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THE DEVELOPMENT OF THE JUNKERS JUMO 004B – THE WORLD'S FIRST PRODUCTION TURBOJET

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ABSTRACT

This paper describes the pioneering work of Anslem Franz who, while working for the Junkers Engine company in Germany designed and made operational the world's first production jet engine the Junkers Jumo 004 which was the powerplant for the formidable Messerschmitt ME 262 fighter. The paper covers the historical background of jet engine development in Germany during the Second World War and discusses design details of this remarkable axial flow, 1980 Lbs (900 Kg) thrust engine. The development represented a historic achievement for Anslem Franz and his design team at Junkers. Approximately 6,000 engines were built at the end of the second world war in the face of acute shortages and damage to German industry. The Jumo was brought from conceptual design to production in a span of four years.

Franz joined Avco Lycoming in 1952 and worked for 16 years. He retired as Vice President in 1968 after making prolific contributions to the development of several Avco engines including the T53, the T55 and the AGT-1500. Anslem Franz passed away at the age of 94 in Stratford, Connecticut. This paper is a modest tribute to a jet engine pioneer who, in spite of his extensive contributions to gas turbine technology, will always be remembered as the man who designed the world's first production turbojet.

1.0 INTRODUCTION

On July 18th, 1942, a small group of people gathered at the airport in Leipheim in Germany to witness the first flight of the revolutionary Messerschmitt ME 262 powered by two Junkers Jumo 004 engines. Included in this group were Willy Messerschmitt and Anslem Franz, the chief designer of the jet engine. As recounted by Franz (1979), the aircraft with Fritz Wendel at the controls was standing at the beginning of the runway ready for take off. The engines were turned on and carefully brought to full power. Releasing the brakes, Wendel rolled forward and accelerated right to the end of the runway. Suddenly, the aircraft climbed almost vertically with unprecedented speed until it disappeared in the clouds. Franz states that it was at this climactic moment that it became clear to him that the jet age had begun.

An account of Franz's achievement is presented here along with technical details on this 1,980 lb. thrust axial turbojet. The Junkers Jumo 004 was the world's first production jet engine and powered the advanced ME 262 which would have presented a serious threat to allied air superiority had it been deployed expeditiously. The ME 262 and the Jumo 004 engine is shown in Figure 1.

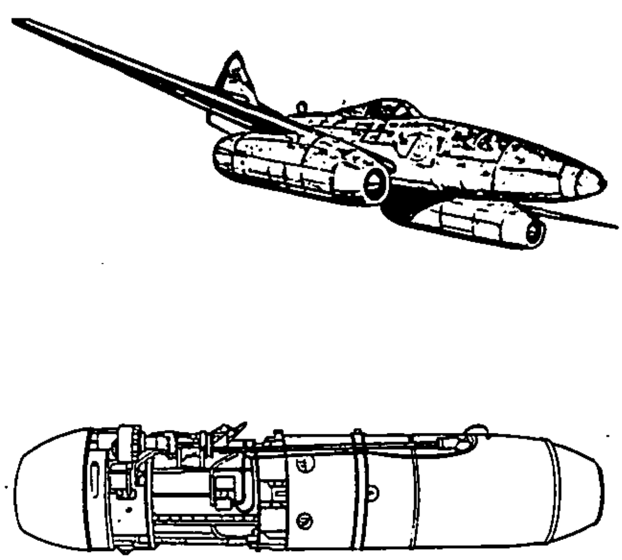

Figure 1. The Messerschmitt ME 262 "Stormbird" powered by two Junkers Jumo 004B turbojets. This formidable fighter was capable of speeds in excess of 550 mph.

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2.0 EVOLUTION OF THE JET ENGINE INDUSTRY IN GERMANY.

In order to put the development of the Junkers Jumo 004 into historical context, it is necessary to trace the development of the jet engine industry in Germany shortly before and during the Second World War.

The invention and development of the jet engine was a profound achievement in man's quest for higher speed. Along with the introduction of low wing monoplanes (circa 1935) jet propulsion allowed a quantum leap in fighter aircraft speeds as shown in Figure 2 (Steven, 1953). Pioneering the turbojet revolution were Sir Frank Whittle in England and Hans von Ohain in Germany, their work being extensively documented in Constant (1980), Schlaifer (1950), von Ohain (1979), Scott (1995), and Jones (1989). Both these pioneers who envisioned flight speeds in excess of 500 mph, at altitudes of 30,000 feet and above, had their revolutionary ideas as students, and developed their engines without the help of the traditional aeroengine companies.

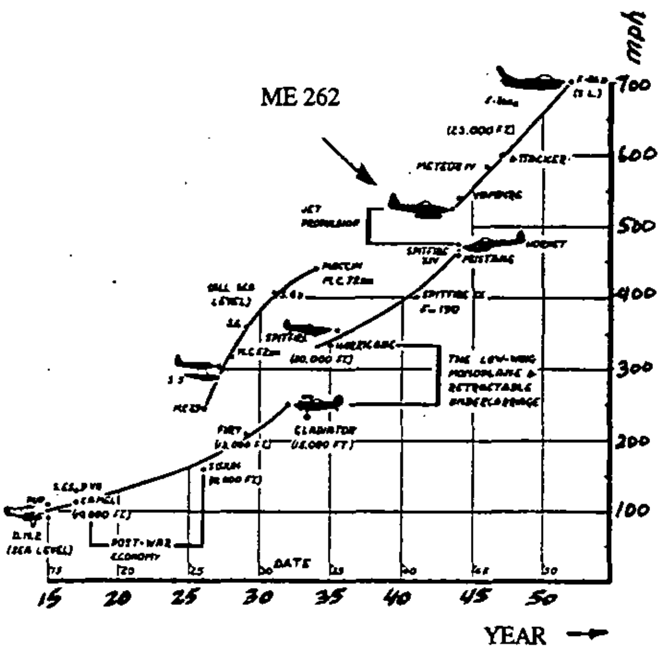

Figure 2. Rise in fighter speeds 1915-1950 (Stevens, 1953). The quantum jump derived from jet powered flight is clearly indicated. The performance of the ME 262 powered by two of Franz's Jumo 004 engines was superior to all fighter aircraft at the end of WW II.

