CHAPTER XIV

German Aircraft Gas Turbines

The Early Private Ventures: 1936-1939

Heinkel: The von Ohain He S-3

Shortly before 1935 a student of applied physics and aerodynamics at the University of Goettingen, Hans von Ohain, had become interested in the possibility of jet propulsion by the exhaust of a gas turbine, and had obtained one or more patents covering a turbojet engine with a centrifugal compressor. This engine was similar in general lines to the design shown in Frank Whittle's patent specification of 1930, but von Ohain was completely unaware of Whittle's patent, and his engine was different in almost all its details. Von Ohain used only a centrifugal compressor instead of the centrifugal stage followed by two axial stages called for in Whittle's patent, his combustion chamber (which was designed and patented by a fellow student, Max Hahn[1]) was outside rather than behind the compressor, and the turbine wheel was of the radial inflow rather than the axial type.

Von Ohain's professor, R. W. Pohl, was personally acquainted with Ernst Heinkel, the president of Ernst Heinkel A. G., which owned the airframe concern Ernst Heinkel Flugzeugwerke G.m.b.H. of Rostock. Even though Heinkel had previously done absolutely nothing with engine development and was completely without either adequate facilities or experienced personnel, Pohl in February 1936 persuaded him to hire von Ohain and put him in charge of the development of this engine. Heinkel seems to have been remarkably farsighted in regard to highspeed aircraft; it was he who in 1937 began as a private

[1]The frequently published statement that the entire engine was patented in the name of Hahn is incorrect.

venture the development of the first airframe for rocket propulsion, the He 176.

Many of Heinkel's engineers were extremely dubious of the possibility of a practical aircraft turbine, and the first engine constructed by von Ohain was intended not as a prototype of a flight engine but simply as a device for demonstrating the fundamental soundness of the principles. It was decided, therefore, to eliminate all the troubles anticipated with combustion of liquid fuel by burning hydrogen in an extremely simple combustion chamber. The demonstration engine, which was begun in April 1936, was built almost entirely of sheet metal with the facilities available in an ordinary airframe plant; a few heavier parts were bought outside. The entire job was carried out by von Ohain and two or three assistants in a little less than a year and at a cost of under 50,000 RM, or roughly $20,000 at the official rate of exchange.

When this demonstration engine was run in March 1937, it developed about 550 lb of thrust. Heinkel's doubts were put to rest, and development of a flight engine was undertaken at once. Both von Ohain and Heinkel always thought of the turbojet as an engine suitable only for an extremely fast fighter, and Heinkel now began the design of the He 178 fighter to be powered by one of the new engines. The first flight engine was designed to have between 1,760 and 1,980 lb thrust. Since serious trouble was anticipated with combustion, von Ohain visited the Leipzig fair to try to interest some builder of industrial oil burners in his problem, just as Whittle had done a year before at the British Industries Fair; but where Whittle was turned down by all but one, von Ohain met with complete failure. No one would believe that the required intensity of combustion was possible, and the problem had to be solved by Heinkel's own staff.

The first flight engine, which was tested in 1938, fell far short of the design thrust, partly because the diameter of the compressor had been made too small in the effort to hold down the diameter of the engine, partly because the combustion chamber was overly cramped for the same reason, and partly because of trouble with combustion itself. The engine was then redesigned, with changes particularly in the exit from the combustion

chamber, and the resulting engine, known as the He S-3b, was ready for test in 1939. It weighed 795 lb and developed about 1,100 lb static thrust; the specific fuel consumption was about 1.6 per hour. The engine was installed in the He 178, and the world's first turbojet-powered flight was made by this combination on August 27, 1939.

Up to this time the work had been financed completely from the resources of the Heinkel company. For competitive reasons the project had been kept completely secret from the beginning in 1936 until about 1938, when it was revealed to the powerplant development group in the Air Ministry. This knowledge, as we shall see, was one of the crucial factors in the Ministry's decision, reached early in 1939, to proceed with large-scale government-supported development of the new type of engine.

Junkers Airplane Company: the Mueller Engines

A second line of aircraft gas turbine development was begun independently by the Junkers Airplane Company (not the Junkers Engine Company)[2] at almost exactly the same time that the von Ohain development was begun by Heinkel. The Junkers development was due to Herbert Wagner, chief of airframe development, who is said to have been one of the most brilliant engineers in German aviation. His primary purpose seems to have been to make possible higher speeds than could be obtained with conventional engines. The directors of the Junkers company, especially the chairman, Heinrich Koppenberg, believed that the engine development being done by the Junkers Engine Company under the direction of Otto Mader was overconservative and much too slow and agreed to support the development of Wagner's turbine within the airframe company, even though that company was completely without experience in or facilities and staff for engine development. The project was kept completely secret from Mader for quite some time, even after the Junkers Airplane Company and the Junkers Engine Company were merged in 1936.

[2]Until July 15, 1936, the Junkers Flugzeugwerk A. G. was a completely separate company from the Junkers Motorenbau G.m.b.H.; even after their merger as the Junkers Flugzeug und Motorenwerke A. G. the airframe and engine divisions operated quite independently.

The first form of gas turbine suggested by Wagner seems to have been a turboprop. Early in 1936 Max Adolf Mueller of Wagner's staff was given the task of preparing the development of this engine. At some time before 1938 development facilities were set up under Mueller in a Junkers engine production factory at Magdeburg, completely independent of the regular Junkers engine-development establishment at Dessau. Mueller's staff consisted in 1938 of perhaps 30 designers and draftsmen and about half as many people in the experimental shop. The preliminary studies were soon extended to include turbojets[3] and both turbine and piston-driven ducted fans, and at some time before 1938 the main emphasis came to be placed on the turbojet rather than on the turboprop. The other engines were not laid aside, however, even for the time being, and Mueller's small design staff scattered its efforts among a large variety of projects.[4]

The turbojet designed by Mueller, later designated the 006, used an axial compressor, chosen mainly in order to have the straightest possible path for the air flowing through the engine, an annular combustion chamber, and a two-stage turbine. The engine had various ingenious and advanced features, such as variable turbine inlet nozzles, but it was chiefly distinguished from later German engines by its extremely small diameter (24.3 in.) and length, and its very low weight. These advantages were mainly due to the use of the stator of the compressor to produce half the pressure rise, so that a pressure ratio of about 3:1 was achieved with only five stages.[5] The engine was completely built and on test not later than the late fall of 1938, but probably not before the beginning of 1938. By the spring of 1939, if not sooner, the turboprop also was under construction, although it was not yet ready for test, and a wooden mock-

[3]The relation between the turbojet and the turboprop designed by Mueller at Magdeburg was not the one which later became usual, where a common basic engine was used for both and the propeller version was created simply by the addition of another stage or stages to the turbine or adding a second turbine to the engine. In this case the two engines were completely different designs.

[4]They did not even limit themselves to aircraft engines; one of the projects was a stationary turbine to use the by-product gases of chemical processes.

[5]This compressor was designed by Rudolph Friedrich, an aerodynamicist in the Junkers airframe division, and was apparently independent of the work of Betz and Encke, who designed the compressors of the two German engines ultimately put in production (cf. below, p. 431).

up had been built of a ducted fan driven by a 16-cylinder X-type two-stroke Diesel engine.

All this work was kept completely secret until about the middle of 1938, and was entirely financed during this period from the funds of the Junkers airframe division. When Wagner heard, however, about the middle of 1938 that certain officials in the Air Ministry were talking favorably of gas turbine development, he revealed the project to the Ministry, presumably with the intention of eventually obtaining a subsidy, although it is not certain that he formally requested one at this time. The response was the same as the response made to Heinkel's request, that development of an aircraft engine could be carried out satisfactorily only by an aircraft engine concern.

The work continued at the expense of the company for most of another year,[6] until about May 1939. Even then none of the Magdeburg engines was able to run under its own power, and only one engine, the turbojet, was even in a state to be tested.[7] Although there is no positive evidence, it seems not unlikely that the difficulties experienced with the turbojet were responsible for the fact that by that time the Magdeburg group had begun to put more emphasis on the Diesel-powered ducted fan, which still, however, existed only in the form of drawings and a wooden mockup.

The Origins of Government Support for Gas-Turbine Development to the End of 1939

Early Dependence on Private Initiative

The first financial support given by an agency of the German government to any form of jet propulsion began in 1931. Paul Schmidt, an independent engineer or inventor in Munich, had designed as a primary propulsion system for aircraft an engine of the type which is now called a pulsejet and which was

[6]Much later, after the development was ended, the government reimbursed the airframe division for its expenses.

[7]If air was supplied to the intake of this engine under pressure from an outside compressor the engine could be run up to about half speed (with enormous fuel consumption), but as soon as the intake air was fed at atmospheric pressure the speed gradually fell off and the engine had to be stopped.

used in the war as the power plant of the V-1 flying bomb.[8] Shortly after beginning his work he applied for support to Adolf Baeumker, the head of the Research Division of the Ministry of Communications (Verkehrsministerium), which was the predecessor of the Air Ministry. Schmidt's request was granted, and his work was continuously financed by the Research Division of first the Communications and then (from 1935) the Air Ministry until the end of the war.

The next reaction-propulsion project to be officially supported, and the first to be put in the status of a true development rather than a research project, was in the field of rockets. This project again was originally due to private initiative. In 1935 or 1936 Helmut Walther, an engineer employed by Army Ordnance to develop antiaircraft aiming devices, left the employ of the Army and set up his own shop for the development of ordnance rockets; shortly thereafter he obtained financial support for this development from all three of the armed services. In 1937, again at his own initiative, he began the development of rockets as aircraft power plants, and immediately or very shortly thereafter obtained the support of the Development Division of the Air Ministry. A special section known as "Special Propulsion Systems" (Sondertriebwerke), consisting at first of only two engineers, was set up within the Power Plant Group to administer the rocket program.[9]

In April 1938 Hans A. Mauch became the head of rocket development. Very shortly after taking this post Mauch learned that Walther had been working for about a year on the development of a thermal ramjet, financed like Paul Schmidt by the Research Division of the Ministry.[10] Not long thereafter Mauch learned, again quite by accident, that the Heinkel airplane company had been working at its own expense since

[8]The basic principle of this type of engine was used in the gas generator of the Karavodine turbine before 1910.

[9]The Ministry at this time was interested in rockets primarily for jet-assisted take-off of heavy aircraft. Official interest in rockets as primary power plants for interceptors began about two years later with the Messerschmitt 163 which was flown in 1940.

[10]Formally, Research and Development were closely connected in the Air Ministry, both being Divisions of the Technical Office. In fact, however, the connection of the Research Division with the Technical Office was loose. It was not until the middle of 1939 that Mauch heard of the Schmidt pulsejet.

1936 on the development of a turbojet. Mauch visited the Heinkel plant and was shown both the engine and the special airframe (He 178) which was being developed for it.[11] After learning from the engineers carrying out these projects something about the dependence of the efficiency of jet propulsion on airplane speed, Mauch discussed the subject of airplane speed with members of the Airframe Group of the Development Division, and got the impression that speeds were rapidly approaching the point where the efficiency of jet propulsion would become high enough to be tolerable. Mauch then let it be generally known that the government was seriously interested in jet propulsion. Hearing of this, Herbert Wagner of the Junkers airframe division came to Mauch in the late spring of 1938 to discuss the development which Mueller was carrying out for him, to learn what he could about other developments of the same sort, and to lay the groundwork for future government support.

Schelp's Research

In August 1938 Mauch met the man in charge of jet propulsion in the Research Division, a young engineer named Helmut Schelp. After theoretical training in engineering both in Germany and in the United States, Schelp had been one of a small group chosen in 1936 to follow a new advanced course in aeronautical engineering at the German Research Institute for Aeronautics (DVL) in Berlin.[12] Just about this time two new airplanes had appeared in Germany, the Heinkel 70 transport and the Messerschmitt 109 fighter, whose cleanness had produced a sudden great increase in speed. Until the appearance

[11]The chief of the Power Plant Group in the Development Division, Wolfram Eisenlohr, had been informed of the Heinkel development, and probably also of the pulsejet and ramjet projects of the Research Division, but he seems to have considered them as long-range projects which would be of use only far in the future if at all, and had attached no immediate importance to them.

