent of this influence is uncertain.[39a]

The original MAP specification had not been set to accord with the requirements of any particular airframe, but by April 1944 it had been decided that Supermarine should receive an initiation into the problems of jet-airplane design and that its airplane should use the new Rolls Royce engine. In May Supermarine's Chief Designer discussed the proposed engine with Rolls Royce engineers, and stated that he would prefer an engine of only 3,300 lb thrust and correspondingly smaller size, since he already anticipated serious trouble with compressibility effects at the speeds attainable with 3,300 lb thrust. Rolls Royce immediately scaled down its project to make the RB-41, intended to have a very conservative rating of 3,400 lb thrust. It was expected that this thrust could be obtained with a jet-pipe temperature of only 1,004°F, instead of the 1,148° of the Welland or the 1,202° of the Derwent I, and that the low rating would also help to avoid surging. The company fully anticipated that if the jet-pipe temperature was allowed to run as high as in the Derwent I, the thrust would be at least 4,500 lb. The MAP accepted Rolls Royce's proposal to reduce the size of the engine, and development began of what became known as the Nene.

The Nene was the first Rolls Royce engine the design of which was not limited in any respect by the obligation to facilitate continued production by not departing too far from the original W-2B design. A great number of changes were made, on the basis both of Rolls Royce's own experience with the develop-

[39a]The first reports of the I-40 came to Britain about the beginning of 1944. In May 1944, after the British specification for a 4,200 lb engine had been issued and Rolls Royce had made a project design designated the RB-40, a British mission went to the United States and among other things inspected the I-40. During the absence of this mission the size of the Rolls Royce design was reduced to make the RB-41, which was the engine actually developed as the Nene (see text below). Although Rolls Royce had a full set of I-40 drawings at the time it was designing the Nene, the engines are quite different in detail, but it seems not unlikely that the mere existence of the large engine in the United States was at least one of the factors which decided the British government to request an engine of about the same size in March 1944. On the other hand, it should be remembered that after the goal of 1,600 lb had been set for the W-2 in 1939, the H-1 had been designed for 3,000 lb in 1941, and an increase to 4,200 lb in 1944 does not require any special explanation.

ment of the Welland and the Derwent I, and of Power Jets' work with the W-2/700. One of the chief features of the new engine was the use of a slightly modified version of the so-called type-16 blower casing which Power Jets had developed in its work on the W-2/700. The other important differences from the Welland and Derwent I designs were the use of an impeller diameter larger in proportion to the diameter of the engine, longer and stronger turbine blades, a lighter turbine disk, fewer and larger combustion chambers, and an improved intake to the impeller.

By 1944 the British government was well aware of the intensive development being given to turbojets in Germany, and the highest possible priority was assigned to Rolls Royce's Nene program, with the result that the engine was run in October 1944. The first run was disappointing, but after intake swirl vanes had been added the engine quickly fulfilled all the hopes which had been placed in it; the government had obliged Rolls Royce to rerate the engine at 4,500 lb thrust before it was built, and this figure was quickly attained.

Once the success of the Nene had been established, Rolls Royce proposed, at the suggestion of J. P. Herriot, to scale the engine down to a size which would fit in the Meteor since there was no airframe ready to make use of the Nene itself. On January 9, 1945, it was decided to abandon plans for the production of the Derwent IV and to put the Derwent V, as the scaled-down Nene was known, directly into production from the drawings. In June the first Derwent V on its first run did 100 hours nonstop at 2,600 lb thrust, and in September 1945 production began of Derwent V's with a service rating of 3,500 lb thrust for 1,260 lb weight and a specific fuel consumption of 1.00/hr.[40] Two special engines, with a thrust of over 4,000 lb, were installed in a Meteor IV airframe which was completely standard except for the removal of armaments, and with this plane a world's speed record of 606 mph was set on November 7, 1945. This was the first British jet-propelled fighter to equal the performance of the German Me 262, which it not only equaled but greatly surpassed.