Von Ohain developed the idea of his jet engine while he was a doctoral student at the University of Gottingen. By 1934, he had completed rudimentary design calculations that indicated speeds of 500 mph were possible. He initiated patent procedures and decided to build a working model of the engine. Working with Max Hahn, an expert mechanic machinist and a natural engineer, he built his first model engine which was plagued by combustion problems. Von Ohain's Professor R.W. Pohl, introduced Ohain to Ernst Heinkel the legendary aircraft manufacturer whom, Pohl knew, was obsessed with high speed flight. As a result, the 25 year old Ohain was summoned to Heinkels's house on he Baltic Coast and after a grueling one day interview with Heinkel and his leading engineers, succeeded in convincing Heinkel to take a risk at hiring him[1].

Von Ohain and Max Hahn started work under a shroud of secrecy in a special hut in Marienehe and were given instructions to develop a jet engine as rapidly as possible with the stipulation that ground tests were to begin within a year. Heinkel kept this work secret from the German Air Ministry (RLM), the Luftwaffe, and engine manufacturers. The first engine designated as the HeS1 operated on hydrogen fuel and was successfully test run in March 1937. In about six months, the HeS2a operating on liquid fuel developed 1,100 lbs of thrust. The HeS3A ran in March 1938. The historic first pure jet powered flight of the He 178 powered by a HeS3B turbojet occurred on August 27th, 1939 a few days before the start of World War II. Heinkel immediately informed high air ministry officials of this momentous event but was met with indifference. The German Air Ministry ordered Heinkel to cease all research on jet engines but Heinkel, convinced that his political connections would ultimately result in a lucrative contract, kept von Ohain's team working on turbojets. A few months later, Heinkel's proposal for a jet fighter (the He 280) was accepted by the air ministry. This aircraft was to be powered by two HeS8A engines designed by von Ohain[2]. The RLM cancelled the He 280 on March 27, 1943 and development of the HeS8A was curtailed by the RLM in mid 1942 in favor of the Jumo 004 and BMW 003 engines. Von Ohain (1979) traces the evolution of engines from the HeS 1 to the advanced HeS 011.

During 1938 and 1939, engineers at yet another aircraft manufacturer, Junkers aeroplane company, were working on jet engines under the guidance of Hurbert Wagner. Wagner, a brilliant airframe designer was well versed in steam turbine design and wanted to develop turboprop engines which he felt would make Junkers a preeminent aircraft company. In 1938, Junkers had 30 designers and draftsmen working on the project and were in the process of developing an engine with a 5 stage axial compressor, single combustor and two stage turbine.

At that time, two enterprising engineers Helmut Schelp and his senior Hans Mauch in the German Air Ministry who both had ambitious jet engine development programs in mind, were trying to work with the traditional aeroengine manufacturers and interest them in jet engine development. Schelp was educated in Germany and the USA (Stevens Institute of Technology) and had, in 1936, taken an advanced course at the German Research Institute for Aeronautics (DLV) in Berlin. He was aware of the limitations of piston engines for higher speeds and had concluded that jet propulsion was the solution[3]. Schelp worked on jet engine concepts unaware of the ongoing research at

[1] Part of the reason for Heinkel hiring von Ohain was to avoid him going to his archrival, Messerschmitt. This rivalry continued throughout the war in the race to produce the first jet fighter. For example, in 1940/41, Messerschmitt delayed, for months by political means, Heinkels acquisition of Hirth Moteren Gmbh (Schlaifer, 1950).

[2] Nine prototypes of the He-280 were built and in the spring of 1942 the prospects for this aircraft were favorable as the Jumo 004 was, at that time, plagued by problems. Once these problems were resolved by Franz, the ME 262 proved to be superior to the He-280 and was thus choosen for production.

[3] Schelp was aware of the work of Armengaud and Lemale published before 1910.

Heinkel Aeroplane, or Junkers Airframe Company. The prevailing feeling at that time was that compressor and combustor efficiencies were too low to allow jet engine development. Schelp, however, knew of three leading compressor engineers Professor Prandtl, Betz and Encke who worked at the Aerodynamic Research Establishment (AVA) at Gottingen who had been successful in designing compressors based on aerodynamic airfoil theory and recognized that their work could provide the impetus required in developing a practical engine.

In 1938, Schelp and Mauch visited four dominant aeroengine manufacturers- BMW, Junkers Aeroengine Company, Daimler Benz and Bramo. The head of Junkers Aeroengine, Otto Mader reluctantly accepted a small development engineering contract. He was not aware of the ongoing program at Junkers *Aeroplane* Company. Daimler Benz refused Schelp's offer for funding. Bramo, fearful that they were soon to face severe competition in piston engine orders to their rivals BMW, agreed to perform a study. BMW took on a contract as they were searching for a use of a water cooled turbine that BMW had already developed.

Frustrated by the inaction of the aeroengine companies, Schelp and Mauch, during the early part of 1939, made several visits to the companies trying to stimulate some activity. On his third or fourth visit to Junkers, Schelp was told by Otto Mader that even if there was something in "this jet idea," he had no one to put in charge of such a complex project. At this, Schelp suggested that Anslem Franz who was in charge of internal aerodynamics and turbo supercharger development be deputed to this project[4]. This was, as the project unfolded, a correct choice as Franz went on to develop the world's first production jet engine. It was Franz's engineering and management skills and his perceptive and deliberate choice of a conservative but achievable design target that resulted in the success of the Jumo 004 turbojet.