[12]This course led to the newly invented title of Flugbaumeister. The course had been established to fill the need for engineers who would be neither highly specialized theorists nor practical handbook engineers, but men broadly trained in all aspects of aviation and aeronautical engineering, and who it was expected would soon make their way into responsible positions in industry or government. The course involved theoretical work both in courses and in independent research, practical experience in industry (Schelp had spent a half year in the automobile division of Daimler-Benz), and training as a pilot.

of these airplanes there had been little aerodynamic improvement since the First World War, but great increases in speed had been made by progressive increase of the power of the engine. Now it was natural to ask whether, given this large increase in speed due to the new type of airframe, another such series of increases with increasing power might be expected, or whether there was some natural limit to airspeed which it would be extremely difficult if not impossible to exceed. Schelp was given this problem to study in the DVL, and had decided that such a limit was set by compressibility; on the basis of existing wind-tunnel data he estimated the limiting speed to be about that equivalent to a Mach number of 0.82 (623 mph at sea level at 60° F).

Once this limit had been determined, it was natural to think of the means whereby it might be reached. Schelp believed that speeds nearly this high might conceivably be reached with a conventional engine and propeller, but that to do so in the face of the low efficiency then expected of airscrews above 500 mph would require enormous power,[13] and that a conventional engine developing such power would be so heavy that the airplane would have virtually no capacity for fuel or pay load. He was familiar with the early work on gas turbines, of which he found the work of Armengaud and Lemale, published before 1910, to be the most valuable[14] and he was also familiar with the French theoretical work of 1910-1920 on jet propulsion. Since he had concluded that a much lighter power plant was needed for high speed, and since he believed that airscrews would be very inefficient at these speeds, the logical solution

[13]The Germans believed generally at this time that the efficiency of airscrews was sure to fall off very rapidly after 500 mph. It was not until about 1939 that Guenther Bock of the DVL published research indicating that an efficiency of 75% might be maintained up to 560 mph. In the early stages of his thinking Schelp scarcely considered the reduction in power plant drag which could be achieved with a turbine in place of a conventional engine, since little could be known at this stage about the dimensions which a turbine would have. By 1942 the drag of the conventional engine seems to have replaced the inefficiency of the airscrew in first importance as an argument for gas turbines for high speeds.

[14]On the work of Armengaud and Lemale, cf. above, Chap. XII, p. 325. It was largely on the basis of this same work that Stern of the British Aeronautical Research Committee had in 1920 rejected the gas turbine as impractical for aircraft (cf. above, pp. 329-331).

seemed to be some form of jet propulsion with a nonreciprocating engine.[15]

After reaching this conclusion, Schelp went on to carry out at the DVL a systematic study of jet propulsion engines, and after considering all types including ramjets and pulsejets, decided that the turbine-driven engine was the best solution. While its fuel consumption was almost certain to be considerably higher than that of the conventional engine, its weight would be small enough to permit a useful range, whereas a conventional engine with enough power to attain these same speeds would be so heavy that it would have virtually no range at all.

Within the DVL there was little enthusiasm for research on turbine engines, but in August 1937 Schelp was sent as a temporary employee to the Research Division of the Air Ministry, where he was put in charge of the two developments of this sort then going on in that Division, the Walther ramjet and the Schmidt pulsejet. Even here, however, he was unable to obtain support for basic research on turbines. It is not clear why the Ministry was willing to support basic research on the pulse and ramjets but not on turbines; it has been suggested, but without any actual evidence, that political pressure had been necessary to obtain the support given to Schmidt and Walther.

When Mauch met Schelp in August 1938, Mauch was already very much interested in the general idea of jet propulsion as a result of seeing the Walther ramjet and the Heinkel turbojet and of hearing of the Junkers turbojet and the Schmidt pulsejet. This interest was very much increased when Schelp laid out before him the whole range of possibilities with their theoretical foundations. Mauch immediately invited Schelp to leave the Research Division and come as his assistant in the Development Division, and Schelp, convinced that he could accomplish little where he was, agreed. At about this same time Schelp's own belief in the immediate practicality of turbojets was greatly strengthened by the announcements made by the

[15]Piston-driven ducted fans were considered, but while they did eliminate the airscrew it seemed likely that they would be as heavy as the conventional power plant.

Aerodynamic Research Establishment (AVA) of Goettingen concerning its work on compressors. Here a group headed by Ludwig Prandtl, Albert Betz, and W. Encke had been working for some time on high-speed airfoils and cascade theory and on the use of these in the design of axial compressors. Schelp believed that a useful turbojet could not be made unless compressors could be built with efficiencies of over 70% at pressure ratios of at least 3:1. Since the very best German centrifugal compressors for superchargers barely achieved 70% at 2:1 in 1938, while the average was closer to 65%, Goettingen's announcement of well over 70% from axial compressors was of very considerable importance in convincing Schelp that a useful gas turbine could be built at this time.

The Engine Manufacturers Persuaded by the Government to Enter the New Field: 1938-1939

After discussing jet propulsion and gas turbines with Schelp in August 1938, Mauch was very much inclined to believe that the time was ripe for intensive development of one or more types of unorthodox engine. He believed, however, that even a completely new type of aircraft engine could be developed satisfactorily only by men with adequate experience in the development of conventional aircraft engines, and he refused to support the developments being carried out by Heinkel and the Junkers airframe division. In the fall of 1938 Mauch and Schelp visited all four of the major engine companies in an attempt to interest them in the new field. The whole range of possibilities was sketched out to each of the companies, and each was invited to make a detailed study of the type or types which seemed to it most promising.

The reaction of the engine companies to Mauch's proposals was far from enthusiastic, but it was not completely hostile. The reason for the lack of enthusiasm was essentially that the engineers in the engine industry foresaw much more clearly than less experienced people the practical diffculties which would be encountered, and that as often happens in an established industry they tended to let their fear of the certain difficulties involved in an innovation outweigh the great gains to be made if these difficulties could be overcome.

In Germany as elsewhere the chief difficulties foreseen were with the efficiency of the compressor and turbine and with materials for the turbine blades. The efficiency of centrifugal compressors for the superchargers of reciprocating engines was not over 70% at this time, and that of turbine wheels no higher, and the engineers of the engine companies believed that both these figures would have to be improved by at least 10% if the gas turbine was to have any real possibility of success. Owing to difficulties with the turbine blades the turbosupercharger for gasoline engines was far from an established success in Germany at this time. The DVL had been studying turbosuperchargers since about 1936, but only one private firm, BMW,[16] was developing them and that development was not yet complete. These difficulties with the turbine blades were even more serious in Germany than elsewhere, owing to the shortage of such materials as cobalt and nickel, and success could scarcely be hoped for without the development of hollow, internally cooled blades. Aside from any particular difficulties of the new engines, the engineers in the aircraft-engine industry had their hands more than full with their current task, the development of conventional engines: it was only within the last two or three years that the German aircraft-engine industry had grown to a size comparable with that of the industry in Britain, and the men in charge were extremely conscious that Germany by no means had engines comparable with those available in either Britain or the United States.

Otto Mader, the head of Junkers engine development, and Fritz Nallinger, the head of development at Daimler-Benz, were the most skeptical, maintaining that while some day the turbine might very possibly be of use in aircraft, the time was far from ripe. Nallinger refused completely to do anything in the new field. Mader did accept the proposed study contract; it is difficult to say whether he did so because he was genuinely interested or only because the government was his chief customer.[17] Helmut Sachse, the head of development in the BMW

[16]Junkers had developed a successful turbosupercharger for aircraft Diesel engines, but the exhaust temperature of a Diesel is considerably lower than that of either a reciprocating gasoline engine or a gas turbine engine.

[17]At some time before 1935, at a time when Hugo Junkers was still at the head of the Junkers engine company, studies had been made of free-piston gas turbines for

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Engine Company[17a] of Munich, was a little less skeptical and accepted a study contract willingly, probably because his firm was the one which had had experience with the development of turbosuperchargers for gasoline engines, and had developed a turbine wheel with hollow air-cooled blades which had run at inlet temperatures of 1,652° F if not more. The Bramo engine company of Berlin-Spandau[18] was the easiest of all to persuade. This was not, however, because B. W. Bruckmann, the engineering manager, and Hermann Oestrich, the head of research, were any less skeptical technically than the engineers of the other companies,[19] but because Bramo was in imminent danger of losing all its reciprocating-engine business by withdrawal of government support.[20]

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propeller drive, and Junkers himself had been convinced that engines of this general type would be used at some time in the future. Design studies had also been made before 1933 of turboprops of the modern type with constant-pressure combustion, but these had been rejected because of their high fuel consumption. The first thought in the Junkers company in the general field of jet propulsion was due to Anselm Franz, who before 1938 had considered the possibility of obtaining better performance at high speed and high altitude by developing a conventional engine to deliver more of its total power to the jet exhaust and less to the shaft.

[17a]BMW Flugmotorenbau G.m.b.H., a subsidiary of the Bayerische Motoren Werke A.G.

[18]This company was originally the aircraft-engine department of the old Siemens & Halske A. G., later Siemens Apparate & Maschinen G.m.b.H. In 1936 the aircraft-engine department was organized as a separate subsidiary, Brandenburgische Motorenwerke G.m.b.H., known as Bramo.

[19]Oestrich had already studied theoretically the possibility of jet propulsion in 1929 (results published in Deutsche Versuchsanstalt für Luftfahrt, Berlin-Adlershof, *Jahrbuch* 1931, pp. 316-338), but had concluded that the efficiency was far too low to have any practical ulitity at airspeeds then in prospect, and he still held this view in 1938.

[20]In midsummer 1938 Ernst Udet, the head of the Technical Office of the Air Ministry, which had authority over procurement as well as development, had decided that the number of types of both aircraft and engines and the number of companies developing them should be radically reduced. Until this time the Ministry had had exactly corresponding air-cooled radials developed by BMW and Bramo with the express purpose of promoting competition just as it had liquid-cooled engines developed competitively by Junkers and Daimler-Benz. Now Udet proposed to cut off all development funds from Bramo, and Bramo's current production of perhaps a hundred nine-cylinder engines a month was considered by the company far too small to support development at Bramo's own expense on a scale competitive with BMW, particularly since Siemens, the head of the parent corporation, had never backed his aircraft-engine company very strongly. The Ministry's action was postponed for a while after Bramo, hearing of Udet's decision, immediately rushed through a test of its 14-cylinder engine at 2,000 hp, which was considerably more than the corresponding BMW engine could develop at this time. There was great danger, however, that the postponement would be only temporary.

BMW's studies proceeded the most rapidly. Kurt Loehner, the head of its research department, was put in charge of the project. He decided that the best procedure was to acquire some basic experience in the new field as quickly as possible by building an engine using components of the type with which he was familiar, and very shortly after beginning his studies laid down a design for an engine with a two-stage centrifugal compressor and a single-stage axial turbine with hollow blades. Loehner calculated that because of the low efficiencies to be anticipated with a centrifugal compressor and single-stage turbine it would be necessary to have a combustion-chamber temperature of 1,652° F, but he was convinced that the development of hollow air-cooled blades for supercharger turbines was then at such a point that the design of a turbine for such an engine was certainly possible. While the detailed design of this engine and the construction and testing of the turbine wheel were proceeding, calculations were carried out to determine what would be the ideal form of engine to be built for actual service after the necessary experience and data had been acquired with this experimental model.[21]

Bramo had begun its studies with ducted fans driven by conventional gasoline engines, since Oestrich, who was in charge of the work, believed that the efficiency of a gas turbine would be too low to be practical.[22] Before the end of 1938, however,

[21]Loehner ultimately reached the conclusion that in order to have better efficiency a service engine should have an axial compressor and a two-stage turbine; difficulties experienced with his first experimental turbine convinced him that the combustion temperature should be reduced to between 1,292° F and 1,382° F.

[22]The case for the ducted fan seemed fairly good in 1938, since it was generally believed at this time in Germany that the efficiency of propellers would become intolerably low at speeds little over 500 mph, whereas Oestrich believed that if the inefficiency of the propeller could be eliminated, airframes and power plants might soon be capable of higher speeds. Before the end of 1938 Bramo had built and flown a sort of rudimentary ducted fan consisting of a many-bladed propeller within a sort of Townend Ring, powered by a 160-hp Bramo radial and installed on the Focke-Wulf "Stieglitz" light airplane.