[40]The compressor had an efficiency of 81.5%.

The deHavilland Goblin (1941-1945)

When high priority was given in 1941 to two turbojet developments other than Whittle's, that of the RAE and that of Halford-deHavilland, both were considered as contenders for the first use in the war, and by no means as mere research projects. In view of the greater difficulty of developing the axial type of compressor used by the RAE in its F-2 engine, and of the very late start of the Halford-deHavilland H-1 or Goblin, it is not surprising that neither was ready as soon as the Rolls Royce Welland and Derwent engines.

Drawings of the H-1 were issued to the shops in August 1941. The engine was put on test in April 1942, and was run up to full speed and for brief periods in June of that year. Since production of the Vampire fighter, for which the H-1 was designed, was delayed by the other work of deHavilland, it was decided to make the first flight tests of the engine in a specially modified Meteor. Gloster at this time did not want more than 2,000 lb thrust per engine, and by September 1942 an H-1 had passed the 25-hour special-category test and been cleared for flight at this figure. The first flight of the Meteor with any engines was that made on March 3, 1943, with two Goblins.

In September 1943 the engine was cleared for flight at 2,300 lb thrust, and the first flight of the Vampire was made in that month with an engine of this rating. Early in 1944 the engine was rated at 2,500 lb and flown in the XP-80 and in the second and third Vampires; these were the first British or American airplanes to exceed 500 mph in level flight. In January 1945 the Goblin I was type-tested at 2,700 lb, and with a new combustion chamber the Goblin II passed a type test at 3,000 lb thrust in July 1945, thus attaining the original design rating.

The RAE-Metrovick F-2 (1941-1945)

The F-2 axial turbojet designed by the RAE in 1939 and developed by the RAE and the Metropolitan Vickers company beginning in 1940 had a nine-stage compressor intended

to give a pressure ratio of 4:1, an annular combustion chamber, and a two-stage turbine. The design thrust was 2,400 lb. The compressor was ready for test in September 1941 and showed good efficiency, although the full 4:1 pressure ratio could not be reached.[41]

When the complete engine was run, however, beginning in December 1941, serious combustion trouble was encountered; 2,150 lb thrust at a specific fuel consumption of 1.26/hr was obtained for half an hour in May 1942, but in July it was decided to rebuild the engine with an improved combustion system and new bearings. In November 1942 the modified F-2 was cleared for flight at 1,800 lb thrust after passing a 25-hour special-category test. The fuel consumption at this stage was 1.14/hr, and the weight, 1,510 lb. In June 1943 an engine was flight-tested in the tail of a Lancaster bomber. In August, taxiing trials were made of a specially modified Meteor equipped with two F-2's, and after adjustments had been made to reduce the idling thrust the Meteor was flown on November 13, 1943.

Before the end of 1943 Metrovick decided to make a more thorough revision of the design and produced the F-2/4, with a 10-stage compressor and single-stage turbine, designed for 3,500 lb thrust. This engine reached its design thrust very soon after its first run in January 1945, and was giving 4,000 lb before the end of the year. In November 1945 it was cleared for flight at 3,250 lb take-off thrust.

The development of the annular combustion chamber for the F-2 engine gave a good deal of trouble because of the lack of adequate air supplies for rig testing, and the final development of the F-2 chamber had to be done almost entirely on actual engines. The result was that the development of the annular chamber was much slower than that of the can-type chambers used on all the other British engines.

Faced with one particular military situation, the British developed their turbojet engines to a very good degree of reliability and efficiency before releasing them for service. Only the Whittle-type centrifugal engine was ready for service before

[41] 90% up to 3.6:1; Constant, loc. cit., p. 421, fig. 17.

the end of the war, and even this engine gave little real service. The axial type of engine was still far from ready for service at the end of the war. The following chapter will show how the Germans, faced with a different military situation, made an extremely useful weapon out of the turbojet even though they had chosen the axial type, which was the more difficult to develop.