Wagner of Junkers Aeroplane Company handed over their existing design to Junkers Engine company but Dr. Max Mueller, who worked for Wagner, disliked Otto Mader and, not wanting to give up control of his engine, secretly approached Heinkel and offered to work for him. In May 1939, Mueller and most of his staff resigned from Junkers to go and work for Heinkel. Franz, having surveyed Mueller's work decided against using it and started work on a brand new axial flow design that would finally become the Junkers Jumo 004- the world's first production jet engine.

At the end of the war, the German jet engine program was highly advanced. The BMW company (which had absorbed Bramo) produced the 002 and 003 engines in competition to the 004 engine of Junkers. The general status of German engine development at the end of the war is shown in Table 1.

Clearly, the most advanced engine was the 011 engine developed by Ohain and Bentele at Heinkel Hirth[5]. The technical specifications for this were developed by Schelp who wanted a replacement for the BMW 003 and Jumo 004 engines. The design goals for the 011 engine included a 5:1 compressor pressure ratio, a thrust of 3,000 lbs and the utilization of no strategic materials which called for a completely air cooled turbine. Development of the 011 engine started in May 1943. Designed by von Ohain, this 3,000 lbs thrust engine utilized a completely air cooled turbine developed by Dr. Max Bentele.

RLM Engine Designation	Maker	Salient Features
001	Heinkel	Centrifugal machine designed by von Ohain. Design thrust of 1,100 lb, axial flow inducer, centrifugal compressor, annular, reverse flow combustor, and radial inflow turbine. This engine powered the He 178 (first jet flight)
002	BMW Bramo	Contrarotating turbojet. Design dropped in favor of the 003 engine.
003	BMW Bramo	Project headed by Dr. Hermann Oestrich, pressure ratio 3:1, annular combustor air cooled turbine.
004	Junkers	Design team leader Anslem Franz. 1980 lbs thrust, 3:1 pressure ratio, 6 combustors, single stage turbine. Powered the ME 262.
006	Heinkel	Advanced axial flow engine designed by Mueller for turboprop applications. Had variable turbine inlet nozzles. At the end of 1942 this engine developed 1900 lbs thrust (Weight = 875 lbs). Schelp instructed Heinkel to stop work on this engine to concentrate on the HeS 011.
007	Daimler Benz	Turbine driven duct fan. Turbine design based on partial admission cooling air cooling over 30% of blade circumference and 70 % hot working gas admission.
HeS8	Heinkel	Engine tried on the ME 262 but did not have enough thrust. Similar to the He S3b but, straight through combustor.
HeS 011	Heinkel Hirth	2,860 Lb. Static thrust, 10,200 RPM Axial flow compressor followed by diagonal (mixed flow) stage. Annular combustion chamber, 2 stage turbine, adjustable tail cone. W_t = 2,085 lbs, Dia.= 34.4", Length = 138.1"

Table 1: Status of German Jet Engine Development Programs at the end of WW II.

3.0 DESIGN AND DEVELOPMENT OF THE JUNKERS JUMO 004 ENGINE.

From the outset, Anslem Franz made a deliberate decision that his design would not aim at the maximum achievable but would focus on a very conservative goal that had the greatest chance of success. The reason that Franz did not aim high was that he recognized the need for rapid engine development and that failure may have caused Junkers or the Air Ministry to drop the entire program. This choice was the fundamental reason why the Jumo 004 was the first jet engine to reach production. Franz was initially given a few people from his supercharger department, but his group grew steadily to about 500 people in 1944. According to Franz, there were never any constraints in terms of funding or test facilities. His facilities were well equipped with test rigs and stands and even had an altitude chamber test cell (Franz, 1979).

3.1 Development of the 004 A Experimental Engine.

As Franz had no opportunity to design individual engine components a decision was made to design an experimental engine, the 004A, which would be thermodynamically and aerodynamically similar to the final production engine. The goal in developing the 004A was to have an operating engine in the

[4] It should be mentioned that Junkers had began, in 1938, a general survey of the field of gas turbines and jet engines under the charge of Anslem Franz.
[5] At Schelp's insistence, Heinkel and bought out the Hirth aeroengine company in August 1939 which provided them with excellent shops and facilities but also with the talents of people such as Dr. Max Bentele a renowned expert in blading vibration.

shortest time frame without consideration for engine weight, manufacturing considerations or minimizing the use of strategic materials. Based on the results of the 004A engine, the production 004B engine was to be built.

Even though Franz was familiar with centrifugal compressors because of his supercharger work, he chose an axial compressor design because he was convinced that frontal area was of fundamental importance and that gains could be achieved in efficiency with an axial design. The design of the 004 compressor was based on the work done by the AVA[6] in Goettingen, the compressor being designed by Encke with a peak efficiency of 82% and an operating efficiency of 75-78%. The compressor utilized pure reaction blading which resulted in a pressure ratio of 3.14:1 in 8 compression stages. The engine airflow rate was 46.6 lbs/sec (21.2 Kg/sec). The turbine was based on steam turbine experience of AEG , Berlin and blades were not of the vortex design as proposed by Whittle.

Franz recognized the superiority of an annular combustor design but opted for a 6 can type combustor as he knew that these would present less of a problem and permit bench testing with a single can. When the design of the Jumo 004 was reviewed by Schelp, he was critical of the conservative design in comparison to the BMW 003 but did not try to make Junkers institute any changes.

By the spring of 1940, the 004A had made its first test run and by January 1941 the engine was brought to full speed of 9,000 RPM and a thrust of 946 Lbs (430 Kg). At this juncture, the engine was plagued by compressor blade vibration failures. The sheet metal stator vanes which were originally cantilevered from the outside, suffered from vibration difficulties and renowned blade vibration specialist Max Bentele was asked to help in solving the vibration problems. Stator design was changed and by August 1941, a thrust of 1,320 lbs (600 Kg) was attained. In December 1941, a ten hour run at a thrust of 2,200 lbs (1,000 Kg) was demonstrated. On March 15, 1942, the engine was flown in a ME 110 test bed and later that year, on July 18th, the first flight of the ME 262 powered by two Jumo 004 jets took place and lasted for 12 minutes.