The results of this experiment were encouraging enough for Bramo to go ahead with the design of a more elaborate ducted fan, based on the Bramo 1,200-hp, 14-cylinder radial engine, and with provision for afterburning. When a model of this power plant was tested in the Goettingen wind tunnel, however, the results were extremely poor. Before enough investigation had been made to discover the reasons for these results contrary to theory, Bock of the DVL had announced tests showing that airscrew efficiency could probably be made better than 75% up to 560 mph, and since this efficiency was better than that of Bramo's ducted fan under the most favorable assumptions the project was dropped early in 1939.

the program was broadened to include theoretical studies of gas turbines and actual experiments with combustion systems for them. These studies quickly led to two conclusions: (1) that a counterrotating engine would be the best from the point of view of weight and size, being as light as the centrifugal and even smaller in diameter than the axial,[23] but (2) that this type of engine would certainly be slow and difficult to develop, and that the company should first develop an ordinary axial engine, which it considered the second most advantageous form, in order to gain the required experience.

The actual design of the axial engine laid down by Bramo between December 1938 and April 1939 was considerably affected by the imminent merger of Bramo with BMW. As soon as Bruckmann had staved off the shutdown of Bramo in the summer of 1938 he had begun promoting a merger of his company with BMW, and although BMW did not actually acquire Bramo until the summer of 1939 an arrangement for pooling their development work had been reached in 1938. The most important immediate effect of this arrangement was that the design of the Bramo axial turbojet was modified to use the turbine wheel being developed by BMW in Munich.

Junkers had begun in August 1938 with a general survey of the field of turbine and jet engines. All Junkers' work in this field was in the charge of Anselm Franz, the head of the section of Mader's staff which dealt with the general aerodynamic and thermodynamic problems of the reciprocating engine, and who had had charge of the development of superchargers and of jet exhaust.[24] Following the general survey, Franz made a design study of a free-piston jet engine, since Mauch was anxious at this time to have studies made of all possible forms of jet engines, and Junkers already had experience with free-piston engines. This design study was completed early in 1939. It showed that a free-piston engine would be much too heavy,

[23]Another division of the Siemens corporation, of which Bramo was a part, had the German license for the Ljungstrom counterrotating steam turbine.

[24]Junkers had developed turbosuperchargers for use on Diesels but not for use on gasoline engines, partly because the lower exhaust temperature of the Diesel made the metallurgical difficulties less severe, but partly because Junkers had concluded that geared superchargers with jet exhaust were superior to the turbosupercharger for fighters at the altitudes (not over 20,000 feet) at which the Luftwaffe had declared that all fighting would take place.

and Franz soon came to the conclusion that a rotary engine would be the only type suitable for jet propulsion. By this time Mader was willing to begin development of a turbojet on a limited scale.

Government Initiative and Airframe Development

The earliest development in Germany of aircraft specifically designed for reaction propulsion, like the earliest development of the engines themselves, was due to private initiative and financed by private resources. By the latter half of 1938 there were already two such aircraft which had been under development for nearly two years as private ventures. These were both projects of the Heinkel company: the He 176 designed around a Walther rocket engine, and the He 178 for the von Ohain turbojet which was being developed by the Heinkel company itself.

In the fall of 1938, at about the same time that Mauch and Schelp were setting out to create for the first time an official program of jet engine development, Hans M. Antz joined the Airframe Development Group of the Ministry and set out to do the same thing for airframes. Antz was a young engineer who had followed the same special course leading to the title of Flugbaumeister which Schelp had followed, and the two men were well acquainted. Antz encountered a certain amount of opposition to his plans from the older men in the Ministry, but succeeded fairly quickly in overcoming it and in setting up his program of development.

The first step in the program was to interest Messerschmitt in the new type of engine. In the early fall of 1938 Antz requested Robert Lusser, the chief of development for Messerschmitt, to make a preliminary investigation. Meanwhile Antz and Schelp discussed the problem at length, and, largely on the basis of the difficulties which Heinkel anticipated with the large air intake and the long tailpipe of the single-engine He 178, decided that an airplane with two engines mounted in the wings would be superior. This decision led them to rule out the centrifugal compressor as excessively large in diameter,[25]

[25]See p. 353 and n. 21 of Chapter XIII for a discussion of the justification for this view. The British wing-mounted centrifugal engines, moreover, were of the

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and their preference for an axial engine was much increased by the fact that its efficiency was certainly great enough to make a successful engine, whereas that of the centrifugal would have to be considerably improved before it was successful (cf. above, pp. 386-387).

Accordingly when, a little later in the fall of 1938, Antz presented a formal order to Messerschmitt for a fighter for jet propulsion, he instructed the company to base the design on values of specific weight and specific dimensions which had been computed by Schelp on the basis of the AVA data on axial compressors. Antz set very few actual specifications in this order: the airplane was to have one-hour endurance at 528 mph, and a very small amount of armament was required.[26] Although, as has been said, Antz favored a two-engine design, this was neither specified nor even suggested.

On the basis of the weight and dimensions supplied by the Ministry, Messerschmitt's staff, under Woldemar Voigt as project engineer, made studies of a large number of possible arrangements, with one and two engines, and finally settled on a design with two wing-mounted engines.[27] After choosing the two-engine form, Messerschmitt calculated on the basis of the figures for specific weight and diameter supplied him by the Ministry that he would need engines delivering about 1,500 lb static thrust to attain the required speed of 528 mph, and this thrust, on the basis of the Ministry's specific dimensions, led to a diameter of 23.6 in.

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double-sided type, which has much smaller frontal area than the single-sided centrifugal; no attempt was made to develop a wing installation for the single-sided Halford engine. The double-sided compressor seems not even to have occurred to any of the Germans involved in jet-engine development, but it should be observed that by their own account all of them attached so much emphasis to straight-line air flow that even if it had they would still have preferred the axial compressor.

[26]This may be due directly or indirectly to Udet, who believed in the sacrifice of armament and armor to speed, and whose policy was seen in the early conventional German fighters like the Me 109E.

[27]There were three principal reasons for this decision: (1) the difficulties with the intake and exhaust of an engine in the fuselage; (2) the single-engine design was sensitive to a change in the center of gravity, and such a change would be caused by any difference in the engine finally supplied from the estimates on which the airframe design was based; and (3) Messerschmitt knew at this time that there would be various competing engines, and wanted to design so that any one could be used at the last minute.

The Me 262 was first flown, with a conventional engine and propeller, in 1940; the first flight with jet power (004A's) was made on July 18, 1942 (cf. below, p. 422).

In the late summer of 1939 another jet fighter development was begun with official support; this was the Heinkel He 280. The He 178 had by then been flown, and there had been so much trouble with the installation of the single engine that most of the Heinkel engineers were anxious to shift to a two-engine design. The designer of the He 280 was Robert Lusser, who had come to Heinkel very shortly after the design of the Me 262 was begun at Messerschmitt. Since the Me 262 had been designed very conservatively to make as sure as possible of success, the Ministry encouraged Heinkel to make a somewhat more advanced design, smaller and faster than the Me 262. To a considerable extent Heinkel based the design on the performance which he expected from the 006 turbojet which he was then developing (cf. below, pp. 396, 406).

The Formation of the General Program of Turbojet Development: 1939

By the spring of 1939 three of the four major engine companies (BMW, Bramo, and the Junkers engine division) were willing to begin the development of turbojet engines. Heinkel and the Junkers airframe division were continuing their developments at their own expense. Finally, Mauch now learned that still another gas turbine development was in progress. He first heard that Helmut Weinrich of Chemnitz was developing a gas turbine for the Navy. On investigation it appeared that Weinrich had in 1936 sent to the Air Ministry plans for a turboprop with a counterrotating compressor and turbine, but no attention had been paid to the proposal and it had been completely forgotten in the Ministry. After receiving no answer Weinrich had redesigned the engine as an auxiliary power plant for PT boats, and it was this which he was currently developing with Navy support. It was intended to produce about 100 hp, and an experimental engine was actually developing about 50 hp on test.

In view of all these results Mauch was convinced by the spring of 1939 that the time was ripe and had formed a plan for the general development of jet propulsion. His plan had two primary objectives. The first was to make sure that all types of engine would be adequately studied or developed until it became really clear which would be the best for service. The second was to have all the developments carried out by experienced manufacturers of aircraft engines. The Junkers engine division was to take over the airframe division's axial turbojet, turboprop, and piston-driven ducted fan. Since Daimler-Benz had done nothing on its own, that company was to take over the Heinkel centrifugal turbojet. BMW-Spandau, as the former Bramo plant was known after the purchase of Bramo by BMW about this time, was to develop the counterrotating turbojet, and Weinrich was to be persuaded to collaborate in this development rather than to try to develop an aircraft engine on his own. Although BMW's purchase of Bramo had been made with the intention of concentrating all jet-engine work in Spandau, the Munich group under Loehner were to continue the study of their centrifugal turbojet at least for the time being.[28]

Within the Ministry there was strong opposition to this plan from Mauch's superior, Wolfram Eisenlohr, the head of power plant development. Eisenlohr had been inclined to attach little importance to jet propulsion at the time Mauch came into the power plant group, in 1938, and since then not only technical but personal differences had been growing between the two men. Mauch, however, was personally acquainted with Ernst Udet, the head of the Technical Office of the Air Ministry and thus in charge of all research and development, and Udet personally gave Mauch authority to proceed with the plan.[29]

In the industry Mauch's plan met with only partial success. The development of the centrifugal study engine at BMW in

[28]The Schmidt pulsejet development was to be transferred to the small Argus Motoren Gesellschaft.

[29]Ernst Udet, a fighter pilot of the First World War, was made Director of the Technical Office of the Air Ministry in 1936; from the beginning of 1939 until his death in 1941 he was Director General of Equipment. Udet tended in general to favor radical developments. It is worth remarking that the receptive attitude toward turbojets of Udet, a tactical officer with no engineering background whatever, corresponds exactly to the attitude of General H. H. Arnold in the United States, who was extremely anxious to promote the development of turbines in that country as soon as he learned early in 1941 that they were being developed in England.

Munich went ahead with no delays and no administrative problems. Bramo was considerably impressed by the fact that Weinrich had a counterrotating engine actually running, and was quite willing to give him a consulting contract. Although Weinrich at first wished to develop an aircraft engine himself, he finally agreed to the arrangement with Bramo when Mauch refused to give any funds for an independent development. A development contract was given to Bramo for the counterrotating engine ultimately designated 002. At the same time the company was authorized to develop a straight axial engine for general research; this engine ultimately became the 003.

Difficulties arose, however, in the parts of Mauch's plan which called for transferring the Heinkel development to Daimler-Benz and the Junkers airframe division developments to the engine division. Mauch succeeded in persuading Daimler-Benz to agree to take over the Heinkel development, but with Heinkel he failed completely. Heinkel was anxious to become a producer of both engines and airframes, like Junkers. He believed that his three-year head start in turbojets at last gave him an opportunity to achieve this goal,[30] and insisted on going ahead on his own, even though Mauch absolutely refused any government support. In fact, Heinkel not only continued development of the von Ohain engine on this basis, but a month or two later undertook several new jet developments, as we shall see, despite the fact that his facilities and, much more important, his staff were at that time quite inadequate for a single full-scale engine development. They had been enlarged as soon as it was decided in 1937 to proceed with a flight engine, but it was extremely difficult at that time in Germany to obtain either qualified men or suitable machinery, and at the beginning of 1939 Heinkel had only about 30 engineers and designers, almost all with little experience, to assign to the turbojet development.