3.2 Development of the 004 B Production Engine.

Based on the excellent flight results, the air ministry issued a contract for 80 engines, These engines, rated at a thrust of 1,850 Lbs were used for further engine development and airframe testing. The 004A engine was unsuitable for production because of its considerable weight and its high utilization of strategic materials (Ni, Co, Molybdenum) which were not available to Germany at that time. Because of this, the 004B engine was designed to use a minimum amount of strategic materials. All the hot metal parts including the combustion chamber were changed to mild steel (SAE 1010) and were protected against oxidation by aluminum coating. Extensive air-cooling was used throughout the engine as shown in Figure 3 (Franz, 1979). The later version of the 004B engine had hollow air-cooled stator vanes. Compressor discharge air was used to cool the blades. With the hollow Cromandur sheet metal blade, the complete 004B engine had less that 5 lb of Chromium. A discussion of the materials used is provided in section 3.3.

The first production model of the 004B-0 exhibited a weight reduction 220 lbs (100 Kg) from the 004A engine. Additional modifications were made to the first compressor stages. A series of 100 hour tests were completed on several engines an a time between overhaul of 50 hours was achieved.

During the summer of 1943, several turbine blade failures were experienced due to a 6th order excitation (6 X No. of

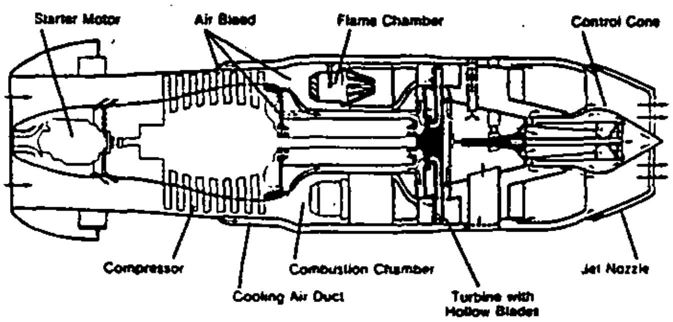

Figure 3. Air cooling flows in the Jumo 004 (Franz, 1979)

Combustors) when operating at full speed. The Junkers team worked diligently to resolve the problems. Franz recalls that he used the unconventional method to determine blade natural frequency by asking a professional musician to stroke the blades with a violin bow and then use his trained musical ear to determine the ringing natural frequency. The Air Ministry was, however, getting increasingly impatient and scheduled a conference in December 1943 at the Junkers Dessau plant, to be attended by turbine experts from government, industry and academia. Max Bentele who was instrumental in solving the problem attended this conference and listened to the numerous arguments pertaining to material defects, grain size, and manufacturing tolerances. As recounted by Bentele in his autobiography (Bentele, 1991), these were only secondary factors. When his turn came, he stated clearly, to the assembled group, the underlying cause of the problem, namely that the 6 combustor cans and the three struts of the jet nozzle housing after the turbine were the culprits. These induced forced excitation on the turbine rotor blades where a 6th order resonance occurred with the blade bending frequency in the upper speed range. The predominance of the 6th order excitation was due to the 6 combustor cans (undisturbed by the 36 nozzles) and the second harmonic of the three struts downstream of the rotor. In the 004A engine, this resonance was above the operating speed range but in the 004B it had slipped because of the slightly higher turbine speed and due to the higher turbine temperatures. The problem was solved by increasing the blade natural frequency by increasing blade taper, shortening blades by 1mm, and reducing the operating speed of the engine from 9,000 to 8,700 RPM. Performance curves for the Jumo 004 engine (Lewitt, 1953) are shown in Figure 4. The abscissa represents the air speed (mph) and the ordinate, the thrust in lbs. Curves of constant SFC are also plotted.

The leading particulars of the production engine are shown in Table 2. Volume production of the 004B-1 started in early 1944. In spite of difficult conditions, the engine was manufactured in increasing quantities. Approximately 6,000 engines were built by the end of the war.

According to Franz (1979) the 004E version was equipped with an afterburner. With turbine inlet gas temperature raised to 1600°F (870°C), the thrust increased to 2,640 lbs (1,200 Kg). The 004E was the first turbojet with an afterburner.

[6] Aerodynamische Versuchs Anstalt.

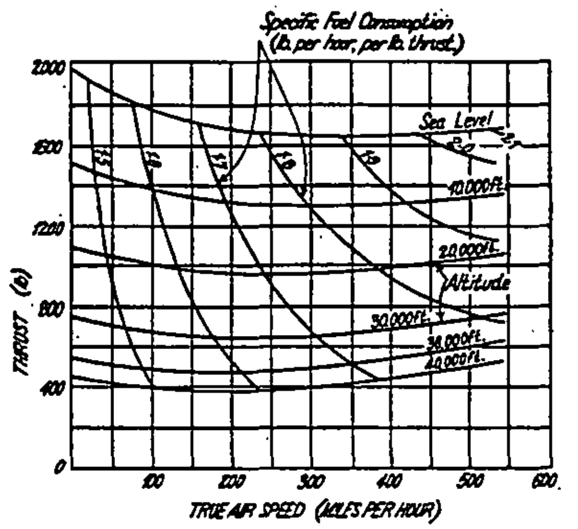

Figure 4. Jumo 004 Performance Map (Lewitt, 1953).

Airflow	46.6 lbs/sec (21.2 Kg/sec)
Pressure Ratio	3.1:1
Turbine Inlet Temperature	1427 °F (775°C)
Thrust	1980 Lbs (900 Kg))
SFC	1.4 lb/lb-hr
Engine Weight	1650 Lbs (750 Kg)
Thrust/Weight Ratio	1.21
Engine Diameter	30" (760 mm)
Engine Length	152" (3860 mm)
Compressor Blading Reaction	100%
Turbine Reaction	20%
$\eta_{Compressor}$	78%
$\eta_{Combustor}$	95%
$\eta_{turbine}$	79.5%

Table 2: Leading Particulars of the Junkers Jumo 004 B-1 Production Engine

3.3 Hot Section Materials.

In 1936, when development work on the Jumo 004 started, a high temperature Krupp steel known as P-193 was available. This material, which contained Ni, Cr, and Titanium, could be given good high temperature strength by means of solution treating and precipitation hardening. Krupp developed an improved version of P-193 known as Tinidur[7]. It was of the same type as Nimonic 80 which was used in British Gas turbines from 1942 but contained over 50% iron (which was replaced by Ni in Nimonic 80) and this caused a rapid drop in creep strength at 1,080°F (compared to 1,260°F for Nimonic 80). While Krupp knew that Tinidur could be improved by increasing the Ni content from 30% to 60%, there was a recognition that Ni would not be available. The Ni content was therefore left at 30%. Similarly, work on cobalt based alloys was also shelved due to a shortage of cobalt.

Junkers had investigated several materials, and by the summer of 1939, had concluded that Krupp's Tinidur was the material that would have to be accepted. The first turbine blades of the 004A version were solid. Early tests showed that even supposedly identical blades would have a large scatter life. By 1944, Junkers had solved the problem and obtained uniform quality of the blade by close control of the manufacturing process especially of the critical forging process. When the hollow blades were employed, attempts were made to produce them by folding flat sheets of Tinidur and welding down the trailing edge. This resulted in failure as Tinidur was not weldable. Eventually, a deep drawing process was utilized where the stock used for the blade was a flat circular blank. Blades could be manufactured by this process faster than the solid blades.

Considerably before 1944, work was initiated to search for a new material which would not have a 30% Ni content. Krupp developed another alloy material called Cromadur[8]. Cromadur proved easy to weld and the process of folding the blade flat and welding turned out to be superior to deep drawing, so that the Cromadur blades turned out to be more reliable than the Tinidur blading despite the lower creep strength of Cromadur. Comparative creep strengths of the materials is shown in Figure 5.

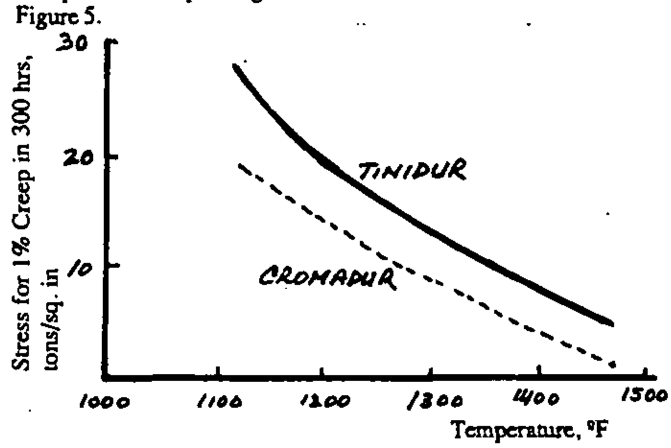

Figure 5. Comparative Creep Strength of Tinidur and Cromadur. (Data derived from Schlaifer, 1950, p 428)

4.0 DESIGN AND CONSTRUCTION OF THE JUMO 004 ENGINE.

Figure 6 shows a cross section drawing of the Junkers Jumo 004 turbojet (Neville & Silsbee, 1948). The total engine represented a design compromise to minimize the use of strategic materials and to simplify manufacture. Evidence of this is the high usage (approximately 7%) of compressor air bleed for cooling. In practice, time between overhaul was only 10 hours verses a design life of 25 to 35 hours[9]. The Jumo 004 was a large engine 152 inches (3,860 mm) in length and with a 30" (760 mm) diameter at the skin around the six combustion chambers.

4.1 Inlet Section.

The diameter of the intake was 20". The circular nose cowling contained two annular gas tanks. The upper 0.75 gallon

[7] Tinidur Composition: 15% Cr, 30% Ni, 2% Ti, 0.8% Si, 0.7% Mn, <0.15% C, Balance Fe.

[8] Cromadur Composition: 18% Mn, 12%Cr, 0.65%V, 0.5%Si, 0.2% Ni, <0.12%C, Balance Fe

[9] At the end of the war a heat resistant alloy had been developed which gave 150 hours in test flights.

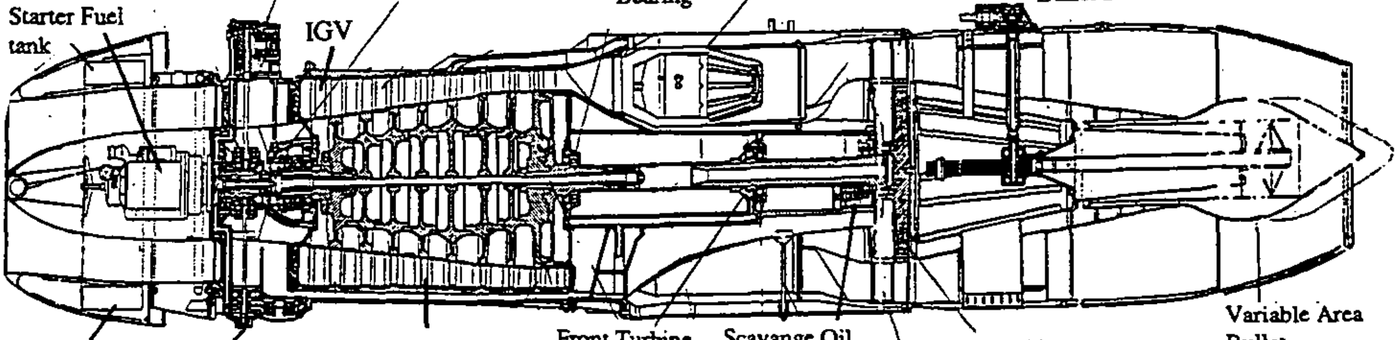

Figure 6. Cross Section of The Junkers Jumo 004 Turbojet (Neville & Silsbee, 1948)