Wagner of the Junkers airframe division raised little objection to handing over the Magdeburg developments to the

[30]This desire of Heinkel's was shared by Messerschmitt. In 1940 or 1941, when Schelp had almost succeeded in arranging the sale of Hirth Motoren G. m.b.H. to Heinkel in order to provide him with facilities for jet development, Messerschmitt got wind of the deal and by complaining vehemently to Udet forced it to be postponed for several months (cf. below, p. 409).

engine division, perhaps because he was already about to leave Junkers for reasons unconnected with the engine project, and Mader of the engine division agreed to look over the Magdeburg engines. Wagner's successor was unwilling to continue to spend airframe-division money on an engine development, and since Mauch continued to refuse to support an engine development by an airframe manufacturer, Mueller was forced to enter into the negotiations with Mader which Mauch desired. Mader visited Magdeburg about April 1939, and immediately concluded that the development as administered by Mueller was dispersing its efforts far too widely. He offered nevertheless to take over the sponsorship of Mueller and his staff, provided that they would concentrate on some one project, preferably the turbojet. Mueller, however, did not at all like the idea of giving up complete control, and while the talks with Mader continued he entered into negotiations with Heinkel. Heinkel offered him complete authority to continue as he liked, and agreed to take over all his staff at increased salaries.[31] Before the end of May Mueller and all but two or three of his staff resigned from Junkers to go with Heinkel. At the request of Koppenberg, the chairman of Junkers, this change of employment was not permitted by the Arbeitsamt for about a month, but the ultimate result was that while only about half the staff actually went to Heinkel, most of the others took employment elsewhere rather than with the Junkers engine division.

Meanwhile, before Mueller had reached a definite agreement with Heinkel, Franz had come to Magdeburg about May 1939 to inspect the turbojet which Mader was thinking of sponsoring. After a few tests he concluded that this engine, which still could not run under its own power, was not worth further development. Mauch at first strongly resisted the idea of abandoning the results of all Mueller's work, but after Heinkel took it over, a contract was given to the Junkers engine division in the summer of 1939 for a new axial-flow turbojet, ultimately known as the Junkers 004.

[31]Heinkel was already anticipating trouble with the installation of the centrifugal von Ohain engine in the fuselage of the He 178, and was very much interested in the possibility of installing two of the very small diameter Mueller turbojets in the wings of a new airplane.

Late in 1939 Heinkel finally secured government support for all his developments. Mauch had continued to refuse support for an engine development by an airframe manufacturer as long as he remained in charge. After Mauch left the Ministry in the fall of 1939 and was replaced by a completely unqualified man, Ernst Beck, Schelp acquired much more authority de facto if not de jure. Schelp, unlike Mauch, favored in principle the combination of airframe and engine development in a single firm, and believed that the previous separation of the two fields was at least in part responsible for the late date at which jet-engine development was begun, but he disapproved of Heinkel's attempt to develop a whole variety of engines instead of concentrating on one and for this reason continued Mauch's policy of refusing support. Heinkel, however, was personally acquainted with Udet and brought pressure to bear on him directly; and Schelp did not have Mauch's personal influence on Udet. The result was that Udet ordered Schelp to give Heinkel a contract covering all the developments which Heinkel had chosen to undertake.

After BMW and Junkers had shown that they were certainly going ahead with jet development, Daimler-Benz was persuaded to enter the field with studies of its own. The government pointed out that there was little use entering the field of straight turbojets, owing to the head start of Heinkel, Junkers, and BMW, and the company decided at the government's suggestion to study a turbine-driven ducted fan. The work was put in charge of Karl Leist, who had come to the company early in 1939 to continue the work on turbosuperchargers which he had begun in the DVL.

By the end of 1939 the jet engine development program was in definitive form. Junkers was working on a very conservatively designed axial turbojet, the 004. Bramo was working for the present primarily on a somewhat more advanced axial turbojet, the 003, which had been originally designed merely as a part of the development program of the counterrotating 002 but which had by now taken on independent existence. Heinkel was developing two turbojets, a new centrifugal engine, the 001, designed by von Ohain on the basis of the He S-3 but with smaller diameter in order to be suitable for wing installation, and the extremely advanced axial turbojet which Mueller had brought from Magdeburg, and which was now designated the 006.[32] Finally, Daimler-Benz was working, although very slowly, on the 007 turbine-driven ducted fan, another engine of rather advanced design, with a counterrotating axial compressor.[33]

Development During the War

Air Ministry Policy on Turbojet Development During the War

Throughout the development of gas turbines and jet engines in Germany there was a serious shortage of trained personnel. This was bound to be true to some extent because of the late date at which the German aircraft-engine industry had been created, and it was bound to become more true during the war, when quantity procurement became the most immediately pressing problem. The shortage was exceptionally severe for about a year after the middle of 1940, when orders were given by the General Staff that development was not to interfere in any way with production, since the war would be short and what was needed was immediate production of existing models. The resources being used for development of gas turbines were so small at this time that there was no actual reduction of development personnel as there was in other fields, but the order of 1940 did mean that there was a less rapid rate of growth than there would have been otherwise.

The allocation of manpower among the various types of engines being developed was within the power of Eisenlohr, the head of Power Plant Development in the Ministry. Although hostile to the new engines at first, Eisenlohr had by 1941 become convinced that the development was a sound one and did all that he reasonably could to give it adequate resources within the limits set from above. In 1941 Schelp succeeded in getting one fairly large addition of manpower to his field when

[32]Work on Mueller's ducted fan driven by a Diesel engine was also continuing, but at lower priority.

[33]Schmidt had refused to relinquish his pulsejet development, and the Research Division of the Ministry continued to support him, but an independent development had been started in the Argus company by the Development Division, and it was Argus which ultimately produced the engine of the V-1 buzz-bombs.

he was permitted to arrange the purchase of Hirth Motors by Heinkel, but in general he was forced to resort to a sort of black market for manpower, taking men direct from the universities and in other ways which circumvented the usual procedures of the Arbeitsamt.

By 1942 the advocates of gas turbines were faced with a still more difficult problem in the attitude of the top officials of the Ministry. In this year it began to seem that the first models of turbojet engines and the Me 262 airplane would soon be ready for small-scale production, and this of course would require the direct diversion of appreciable quantities of manpower and facilities from the production of existing engines. Since the suicide of Udet on November 17, 1941, such decisions were made directly by Col.-General Erhard Milch, the Deputy of the Air Minister, Hermann Goering, and Milch preferred large output figures which would make a good impression on Hitler to the improvement even of existing types of aircraft,[34] let alone the substitution of completely new types.

Because Milch and others like him were completely unaffected by technical arguments offered by engineers, advocates of gas turbines resorted to trying to influence them through the opinions of nontechnical flying officers of high rank. Virtually all the officers with actual experience at the front realized more and more strongly after 1941 that German equipment was seriously inferior to that of the Allies, and that something better was desperately needed. One of the events most important in ultimately changing the attitude of top officials in the Ministry, although by no means the only one, was the flight of Major-General Adolf Galland in an Me 262 in May 1943. As soon as he landed Galland declared with great emphasis that the airplane should be put in production at once, and within two days he had organized a conference at the Ministry at which it was decided to shift almost all Messerschmitt production from the 109 to the 262. This decision, however, had little immediate effect; the Me 262 was ordered into production on June 5, 1943, but airplanes did not begin to come off the lines

[34]Thus, according to Knemeyer (see text below) the fighter produced in largest quantity even at the end of the war was the Me 109E, which had already been superseded by better models in 1941.

until nearly a year later. Galland, who was no engineer, did not realize the very great practical problems which such a change involved, and the conservatives like Milch did little or nothing to facilitate it.

Action finally came when Colonel Siegfried Knemeyer, one of those who had had experience at the front and who realized the desperate need for better materiel, became Goering's technical adviser and then, in September 1943, became head of the Development Division of the Air Ministry. The situation was then so critical that resistance was overcome. It was becoming clear that even on the most optimistic estimates the Germans could not equal the Allies in either quantity or quality of conventional aircraft, and that the only hope lay in radical change.[35] Late in 1943 the decision was reached to devote the largest part of available resources to the production of jet fighters.[36]

Just after production had begun, however, in the spring of 1944, Hitler himself delayed it another six months by ordering the Me 262 to be used not as a fighter but as a bomber carrying a single 1,100-lb bomb to England.[37] Extensive design studies were necessary to find a way of altering the airframe to carry the bomb, and after an arrangement was chosen, the making of the alterations interfered seriously with production. Eventually Hitler changed his mind and the Me 262 was produced as a fighter, but as a result of this delay the airplane did not

[35]It was not true that in the long run engine production would have been decreased by a change from conventional to turbojet engines. Where conventional engines required 3,000 to 5,000 man-hours to produce, the 004 turbojet required only 700, and the 003 only 500. Although the life of these engines was only a very small fraction of the normal life of a conventional engine, it was a very large fraction of the average life of German conventional engines in fighters on combat missions.

[36]Shortage of high-octane fuel was perhaps a minor consideration in this decision, but actually it was more of a justification advanced by people who really desired jet propulsion for other reasons. It was only late in 1943 that BMW began the development of burners for J-2 fuel (similar to Diesel oil) instead of gasoline, and although Junkers had done this from the beginning, it was for reasons of safety and economy rather than because of any shortage actual or anticipated.

[37]The order to change the Me 262 into a bomber was due to Hitler himself; no one in the Air Ministry or elsewhere could understand it, and while the development of the bomber version was going on Goering continued to try out in actual service as many fighters as he could obtain. In 1942 the Germans had begun the equally absurd development of the Me 264, intended to bomb New York with a bomb load of 4,000 lb.

appear in quantity until the fall of 1944 although large-scale production could have begun in March.

The Evolution of the Technical Program

From 1939 until 1942 German development of jet and turbine engines continued essentially along the technical lines established at the end of 1939, and the changes which were made were rather in the direction of eliminating the less promising projects than in that of beginning new ones.

The ducted fans driven by reciprocating engines had been abandoned by 1942. Already by 1939 or 1940 at the latest it had been decided that the efficiency of propellers would be good enough up to 560 mph to make them superior to a ducted fan driven by an ordinary gasoline engine. During the next year or two there was still some interest in ducted fans driven by special two-stroke engines with provisions for combining the thrust of the fan with thrust derived from the exhaust of the engine and cooling heat. A certain amount of development was done on the Mueller-Heinkel engine of this sort (below, p. 407), and studies were made by BMW-Spandau. Before the end of 1941, however, BMW had stopped its studies in order to devote its entire resources to gas turbines, and early in 1942 Heinkel abandoned its ducted-fan project, which had always had a relatively low priority.

By the end of 1941 the centrifugal turbojet was also dead. Work on the BMW-Munich two-stage centrifugal engine had been stopped at the outbreak of war in September 1939 by the common decision of the Ministry and the company, in order to devote all the resources of the original BMW company to the development of conventional engines and to collaboration in the development of the BMW-Spandau turbines. This Loehner engine had never been considered as a prototype of a service engine in any case, but only as a piece of experimental apparatus; certain of its features, particularly the design of the turbine wheel, had been incorporated in the 003 axial turbojet. Intensive development of the von Ohain 001 centrifugal turbojet had been continued by Heinkel until the latter part of 1941, but by that time this engine was clearly behind the 003 and 004 axial engines, and Heinkel was about ready to drop it. The work done on it after this time was rather an attempt to learn what could be learned from the work already done than to develop a service engine.

Finally, the plans for counterrotating engines were very nearly dead by the beginning of 1942. BMW-Spandau had originally had the 002 counterrotating turbojet as its major project, the axial 003 being only a study engine for use in acquiring basic data which would be useful in the development of the 002. By 1941 or early 1942 at the latest, however, BMW had decided that the counterrotating engine was years in the future at best, while the plain axial engine had encountered so many difficulties that it was necessary to devote all the available resources to its development; the 002 was accordingly abandoned. The Daimler-Benz 007 ducted fan driven by a counterrotating turbine was still technically alive in 1942, but in actual fact this company did not even yet believe in the future of gas turbines and had assigned a minimum of personnel and facilities to the 007; it would appear that even this minimum was assigned more to keep the Ministry happy than to make a real effort at developing an engine.[38]

The only really active projects remaining by the beginning of 1942 were three axial turbojets. The first was the very conservatively engineered Junkers 004, which delivered a thrust of 2,200 lb on the stand in January 1942 and was flown under its own power in July. The second was the BMW 003, which was intended to be smaller and lighter for the same thrust as the 004, but which was not able to deliver more than about half its design thrust at the beginning of 1942. The third was the Heinkel 006, designed by Mueller, an extremely advanced design which was first able to run under its own power in April or May 1942.

In the fall of 1941 Schelp had replaced Beck as head of the section of the Air Ministry which directed all development of jet and rocket engines. By this time, if not before, Schelp had decided that none of the turbojets laid down in 1939 was advanced enough in its basic design to be worth development to

[38]Daimler-Benz alleged that its lack of activity in this field was due to a lack of manpower, but in reality this company had more of both manpower and facilities than any other German company.

its maximum performance and reliability for use in large-scale service. Instead, he believed that one or two of these engines should be put in limited production as soon as possible and used in limited service as a means of acquiring both technical and tactical information on the new type of engine and airplane. The information thus gained was to be used in developing completely new basic designs, and it was engines developed from these new designs which were to become the first real service types.[39] Schelp was always very much inclined to underestimate the practical difficulties which might be encountered in a development and the time it would take, and before the end of 1941 he was convinced that the Junkers 004 was virtually ready for limited production and service and that the BMW 003 would be ready very shortly thereafter.

Thus in Schelp's opinion the most pressing problem at the end of 1941 was not the development of a flyable turbojet but the design and development of an engine suitable to become an ultimate service type. Junkers and BMW were not yet free to undertake this task, but Schelp believed that Heinkel was; in his opinion the centrifugal Heinkel 001 had already been shown to be inferior to the 004 and 003, so that there was no use at all in continuing its development, while the axial 006, which had not yet run under its own power, could not be ready in time to be of use in the stage of preliminary, experimental service, which Schelp believed would last only a rather short time. With these arguments he persuaded Heinkel to stop trying to produce an engine for immediate use, and to try instead to produce the first of the true service engines. This was the origin of the 011, intended to become the ultimate replacement for the 004 and 003 as the power plant of twin-engine fighters;

[39]This was part of a detailed, long-range plan for the development of gas turbines and jet engines which Schelp had been elaborating since 1939 and which reached its final form in 1942. There is no need to set forth the entire plan, which not only did not have but could not have had any real effect on the course of development before the end of the war; it called for four successive four-year development periods, the first of which was deemed to have ended in 1942 with the production of the first engine capable of flight at a speed nearly equal to what Schelp had calculated as the limit set by compressibility (Mach 0.82). Probably the only real effect of any part of the plan was the decision to drop the very promising Heinkel 006 in favor of the more advanced 011 (below, p. 408) and the 011 was not in production at the end of the war.

the preliminary design was completed and development was begun in September 1942.

Schelp also believed that the time was at hand to begin development of larger turbojets and of turboprops, in order to bring larger aircraft than fighters up to the critical limit on speed set by compressibility, or at least to improve their speed considerably. As soon as the 004 and 003 were in production, Junkers and BMW were to undertake the intensive development of such engines, and planning for them was to begin at once. The largest of these engines were to be an 028 turboprop and a corresponding 018 turbojet[40] to be developed by BMW. Preliminary studies of a large turboprop had already been begun by BMW in 1940, and early in 1941 the company had definitely agreed with the Ministry to develop such an engine. In July 1942 the 028, as it was ultimately known, was aimed at a total of 8,000 equivalent hp at 500 mph at 23,600 feet, to meet the specifications set by Focke-Wulf for a two-engine bomber to carry two tons of bombs over a range of 2,500 miles. About the middle of 1942 the company also agreed to develop an 018 turbojet version with 6,600 lb thrust intended to bring short-range bombers up to the critical speed of 0.82 Mach.[41] Junkers was to develop an 012 turbojet and corresponding 022 turboprop intermediate in size between the BMW and the new Heinkel engines; this development was to begin as soon as the 004 was in production.

Owing to unexpected difficulties in getting the two engines of the first phase, the 004 and 003, actually into production, very little of the second-phase program could be realized before the end of the war. Although Junkers devoted almost all its efforts to the 004, it was not until the first half of 1944 that that engine was in full production, and it was not until the latter half of that year that the BMW 003 reached full production. Thus it was not until late 1943 or early 1944 that

[40]Schelp believed that the proper pressure ratio for all these true service engines now to be developed would be between 5 and 7 to 1, whether the engine was a turbojet or a turboprop, so that the same basic engine could be developed in both versions according to the range of the aircraft for which it was intended. As a matter of fact, he planned that the basic engine would also be produced in a ducted-fan version, to take care of ranges too long for the jet and too short for the prop.

[41]The 47,500-lb Junkers 287 bomber was ultimately designed around four 018 engines.

the designs of the 012, 018, and 028 were complete and construction begun.

Development of an 021 turboprop version of the 011 turbojet was begun in the fall of 1943 as a power plant for a long-range reconnaissance version of the Arado 234. The development was to be carried out by Daimler-Benz in place of the 007 ducted fan. It was now clear that the 007 would never be ready in time to be of use in the war,[42] while by now Daimler-Benz was extremely anxious to catch up in the new field, since it saw the progress made by other companies with gas turbines, and knew that the government was on the verge of ordering turbines into production almost to the complete exclusion of conventional engines.

In 1944 design was begun by BMW of a second engine in the smallest size class, the 003D turbojet, intended as an alternative to the Heinkel-Daimler-Benz 021 turboprop for a long-range version of the Arado 234. In that year, however, Allied bombing began to slow down development very seriously, both by direct attacks on the BMW and Junkers plants and by its indirect effects. As a result it was not until December 1944 that a complete 018 was built, and it was then abandoned without even being tested, since it was clear that it could never be ready in time to be of use in the war. One 012 was also built but was not tested before the end of the war. No complete 003D was ever built.

Heinkel was both free from the other commitments of Junkers and BMW and less affected by bombing. Five experimental 011's were built in 1943 and five more in 1944. Despite this no engine had flown under its own power by the end of the war; the reasons for Heinkel's failure are discussed below. Daimler-Benz had not even constructed a single 021 turboprop by the end of the war.

Heinkel Developments: 1939-1945

On August 27, 1939, the He 178 airplane powered by a single He S-3b centrifugal engine made the world's first turbo-

[42]The 007, which had been designed for a thrust of 3,080 lb at 560 mph at sea level, was developing at this time a static thrust which corresponded to 1,340 lb at 560 mph at 23,700 ft but the engine had not yet been flown.

jet-powered flight. After the flight of the He S3b minor modifications were made to produce the He S6 engine, with thrust increased from 1,100 to 1,300 lb for an increase of weight from 795 to 925 lb. The speed attained in flight was still very low, however, partly because the thrust was still low for the weight and diameter of the engine, but still more because of defects in the airframe; the plane was directionally unstable above a certain speed, and it had to be flown with the landing gear down because the retraction apparatus refused to function. Von Ohain believed that if the airframe had been corrected in these respects a speed of about 400 mph could have been made with the He S6, or very little less than the British Meteor did in 1943 with two Rolls Royce Wellands.

No attempt was made, however, to complete the development of either this engine or this airplane. Heinkel had decided that the difficulties with the intake and tail pipe of the fuselage-mounted engine would be too great, and undertook the development of the He 280 fighter to be powered by two wing-mounted engines. Two different engines were to be developed by Heinkel for this airframe. Heinkel had recently hired Max A. Mueller to continue the development of the axial turbojet which the Junkers company had abandoned, and von Ohain was to reduce the diameter of his centrifugal engine by redesigning it with the combustion chamber behind rather than outside the compressor.

In addition to the revised von Ohain centrifugal engine, called the He S8 or 001, and the Mueller axial turbojet, called the He S30 or 006, Heinkel was now also carrying on the development of ducted fans driven by reciprocating engines, one with an ordinary gasoline engine and one with a Diesel, which Mueller had brought with him from Junkers. The Diesel engine was itself a completely new development, starting with single-cylinder research.

By the end of 1939 Heinkel had succeeded in getting government financial support for all these projects, but this did not mean that he could get additional facilities or engineers, which were simply not to be had in Germany at this time. Even before Mueller's projects were taken on, Heinkel's staff had been far less than adequate for the rapid and successful develop-

ment of a single engine. After Mueller came the situation was even worse, since Mueller brought only some 15 engineers and designers with him from Junkers, and Heinkel now had a total of less than 50 engineers, designers, and draftsmen for four projects. It is true that the ducted fans were given a low priority and that most of the work on the special Diesel engine was done outside,[43] but even if his entire force had been concentrated on the two turbojets Heinkel would have been worse off than when he had only one. The staff, moreover, was lacking not only in numbers but in experience; scarcely a man had any background whatever in the development of aircraft engines.

The new centrifugal engine, the 001, seemed quite promising on paper, since its diameter of 30½ in. was only ½ in. greater than the Junkers axial engine, and its weight was very considerably lower, being only 836 lb against 1,870 for the experimental 004A. By 1941 the 001 was developing about 1,100 lb thrust, and two such engines were flown as the sole power of an He 280. Frequent flights were made in 1942, and at least 15 engines had been built and tested by April of that year.

Even in 1942, however, the performance of the 001 was still poor, with only 1,200 or 1,300 lb thrust. The chief difficulty was with the diffuser, designed to minimize the diameter of the engine. At the same time the He 280 airplane was in serious difficulty, particularly with tail flutter. An attempt was made in 1941 to fly the Me 262 with two 001's, but this airplane, which was larger than the He 280, could not take off with engines developing only 1,100 lb thrust.

The axial Heinkel 006 was even less far along than the 001 at the beginning of 1942. Development had been delayed principally by the difficulties experienced in matching the turbine to the compressor, which gave a mass flow considerably larger than the design value. Since facilities were insufficient for building experimental engines or components rapidly, or for running several at one time, the modification of the turbine to match the compressor had taken a long time, and the engine first ran under its own power in March or April 1942.

[43]This single-cylinder development was done by Professor Wunibald I. E. Kamm of the Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren of the Stuttgart Technische Hochschule.

The Junkers 004, on the contrary, was making rapid progress —it produced a thrust of 2,200 lb on the stand in January 1942 —and at least according to Schelp of the Air Ministry was virtually ready to go into production. Schelp, as we have seen, was already anxious by the end of 1941 for some manufacturer to begin development of a much more advanced type of engine than any in existence, and believed that Heinkel should drop his existing developments and undertake such a project. Heinkel was now thoroughly alarmed about his competitive position, which had seemed so secure in 1939 when he was far ahead of the field in the development of turbojets, and was ready to follow the Ministry's lead.

Schelp believed that the smallest engine which would be suitable for regular service, as a replacement for the 004 and 003 in two-engine fighters, should have a thrust of at least 2,640 lb at 560 mph at sea level, and for satisfactory fuel economy should have a pressure ratio of about 6.1:1 instead of the 3:1 of existing engines.[44] Schelp had not only decided on the general specifications for the new engine but had decided that it should have a compressor of a completely new type, with a "diagonal" first stage followed by three axial stages. The diagonal stage was a cross between the centrifugal and axial types, intended to avoid the large diameter of the centrifugal type while still retaining a good share of its advantages: a broader characteristic, especially useful in fighters, and greater mechanical robustness. Since no one at Heinkel had done any planning at all toward a future engine, Heinkel agreed to follow Schelp's suggestions completely.

A definite agreement was reached between Schelp and Heinkel for the development of the new engine before the end of 1941. The 011, as this engine was designated, was to produce 2,640 lb thrust initially, and ultimately 3,520 lb, at 560 mph at sea level. Von Ohain was put in charge of its design and development. In accordance with Schelp's general program, a turboprop version of the same basic engine, called the 021, was also planned, although development was not to begin until later.

[44]He believed that enough experience had now been gained with compressor design to make it possible to attain this pressure ratio with an efficiency of 80%.

As a result of Heinkel's undertaking the new development, Schelp was finally able to persuade higher officials in the Ministry to give Heinkel additional manpower. Schelp had previously tried, probably in the first half of 1941, to arrange the purchase by Heinkel of the small trainer-engine concern, Hirth Motoren G.m.b.H. of Stuttgart, but the deal had fallen through because of the opposition of Messerschmitt. Now Schelp succeeded in using the plans for the development of a really advanced engine by Heinkel as an argument to overcome the opposition which Messerschmitt had aroused within the Ministry, and before the end of 1941 Heinkel was permitted to acquire control of Hirth. The Mueller developments, particularly the axial 006 turbojet, were moved to Stuttgart almost immediately, and von Ohain was able to use the entire staff and facilities of the Heinkel plant at Rostock for the design of the 011 and for the development of the centrifugal 001, which was continued in order to acquire background experience while waiting for the design of the 011 to be ready and actual development of that engine to begin.