gas tank contained fuel for the two cylinder 2 stroke horizontally opposed gasoline engine (made by Riedel). This engine produced 10 HP at 6,000 RPM. The Riedel starter engine had its own electric starter motor but for emergency purposes, also had a cable "pull starter" located in the nose cone as is seen in Figure 7. The lower 3.75 gallon capacity tank was to feed starting fuel to the combustion chambers. Details of the starter motor, auxiliary drive and main compressor bearing are shown in Figure 8.

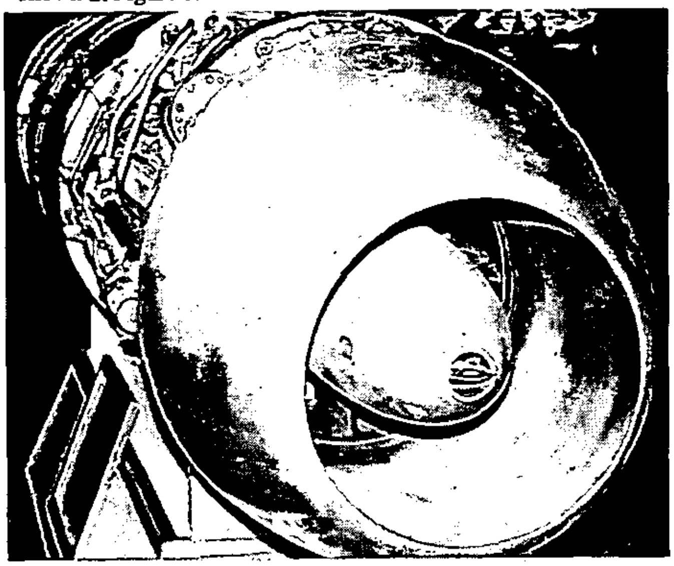

Figure 7. Intake nose cowling of the Jumo 004. Intake diameter was 20". The cable "pull starter" handle can be seen in the nose cone.

The starter engine was bolted to the 6 struts in the bevel gear casing which contained gears to drive the accessories. Two drive shafts were used, one extended down to the main oil pumps which were located inside the lower part of the casing. The rear part of the casing housed the front compressor bearing mounted in steel liners set in a light hemispheric shaped housing which was kept in contact with the female portion of the intake housing by the pressure of 10 springs held in place by a plate bolting to the intake casting. The outer bearing races were mounted in separate sleeves that fit on the compressor shaft. This design allowed preloading of the bearings to ensure an even distribution of thrust. The other advantage was that the bearing assembly could be left intact during disassembly by withdrawing the compressor shaft from the inner sleeve.

4.2 Compressor Section.

The Jumo 004 compressor was an 8 stage unit, (air flow rate 46.6 lbs/sec) the outer casing being of uniform diameter. The compressor rotor was made of 8 aluminum disks held together by 12 bolts and located by spigots. The entire assembly was pulled together by a 38.75 inch long (0.75" diameter) tie rod, estimated to have a stress of 40,000 psi with a pull force on the assembly of 16,000 pounds. The compressor section is shown in Figure 9. This figure depicts how each of the compressor sections were bolted together on shoulders of individual disks. There were 27 stamped aluminum blades in the first two rows and 28 blades in the rest of the stages. All had machined roots which fitted into the pyramid shaped slots in the rotor disk. A small screw was attached to the blade and extended into the disk (Figure 10). The stagger of the blades increased and the chord decreased in successive stages. The rotor turned on two steel shafts which were attached to the outside faces of the first and last discs. The compressor front bearing was made up of three ball races, each capable of taking end thrust. The rear bearing consisted of a single roller race.

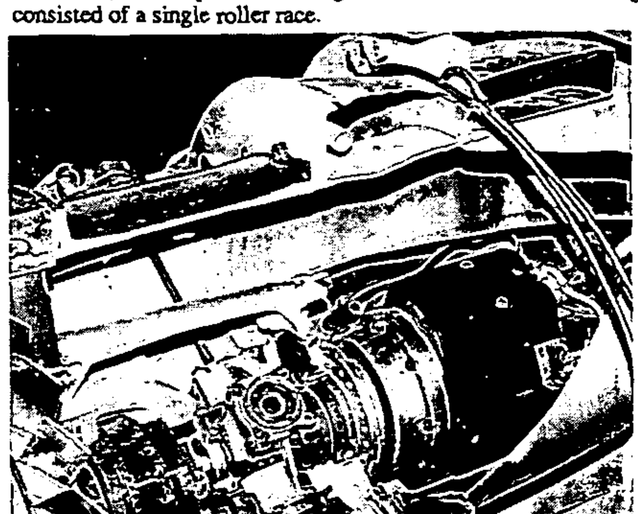

Figure 8. Inlet section showing the Riedel starter motor, the auxiliary drive, and front compressor bearing. The annular fuel tank for the starter motor can be seen within the nose cowling.

Cooling air flow were derived from between the fourth and fifth compressor stages and led to the double skin around the combustion chamber assembly. Most of the air passed down one of the exhaust cone struts to circulate inside the cone and passed through small holes to cool the downstream face of the turbine disk. Air was also taken through three tunnels in two of the ribs of the casting and into the space between the two plate diaphragms in front of the turbine disc. Most of this air passed through the hollow turbine nozzle guide vanes, emerging through slits in the trailing edges.

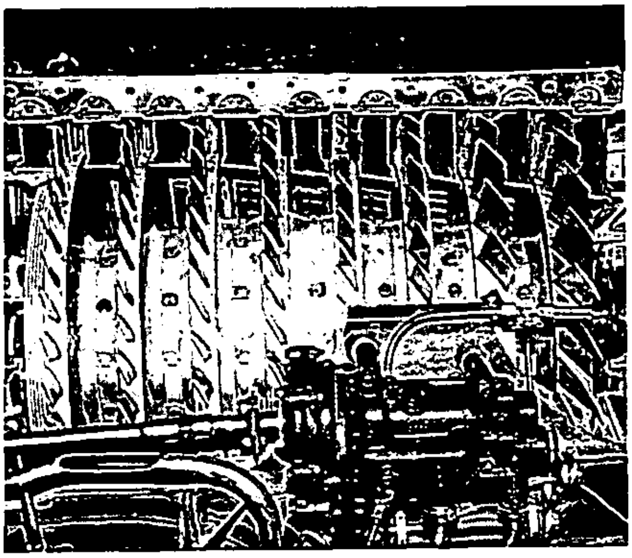

Figure 9. Compressor section of the Jumo 004.

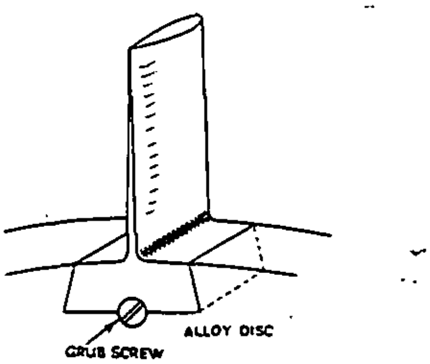

Figure 10. Grub screw attachment for compressor blading.

4.3 Combustor.

The Jumo 004 had six combustor cans arranged around the central casting carrying the rear compressor bearing and the turbine shaft bearing. Three of the cans carried spark plugs. The engine was designed to run on diesel fuel. Figure 11 (Judge, 1950) shows an individual Jumo 004 can. The approach to the combustor design was to derive a flame chamber region in the combustor for primary combustion at close to stochiometric ratio. To obtain good mixing, and a short flame length, the primary combustion air was introduced in this chamber with swirl and fuel was injected with a swirl against the airflow. Spark plugs were located in three cans and interconnectors were provided. The combution chambers were made of aluminized sheet steel. A cutaway view of the combustor can is shown in Figure 12.

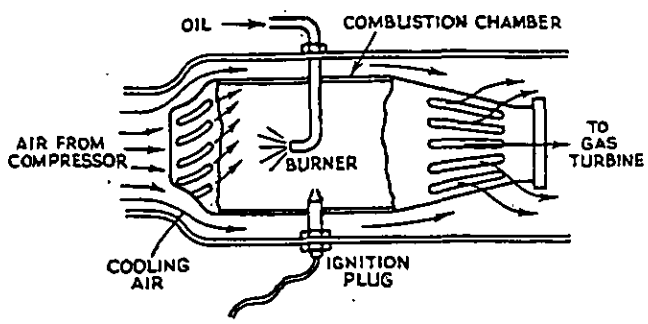

Figure 11. Combustor can arrangement of the Jumo 004. Helical slots were provided for combustion air to provide a swirl. The burner injected fuel upstream. Hot gasses passed out of the slots shown to the right and mixed with cooling air.

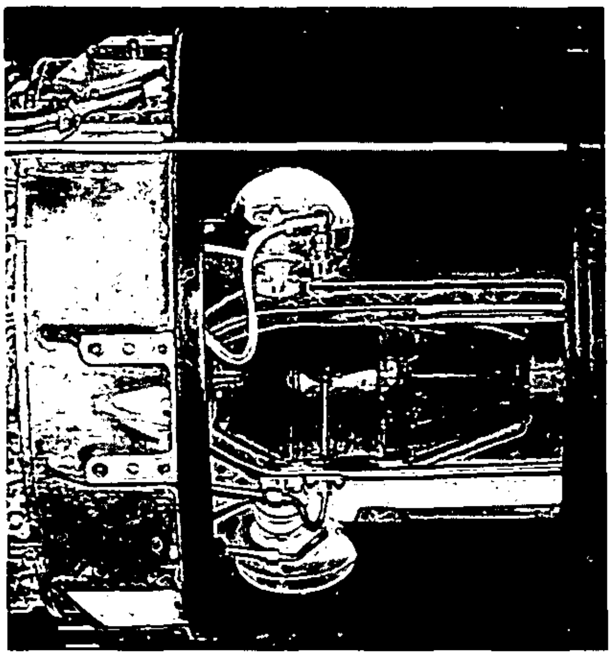

Figure 12. Cutaway of cumbustor can showing fuel nozzles and mixing slots (right). Six large hand holes were cut in the casing to allow access for making minor burner arrangements.

4.4 Turbine.

The turbine, designed in collaboration with AEG, had a degree of reaction of 20 % which represented a compromise between AEG who wanted less and Junkers who wanted more (afterburner considerations). The single stage turbine had 61 blades that were fixed to the turbine disk by a formed root and kept in position by rivets. Figure 13 shows the turbine disk and blading. The production version had air cooled hollow blades as shown in Figure 14 (Shepherd, 1949). Figure 15 shows the turbine inlet and exit velocity triangles (Lewitt, 1953). The absolute discharge velocity is 663 ft/sec. The heat drop across the turbine was approximately 64 BTU.