The general layout of the 011 was completed by von Ohain in September 1942 and development was begun. Development of the centrifugal 001 now came to a stop; it was still unable to deliver over about 1,300 lb thrust.

The axial 006, however, had made remarkable progress by this time. Mueller had fallen into a dispute with the management and had quit Heinkel about May 1942, and the development of his ducted fans had been dropped at once,[45] but the development of the 006 had been continued. By the end of 1942 it was developing nearly 1,900 lb thrust for 857 lb weight, or about the same thrust as the Junkers 004 for little over half the weight. Heinkel wanted to continue the development of this very promising engine along with the completely new 011, and when the 011 project was moved to the Hirth plant in Stuttgart in the fall of 1942 a part of the staff and facilities there was reserved for the 006.

Schelp believed, however, that this very small engine, with its diameter of only 24.3 in., could never produce the thrust which he believed necessary in a service engine; and although

[45]These engines had never got beyond the single-cylinder and mockup stage.

the remarkable performance of the 006 was due in large part to its use of a compressor with 50% reaction blading instead of the pure impulse type designed by Betz and Encke of the AVA for the 004 and 003, Schelp mistakenly believed that the 50%-reaction blading was less efficient. Consequently before the end of 1942 Schelp instructed Heinkel to drop the 006 and put all his efforts on the development of the completely new 011.[46]

The total number of engineers, designers, and draftsmen now working on the 011 was in the neighborhood of 150. Five experimental engines were built in 1943 and five more in 1944; by the end of the war nine experimental engines had been bench-tested, and one or two flights had been made on a Ju 88 flying test bed, but no engine had been flown under its own power.

Certainly the first basic and essential reason for the failure of Heinkel to have an engine in production by the end of the war, despite the fact that his He S3b had been the first engine in the world to fly, was his lack of engineers experienced in the development of aircraft power plants. This was the unanimous opinion of experienced German engineers who visited the Heinkel development; all agree that the work was being done in a way suitable for research but not for practical development. The second reason was the extremely unwise decision made in 1939 to carry on several simultaneous developments when both engineering staff and shop facilities were insufficient to carry on a single program at an adequate speed. This dispersal of effort lasted until well into 1942. It was certainly responsible in part for the fact that both the original Heinkel turbojets, the 001 and the 006, were far behind competing engines at that date as regards reliability and general readiness for service.

The decision enforced by the Ministry to begin a completely new type of engine in 1942 was the final important reason for Heinkel's ultimate failure. Even assuming that the diagonal-flow compressor used in the 011 was inherently superior to both the centrifugal and the axial, the change to a completely new

[46]This left the He 280 without an engine. Development of the airplane was continued for a time with the BMW 003, but it was finally dropped in favor of the Me 262 in 1944, chiefly because Heinkel, overoptimistic in 1939 concerning the fuel consumption to be achieved by his engines, had designed the plans with fuel tanks too small to give adequate range.

type of compressor as late as 1942 was virtually a guarantee that even the most able team of engineers could not possibly have an engine ready for service before the end of the war.

The BMW 003

As a result of the general survey of the field of gas turbines and jet propulsion made in response to the Air Ministry's request of August 1938, the Spandau Development Works of the BMW Engine Company[47] had concluded by about the middle of 1939 that the most promising type of engine was the counterrotating axial-flow turbojet, and had been given a contract by the government to develop such an engine, later given the designation 002. A design was produced during the summer and fall of 1939 in collaboration with the independent engineer Helmut Weinrich, who had already partially developed a small counterrotating power turbine. The officials of the company believed, however, and the Ministry agreed, that because the counterrotating engine would be slow to develop it would be wise to develop a straight axial engine as a source of experimental data and experience to be used in the development of the 002. Even though the 002 was intended at this time to be the actual service engine, first priority was given to the axial engine as an essential step in the development of the 002. A good deal of work was done on the 002 in 1940-1941, and individual stages of the compressor were built and tested, but by early 1942 at the latest it was realized that the obstacles to be overcome in the development even of a straight axial engine were far greater than had been anticipated, and the 002 was abandoned.

During 1939 BMW-Spandau drew up the design for its axial engine, eventually known as the 003, which was intended like all the turbojets designed on government contract at this time to produce 1,320 lb thrust at 560 mph,[47a] or approximately 1,500 lb static thrust, at sea level. The engineers at Spandau, unlike those at Junkers and BMW-Munich, had had no ex-

[47]After its purchase by BMW about the middle of 1939 the former Bramo company was known as the BMW Flugmotorenbau Entwicklungswerk Spandau.

[47a]All German turbojet engines were theoretically rated in terms of thrust at 560 mph (250 meters per second), but this was purely a reference figure and implies nothing about the speed at which they were intended to fly.

perience with turbosuperchargers and based their original calculations on the very conservative combustion temperature of 1,112°F. The pooling of the Spandau and Munich development work, however, involved a decision that the 003 should use the turbine wheel with hollow blades developed for the Munich turbojet, and the design of the 003 engine was modified to use the extremely high combustion temperature of 1,652° F, while the pressure ratio was reduced to the very low value of 2.77:1.

An axial compressor was chosen for the 003 almost entirely because of its smaller diameter, not because of superior efficiency. The compressor was designed by Encke of the Goettingen AVA research institute. It was designed to have a certain amount of pressure conversion on the stator, but the amount was small; the compressor needed six stages for the pressure ratio of 2.77:1.

Engineers of BMW-Spandau had already begun experimental studies of combustion systems in 1938, and had been so much encouraged by the results of their experiments on sectors of an annular combustion chamber that they decided to use such a chamber in the 003. This, of course, gave an appreciably smaller diameter than can-type chambers; the original diameter of the 003 was only 26.4 in.[48]

Construction of the 10 experimental 003's ordered in the first Ministry construction contract was begun about the middle of 1939. Tests of the Munich turbine wheel seem to have been begun even before this, in the first half of 1939; at any rate it was soon decided that BMW-Munich had been overoptimistic about the temperatures which its hollow-bladed wheel could withstand when built in the size required for a jet engine rather than in the smaller size of a turbosupercharger, and already by September 1939 it had been decided that the combustion temperature would have to be lowered to about 1,382° F.

[48]Even this was greater than the 23.6 in. which Schelp had calculated for an engine of the required thrust. It is not true, as has often been stated, that the Ministry imposed a definite limit on the diameter of the 003, or that the Ministry required BMW to use either an axial compressor or an annular combustion chamber in order to minimize diameter. The Ministry did set the thrust specification and urge BMW to make the 003 as small in diameter as possible, but this was all; every element of the design represented the company's own idea of what was best.

Thus when the first engine was run early in 1940 it was not at all surprising that the thrust was only 570 lb. To obtain the same thrust at the lower temperature a much larger airflow and a higher pressure ratio were required, but these could only be obtained with a new compressor; and the lowering of the combustion temperature had of course spoiled the aerodynamic efficiency of the turbine wheel by altering the velocity of the gases passing through it. In addition, it was now discovered that there were equally or even more serious difficulties in the combustion system. The conclusions drawn from tests on segments of the annular combustion chamber had been misleading: in the complete chamber combustion efficiency was only about 60%, there were very high pressure losses, and the temperature distribution at the turbine inlet was extremely unequal, with as much as 700° F difference between the hottest and coldest points.

Design and development of a new compressor with 30% greater mass flow and a pressure ratio of 3.1:1,[49] a new turbine, and a new burner for the combustion system were begun not long after the first engine had been tested early in 1940. Considerable help was given in the development of the turbine by Brown-Boveri of Mannheim, Brueckner and Canis, and M.A.N. (Maschinenfabrik Augsburg-Nuernberg)[50], and the new burner was developed with some assistance from the Henschel Airplane Works where work was being done on guided missiles, and from the Luftkriegsakademie at Gatow. Even so the work progressed very slowly, and two years passed before the new components could be incorporated in an engine, largely because as much as six months were required from the time that a design was begun until the component could be built and tested. At the beginning of the development, in 1939, there had been only some 40 engineers and designers assigned to all the turbine and jet work at Spandau, and for about two years nearly half of these had been working on the counterrotating engine. At that time there was no separate shop for the turbine work, and the de-

[49]The new compressor was designed at Spandau. It had seven stages instead of six, and NACA profiles were substituted for the AVA high-speed profiles on the rotor blades.

[50]These firms assisted particularly with research on the effect of blade cooling on efficiency.

velopment of reciprocating engines had first priority in the common shop. Even in 1942, when reciprocating development had completely stopped at Spandau, there were only some 100 engineers and designers, another 100 miscellaneous help in design and testing, and about 700 workers in the shop.

Testing of the ten engines of the original design continued while work was being done on the new components. In the spring of 1941 two of the first ten engines were installed on an Me 262 and flown, but this was primarily to test the airplane; the thrust of these engines was only some 970 lb, and it was necessary to install a conventional engine and propeller in the nose. Flight testing aimed primarily at development of the engine itself did not begin until the summer of 1941, on an Me 110 flying test bed, after the pressure ratio had been increased by the emergency method of simply adding a seventh stage to the old compressor.

By the middle of 1942 the new compressor and turbine, as well as a new combustion system, were at last ready, and the design of a new engine model, the 003A-0, had been made by Hans Rosskopf, now the chief designer of the Spandau plant.[51] It was not until the end of 1942, however, that the first experimental engines of this model could be tested.

The original model of the 003 was developing 1,210 lb of thrust at the end of 1942, and the 003A-0 gradually improved on this, although serious difficulties with combustion still remained, and there was great trouble with the new compressor owing both to mechanical vibration which caused frequent blade failures and to aerodynamic defects which gave very high drag at starting.[52] Development of the first four engines of the

[51]At the same time the accessories were put outside the case and the diameter of the engine was slightly increased, from 26.4 in. to 27.2 in.

[52]The compressor was finally got into a satisfactory state after about a year's development of the 003A-0. The efficiency was 78% at the design point, and the range of very good efficiency was exceptionally broad, being almost as good at the lowest speed used in service as at full speed. In the production compressors there was a variation of about 2% in the efficiency and of about 0.25 in the pressure ratio.

In 1941, at the Air Ministry's instigation, the industrial turbine firm, Brown-Boveri of Mannheim undertook to design a new compressor for the 003. The design, by Hermann Reuter, differed from the AVA designs in using 50% reaction. It was a considerable improvement over the work of Encke; with seven stages it both produced a higher pressure ratio (4:1) than the compressor used in the production 003 (3.1:1) and had 84% efficiency instead of 78%. The work progressed

new model during the first half of 1943 removed the worst of the difficulties: combustion efficiency was raised to about 90%, or a little better, the temperature distribution was made more uniform, in part by the use of information about the Junkers mixing system obtained through the Luftkriegsakademie at Gatow,[53] and the breakage of compressor blades was cured. By the middle of 1943 the static thrust had been increased to 1,760 lb and the specific fuel consumption had been reduced to little over 1.4 per hour. The engine was then put in pilot (0-series) production,[54] and an 003A-0 was flown for the first time, on a Ju 88 flying test bed, in October 1943.

Toward the end of 1943, as has been told above, the Ministry decided to put jet-powered fighters into production as soon as possible. At this time the 004 both produced 1,980 lb thrust against the 1,760 of the 003 and was a more fully developed and reliable engine. On the other hand the 003 was believed capable of ultimately giving the same thrust as the 004, and promised several advantages: it had less frontal area and — what was probably much more important — it was a much easier engine to maintain,[55] and it seemed possible to make it both lighter and more economical to produce. The Ministry accordingly froze the development of the 004 and ordered it into immediate production, while BMW was instructed to hasten the development of the 003 and to take over a part of the Junkers control system instead of waiting to develop one itself. The number of workers in the BMW turbine shop increased from about 700 in 1942 to nearly 1,000 in 1945, and the number of miscellaneous

very slowly, however, and although one experimental compressor had been built and tested by the end of the war the projected 003C using this compressor was never built.

[53]By 1945 the annular chamber seems to have been fully as successful as the can chambers of the 004. The life of the combustion chamber was about 200 hours, compared with 25 to 50 hours for the chambers on the 004; the reason for this difference is not known.

[54]Pilot-production engines are a small batch built in a small-scale line-production shop belonging to the experimental and not to the production department; the purpose of this series, known as the "0-series," is to discover features of the design which would cause difficulties in quantity production and eliminate them before quantity production begins.

[55]The combustion chamber of the 004, which was one of the chief limiting factors on its life, could only be replaced by complete disassembly of the engine. The limiting factor in the life of the 003 was the turbine wheel, which could be replaced without removing the engine from the aircraft.

help in the engineering department increased even more, from about 200 to 500 or 600. The total number of trained engineers and designers at BMW scarcely increased, because such men were simply not available, but they could now be diverted to turbines from the development of reciprocating engines, and the number of engineers and designers working on BMW turbines increased from about 100 in 1942 to about 400 by the end of the war.

A large part of the effort in the final development of the 003 was directed at making alterations in the design to reduce the amount of labor and scarce materials required for its production. The Ministry specifically required that the man-hours for production were not to exceed 500 and the quantity of nickel was to be reduced from the 55 lb used in the 003A-0 to not over 1.3 lb. This limitation on the quantity of nickel may not have been met exactly, but the only nickel used in the production 003 was in the turbine buckets, where it made up only 17% of the weight. The large-scale substitution of sheet metal for castings succeeded in meeting the goal set by the Ministry for conservation of labor, and at the same time reduced the weight of the engine from the 1,650 lb of the A-0 model to 1,345 lb in the A-1, as the first production engine was known. Work was also begun in 1943 on the development of new burners to use J-2 fuel, much like Diesel oil, which could be produced synthetically in much larger quantity than the regular gasoline for which the 003 had originally been developed. The production engines were all equipped to burn the low-grade fuel.

The hollow blades of both the original Munich wheel and the new wheel designed at Spandau for the 003A-0 were constructed in the same way as the blades of the BMW supercharger turbines, by welding together two pieces of metal. The failures of the Munich wheels were eliminated in the 003A-0 by using another method than welding to attach the buckets to the disk, and these wheels were exceptionally satisfactory, with a life of about 200 hours. As soon as plans were made for quantity production, however, it became clear that the original method of producing the buckets themselves was impossibly slow, and a substitute had to be found for the 003A-1 production engine. BMW at first tried to have the blades forged from

tubular stock by the Leistritz company, but these blades had frequent failures at the roots. BMW then itself developed a process for rolling them from Boehler FBD[56] sheet stock with a weld at the trailing edge, and this process not only produced blades which were not subject to failure but reduced the consumption of scarce material.[57] The turbines of the production engines had a life of only some 50 or 60 hours at the most, but as has been said, they could be replaced without removing the engine from the airplane.

The 003A-1 was put in production in the first half of 1944 and the 100th engine was delivered in August. Only minor changes were made in the later production model, the A-2. The primary use of the production engines was in the He 162 "People's Fighter", only about 60 of which had seen service by the end of the war, when the Arado 234C powered by four 003's was just going into production. The thrust of the production 003 remained at 1,760 lb. Its specific fuel consumption averaged about 1.4 per hour.

In 1944 the Ministry decided to try to develop an engine for the Arado 234 light bomber and reconnaissance airplane with somewhat more thrust than the 003 or 004 and with much improved fuel economy. The Heinkel 011 was being developed for exactly this thrust category, but Schelp believed that for long range the superior efficiency of a straight axial compressor would be preferable to the mixed-flow compressor of the 011. BMW agreed to develop an 003D, which was really not a new model of the 003 so much as a completely new engine with the external dimensions of the 003. The compressor for this engine was to have eight stages, a 30% greater mass flow than the 003A, and a pressure ratio of 4.9:1; the engine was to have a two-stage turbine. Both BMW itself and the firm of Brueckner and Canis were to develop compressors for the new engine.[58]

[56]Composition: 17 Cr, 15 Ni, 2 Mo, 1.15 Ta-Niob, 0.9 Mn, 1.0 Si, 0.1 C, balance Fe.

[57]The actual quantity production was done by the Württembergische Metallwarenfabrik. Exactly the same process was developed independently by Saechsische Metallwarenfabrik Wellner Soehne A.G. for producing blades of Cromadur for the Junkers 004B; cf. below, p. 428.

[58]Brown-Boveri was still working at this time on the compressor for the projected 003C (above, p. 414, n. 52). It was intended that if this compressor proved superior to the new compressors designed specifically for the 003D it should be used in their place.

The work done at Brueckner and Canis was under the direction of Rudolf Friedrich, the designer of the compressor of the 006. Before the end of the war an experimental compressor with less than the full number of stages, built as a preliminary step in the development, showed on repeated tests an efficiency of 89% at a pressure ratio of 3.2:1, and it was believed certain that the full pressure ratio of 4.9:1 could be achieved with an efficiency of 85%.[59] The war ended, however, before a complete compressor had been built, let alone a complete engine.

The Junkers 004

The general survey of the field of turbines and jet propulsion which the Junkers engine division carried out in response to the Air Ministry's request of August 1938 led, as we have seen, to a decision to undertake the development of a turbojet. The engine division refused, however, to take over the engine previously developed by Mueller for the airframe division of the company, and insisted on making a completely fresh start. A contract for the development of a new turbojet was given by the Air Ministry in the summer of 1939.

The design and development of the 004, as the new Junkers engine was called, were put in charge of Anselm Franz, who had carried out the preliminary studies. The staff which Franz already had for research on the aerodynamics and thermodynamics of reciprocating engines and superchargers was only very slightly enlarged when the new project was undertaken: Franz had under him 30 or 40 engineers, designers, and draftsmen; mechanical work was done in the same experimental shop as the work on reciprocating engines. When Mader, the head of Junkers engine development, had first agreed in 1938 to make a preliminary study of jet propulsion, Franz had urged him to set up a special division for the development of unorthodox engines, but although Mader agreed that intensive development of such engines should certainly be undertaken eventually, he felt very strongly that since Germany did not have high-power reciprocating engines comparable to those of foreign countries, his first task was to develop such an engine. He re-

[59]This compressor, like Brown-Boveri's and like British and American axial compressors but unlike the AVA designs, used 50% reaction.

fused at this time, therefore, to allow the diversion of a large part of his engineers and facilities to long-term projects, and it was not until about 1940 that the process was begun of creating a separate division for the development of turbine engines. This process was not completed until Franz, who had become Mader's second in command in 1941, became head of all Junkers engine development upon Mader's death in 1944. By 1942 or 1943 Franz had a turbine staff of perhaps 500 including the mechanics in an independent experimental shop. Figures for the staff at the end of the war are not available.

The guiding principle behind every decision in the design of the 004 was to make the choice which would lead with the greatest certainty and speed to an operating engine, even though this entailed some sacrifice in performance. This conservatism is shown, for example, in the fact that the ratios both of weight to thrust and of diameter to thrust were appreciably greater in the 004 than in the Mueller turbojet. It is also shown, as we shall see later, in the use of can-type combustion chambers and of solid turbine buckets in the earlier models. It was Franz's opinion that since there was available virtually no practical information at all on this type of engine, it was better to build an engine which would run and supply these data as quickly as possible, and then to use the data as the basis of an advanced design, than to attempt the advanced design immediately. In the results of the less conservative Magdeburg work he saw the confirmation of this opinion; and that conservative engineering could in fact lead more rapidly to an operating engine is demonstrated, of course, by the fact that the 004 was the only German turbojet to reach true quantity production before the end of the war. Franz also believed that after the failure and abandonment of the Magdeburg engines another failure, which might result from aiming too high at first, might cause either the company or the Ministry to drop the entire development of the new type of engine, since many people in both places were still completely unconvinced that it would ever succeed.

The only specification set by the Air Ministry for the Junkers 004 called for a thrust of 1,320 lb at 560 mph[59a] at sea level,

[59a]Cf. above, p. 411, n. 47a.

corresponding to about 1,500 lb static thrust. The design of the engine was entirely the result of the company's free choice. The engine comprised an eight-stage axial compressor giving a pressure ratio of about 3.1:1, six can-type combustion chambers, a single-stage turbine, a tail-pipe designed for afterburning, and a variable exit nozzle automatically controlled to secure approximately constant gas temperature at full power under all operating conditions.

Franz was more familiar with centrifugal than with axial compressors, because of his earlier work on superchargers, and he was convinced that the greater peak efficiency of the axial type was more than outweighed by its more sharply peaked efficiency curve and by its characteristic of stalling just off the point of peak efficiency, two factors which made design with the axial compressor very critical. He nevertheless chose to use an axial compressor in spite of these facts for two principal reasons: (1) he was convinced that small diameter was of great importance in the design of any aircraft engine,[60] and (2) he believed that really important gains could be made in over-all engine efficiency because of the straight air path through an engine with an axial compressor.

The blading of the compressor was designed by Encke of the Goettingen AVA, the same man who designed the original compressor of the BMW 003. The average peak efficiency of the compressor designed for the 004 was somewhere between 81% and 82%.[61] Since, however, it is in general impossible to use an axial compressor at its peak efficiency, the operating efficiency was about 78% under static conditions or about 75% at full speed at sea level.

Franz always believed that the ultimate turbojet engine would have a single, annular combustion chamber because of its smaller diameter, but he used can-type chambers on the 004 because he felt that these could be made to function success-

[60]It is not true that a maximum diameter was specified by the Ministry, as has been sometimes reported, or that the Ministry required or even strongly urged an axial compressor in the early stages of turbojet planning. As we have seen, Mauch, who was in authority until the fall of 1939, had no convictions of his own concerning the principles of turbojet design and wanted each company to follow the course it believed best.

[61]Certain experimental compressors reached 83% or 84%.

fully more surely and quickly than the annular type. The Junkers laboratory had a supply of compressed air sufficient to test a single full-scale can-type chamber, but not a full-scale annular chamber, and Franz knew that Mueller's attempt at Magdeburg to develop the annular chamber by experimenting with only a sector of it had failed largely because conditions within a separate sector were not the same as in a complete annular chamber.

The turbine wheel was designed in collaboration with the Allgemeine Elektrizitäts Gesellschaft according to the standard principles of steam turbine design current and generally accepted at the time. The use of a certain amount of reaction instead of a straight impulse turbine was due to the intention of having afterburning; the figure of 20% was a compromise between Junkers, which wanted more, and the AEG, which wanted none at all.

The turbine buckets of the original 004A and of the first production engine, the 004B-1, were solid forgings, cooled only slightly by the passage of air between the roots. Junkers had already had experience with hollow blades on the turbosuperchargers which it had developed for aircraft Diesels and intended from the beginning ultimately to use hollow blades on the 004, since they would permit the use of higher temperatures and thus reduce fuel consumption. Solid blades were used on these first engines in order to get engines running in the shortest possible time. Development of hollow blades for the 004 proceeded simultaneously with the development of the engine with solid blades.

The Junkers 004 was developed from the beginning to use Diesel oil as fuel. This was not done because any shortage of gasoline was foreseen at that time, but, in order of importance, for greater safety, economy of space in the aircraft, and the lower cost of the fuel.

When the design of the 004 was shown to Schelp of the Air Ministry, he criticized it strongly as overconservative in comparison with the BMW 003, which promised the same thrust for less weight and smaller diameter. He did not, however, try to force the company to make any changes, and Franz, convinced that it was better to be as sure as possible of success rather than aim too high, went ahead with the engine as he had originally designed it.

As a first stage in the development of the 004, Junkers originally intended to build and study a small-scale model, the scale being chosen so as to require only 400 hp to drive the compressor and thus make possible the systematic development of the individual components on existing test apparatus. This small-scale model was built in the fall of 1939, and if peacetime procedures had been followed, no work would have been done on a full-scale engine until everything possible had been learned from the study of the model. Owing to the war, however, construction of a large engine was begun only a few months later, toward the end of 1939. Experience soon showed that although the aerodynamics of turbojets could be usefully studied in a scale model, little or nothing could be learned in this way about such phenomena as combustion and vibration. Since these problems were as acute in the small engine as in the large, it appeared that it would be a considerable waste of effort to make the model function satisfactorily, and when its compressor broke in a test the model was abandoned.

The first engine of the first full-scale model, called the 004A, was put on test in November 1940. The most serious problem encountered at first was the vibration of the sheet-metal stator blades of the compressor, and it was not until about the middle of 1941 that this problem was solved. By January of 1942 all the worst difficulties had been overcome; the fifth experimental engine had developed a maximum thrust of 2,200 lb on the stand and was normally rated at 1,848 lb, for a weight of 1,870 lb. The first flight of an operating 004A, on an Me 110 flying test bed, took place on March 15, 1942, and two 004A's provided the sole power of an Me 262 for the first time on July 18, just about a year before the Whittle engine had been developed to the point where it could make its first flight in a Meteor. The 004A was put in pilot production (cf. above, p. 415, n. 54) in the late spring or early summer of 1942, and about 30 engines were built.

The 004A had never been intended, however, to be put in quantity production, the design being arranged to facilitate building in the experimental shops. While the tests of the A

were continuing through 1942, the design of the first production model, the B, was being prepared. The preliminary layout had already been made in December 1941, and the detailed design was complete by October 1942. Manufacture of the larger parts had begun well before the design was complete, and the first experimental engine of the B-0 model was delivered in January 1943. The 004B-0 was virtually identical to the 004A in layout, the differences being essentially in the substitution of sheet metal parts for castings, both to reduce the weight and to facilitate mass production, and in the elimination of strategic materials wherever possible. The thrust of the B-0 was consequently the same as that of the A, or 1,848 lb, but the weight was reduced from 1,870 to 1,650 lb and the weight of strategic materials was reduced by over half.

Very few engines of the B-0 model were built, however, since it was decided that a considerable improvement could be made by a change in the compressor design. The first two stages were altered in the first half of 1943, producing the B-1 model with the thrust increased from 1,848 to 1,980 lb. The first experimental engine of this new model was delivered in May or June 1943, and B-1's were flown on the Me 262 in October, but there was serious trouble with vibration of the turbine buckets, and it was not until December that these had finally been ironed out. Despite these troubles, the B-1 was put in pilot production about the middle of the year. The Ministry finally decided to put jet engines into production toward the end of 1943, and 004B-1's began coming off the lines in quantity about March of 1944.

Before the end of the war the 004B-1 was replaced in production by the B-4,[62] which incorporated one important change: the use of hollow turbine buckets instead of solid. Although the rating of the B-4 was the same as that of the B-1, it was really capable of higher temperatures and higher thrust, and only a slight modification of the combustion chamber was needed to produce the D-4 model which was rated 2,310 lb instead of the

[62]The design for the B-2 model was completed in the middle of 1943. This engine had a completely new compressor, designed like those of the A, B-0, and B-1, by close cooperation between Junkers and the AVA. The new compressor suffered from blade vibration troubles which were never overcome, and the B-2 was never put in production.

1,980 lb of the B,[63] and which was about to go into production at the end of the war.[64] The greatest advantages of the hollow blades in the B-4 production engines as actually rated in service were ease of production, conservation of scarce materials, and greater reliability and durability at the same gas temperature used with the solid blades.

The Junkers 004B engine was the only product of the entire German program of gas-turbine development to be actually produced and see service in quantity before the end of the war. About 5,000 engines were built. Their principal use was on the Messerschmitt 262 twin-engine fighter, some 1,400 of which had been built by the end of the war (including bomber and reconnaissance versions), and which was the only German jet-propelled fighter to be produced in quantity. A few were used on the twin-engine Arado 234B fighter-bomber, which was just going into service at the end of the war.

Development of Materials for the Junkers 004

Since the Junkers 004 was the only German turbojet engine to see service in quantity before the end of the war, the successes and failures of the German development program as a whole must be judged largely in terms of the performance and reliability of this engine. But the German engine cannot be fairly compared with engines developed in Britain and in the United States unless it is remembered that the Germans worked under an extremely severe shortage of certain materials, particularly nickel, which were of great importance in gas turbine engines, and of which the British and Americans had enough.

The most serious, although not the only, materials problem of the gas turbine is with the blades or buckets of the turbine wheel itself. Until 1938 the only considerable work which had been done in Germany on materials for this use had been carried out by the DVL as a part of its work on turbosuperchargers. This work had begun in 1935 or 1936 under the direction of Franz Bollenrath. Bollenrath had collected samples of virtually all the known alloys for which good high-temperature strength

[63]An Me 262 was flown experimentally at a top speed of 578 mph with an 004B-4; the maximum speed with the engine limited to its official rating was 541 mph.

[64]The D was also to have been the first production engine with afterburning.

was claimed and had subjected them to systematic creep tests,[65] and after the known alloys had been tested, Bollenrath had gone on to develop still others.

One of the materials available in 1936 and tested at the DVL was a Krupp steel called P-193. This material was protected against corrosion by the presence of chromium and rendered austenitic by the presence of nickel, and owing to the presence of titanium could be given good high-temperature strength by solution-treating and precipitation-hardening. Under the stimulus of the systematic tests of the DVL, the larger steel manufacturers began the first systematic development of steels intended to withstand high stress at high temperature. Krupp's research led to an improved version of P-193 called Tinidur.[66] Tinidur obtains its strength at high temperature by precipitation-hardening, and thus is a material of the same general type as Nimonic 80, which was used for the buckets of all British gas turbines after 1942. Owing, however, to the fact that Tinidur contained over 50% iron, virtually all of which was replaced by nickel in Nimonic 80, the creep strength of Tinidur fell off very sharply above about 1,080° F, whereas Nimonic 80 maintained good creep strength up to about 1,260°. Krupp was fully aware by 1938 at the latest that Tinidur would be improved by increasing the nickel content from 30% to at least 60%, but since it was clear that nickel would be extremely scarce in Germany in time of war everyone realized that an alloy with 60% nickel would never be available for quantity production. The nickel content was therefore left at 30%, the minimum amount which would maintain a stable austenite. It was for this same reason that nothing was done with the development of cobalt-base alloys, such as were used for the turbine buckets of American gas turbines and turbosuperchargers. The DVL had made up and tested a number of cobalt-base alloys before 1938,[67] and had shown that above about 1,350° F they were very much superior to any other

[65]His results were presented in terms of stress to produce 1% creep in 300 hours, which became known as "DVL strength".

[66]Composition: 15 Cr, 30 Ni, 2 Ti, 0.8 Si, 0.7 Mn, less than 0.15 C, balance Fe.

[67]The Germans were perfectly familiar with cobalt-base casting alloys of the same general type as the American Vitallium (cf. below, pp. 495, 497) and used them for metal cutting before the war.

known bucket material. Everyone knew, however, that the entire German supply of cobalt would be required for high-speed tool steel, and further work with cobalt-base bucket alloys was dropped as impractical.

About the middle of 1938 a materials group was set up by Mueller in the Junkers airframe division's turbine development facilities at Magdeburg; this group was headed by Heinrich Adenstedt. Using the methods developed by the DVL, Adenstedt started out to test all the alloys for which good properties were claimed, but he soon realized that the claims of most of the manufacturers were based on completely inadequate knowledge and that there was no use investigating the products of anyone except Fried. Krupp A.G., Gebr. Boehler A.G., and Deutsche Edelstahlwerke A.G. By the summer of 1939 he had decided that Krupp's Tinidur was the best material which would be available,[68] and comparative testing of materials virtually came to an end.

When the turbine development at Magdeburg was stopped in the summer of 1939, Adenstedt was one of the very few engineers who went to the new turbine project undertaken by the Junkers engine division at Dessau, where he was put in charge of materials. The question of what material to use for the buckets of the 004 was thus settled in advance in favor of Tinidur, and the problem from the beginning of the development of the 004 was not to find a better material but to take Tinidur and make it work.

The first turbines for the 004 were, as has been said, equipped with solid buckets. Very early in the development it was observed that of two apparently identical turbine wheels one would have a life of over 100 hours, while the other would fail after less than five; the problem was to discover and eliminate the causes of the difference. By 1943-1944 Junkers had learned how to obtain satisfactory uniformity from the solid blades by controlling every step in their manufacture, from the original melt to the final polishing of the mounted blades, with 100% inspection of the product at the most critical stages. The most

[68]Adenstedt also verified the DVL's statements concerning the merits of cobalt-base alloys, but had to give up any thought of using such materials because of the shortage of cobalt.

critical process in the manufacture of the solid blades was found to be the forging, since the grain size and thus a part of the high-temperature properties of the product are controlled in an austenitic steel by the forging alone, unlike the more familiar ferritic steels where grain size can be altered after forging by heat treating. The determination of the proper grain size itself proved a difficult compromise, since it was learned that while large grains produced high creep strength they also produced brittleness.

By about the end of 1943 it was decided that the problems of the solid buckets had been solved as best they could be, and attention was turned elsewhere, particularly to the problems of hollow blades, development of which had begun at the same time as the general development of the 004 engine. The original reason for the development was the belief that with hollow, internally cooled blades a higher gas temperature could be tolerated and the efficiency of the engine thus improved. Another reason for the use of hollow blades appeared as soon as the problems of quantity production were really faced: it would have been extremely difficult if not impossible to create sufficient capacity for the manufacture of solid blades in the quantities desired.

Junkers first attempted to produce hollow blades itself by folding flat sheets of Tinidur to the required shape and closing them by welding down the trailing edge of the blade. This attempt failed completely, owing to the unsuitability of Tinidur to welding. The Prym company was then called in on the problem and succeeded in adapting the deep-drawing process which it used for the manufacture of such products as cartridge cases; the stock used for the blades produced by this process was in the form of a flat circular blank. Blades could be produced by this process much more rapidly than solid blades could be made, and the reliability of these deep-drawn hollow blades was at least as good as that of solid blades at the same gas temperature. These blades were introduced to production in the 004B-4 model before the end of 1944.

Considerably before this time, however, the Germans had begun to realize that the shortage of nickel would be even more severe than had been anticipated, and Junkers began to look for a material which would not have even the 30% nickel content of Tinidur. The best one found was another Krupp alloy, Cromadur, in which manganese completely replaced nickel as the austenite-producing component.[69] While Prym had been developing the process of manufacturing hollow blades by deep drawing, the Wellner company of Aue, sheet-metal specialists, had been independently developing a process of producing hollow blades by folding and welding flat sheet stock.[70] When Junkers itself had tried to use such a process with Tinidur it had failed owing to the unsuitability of the material to welding, but Cromadur proved very easy to weld. The process itself was so superior to deep drawing that the Cromadur blades were more reliable than the Tinidur blades in service, despite the fact that the creep strength of Cromadur was very much inferior to that of Tinidur.[71] Deep-drawn Tinidur blades continued to be used along with the folded Cromadur blades, however, in order to obtain sufficient total production.

Although the most critical materials problem for the Germans was in the turbine buckets, they were also obliged to eliminate or reduce to a minimum the scarce metals used in every other part of the engine as well. The turbine disk of the 004B was of a martensitic steel with no chromium and no nickel content at all. The turbine nozzles were hollow and air-cooled, like the buckets, and for this reason could be made of sheet metal containing only about 12% chromium. The combustion chambers were made of a mild sheet steel with no chromium at all to give corrosion resistance at high temperatures; to make this possible a process was developed for giving an aluminum coating to the steel.

The result of all this was extraordinary: a complete 004B with Cromadur buckets used no nickel whatsoever, and one with hollow Tinidur buckets used less than 6 lb. A complete 004B used less than 5 lb of chromium.

[69]Composition: 18 Mn, 12 Cr, 0.65 V, 0.5 Si, 0.2 N_2, less than 0.12 C, balance Fe.
[70]The same process was independently developed by BMW for use on the 003.
[71]The stress to produce 1% creep in 300 hours is (tons per square inch):

	1,112° F	1,292° F	1,472° F
Tinidur	28.0	13.4	4.45
Cromadur	19.0	8.9	....