4.5 Exhaust Nozzle.

A movable "bullet" was mounted in the tailpipe operated by a servo-motor through the throttle lever. A rack and pinion device moved the bullet longitudinally, varying the nozzle area. On the ground, the bullet was fully forward under 50% of maximum RPM and fully back between 50% and 90% maximum RPM. At the beginning of takeoff, the bullet was near the end of its backward travel. In flight above 20,000 feet, at a speed of 400 mph, the bullet was moved even further back to provide maximum thrust. The servo-motor controlling the bullet was interlinked with a capsule surrounded by atmospheric pressure and having ram pressure inside it. This allowed the bullet position to be adjusted according to the ram pressure (i.e., the aircraft speed). The bullet operating gears are shown in Figure 16.

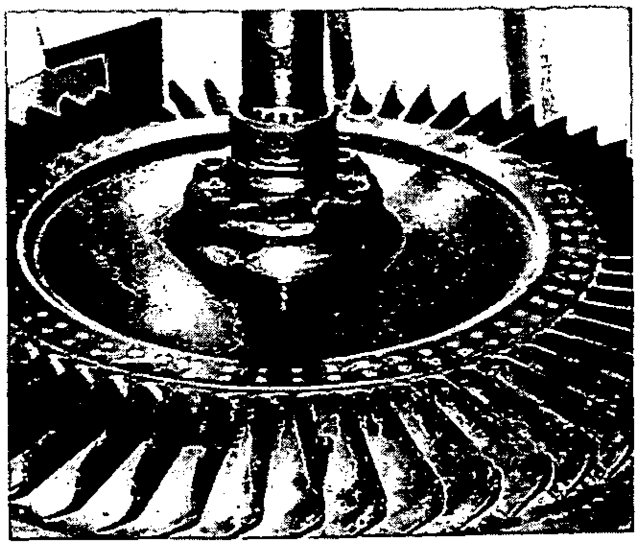

Figure 13. Uncooled turbine blades held by pins and brazed to disk. A special supply of cooling air was directed to the blade roots to maintain the strength of the soldered joint. The splined shaft coupling can also be seen. Each blade weighed 12.25 oz. Rivet diameter was 11 mm. Estimated maximum centrifugal stress ≈ 18,000 psi and gas bending stress ≈ 3,000 psi. Later models had air cooled hollow blades.

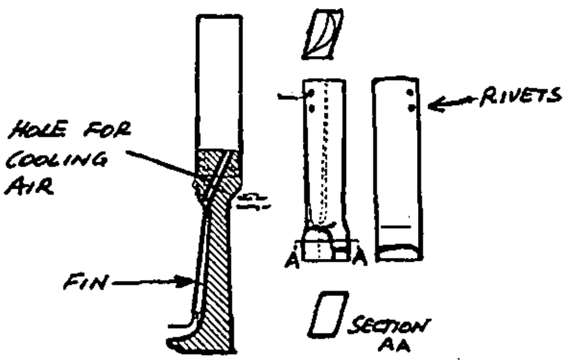

Figure 14. Hollow air cooled turbine blade. The disks for the hollow blade had a thin sheet across the front face flared out near the center. This picked up cooling air and whirled it towards the disk roots where it entered two small holes drilled in the disk rim and then flowed up through the blade. Later production models had two small rivets at the blade trailing edge near the tips needed to avoid a vibration cracking problem. (Shepherd, 1949)

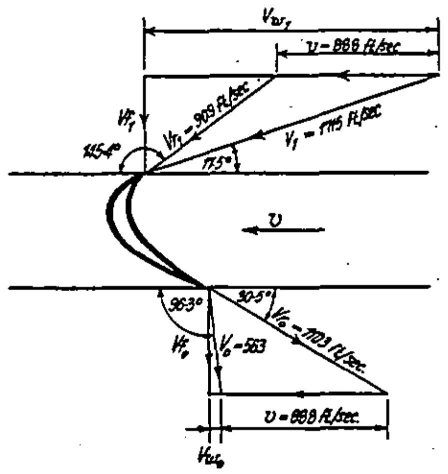

Figure 15. Velocity triangles for the axial flow Jumo 004 turbine. Absolute velocity at discharge was 563 ft/sec. Enthalpy drop across the turbine ≈ 64 BTU. (Lewitt, 1953).

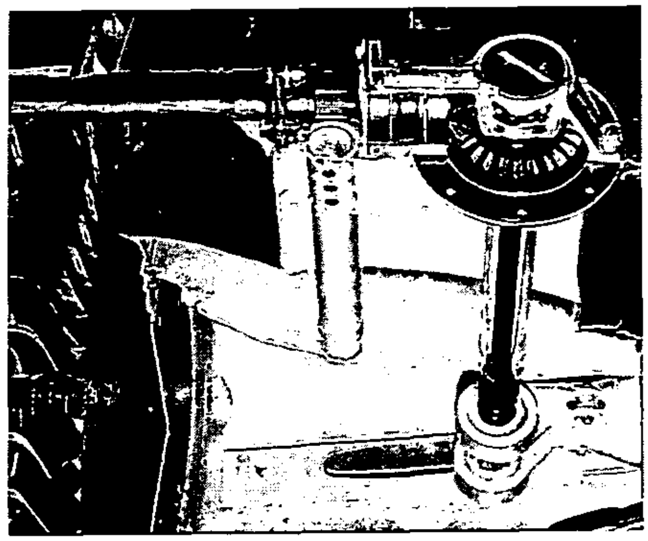

Figure 16. Bullet operating gear. The rack can be seen at the right and was driven by a shaft entering through a strut. This was controlled by the gear type servomotor (located above the compressor section) and driven by a long torque tube to the gears on the exhaust housing shown. Maximum travel of the "bullet" was 18.73 cm.

4.6 Other Engine Systems.

4.6.1 Lubrication System. Lubricating oil was carried in an annular nose tank. Two pressure pumps were provided, one supplying oil to the RPM regulator, oil servo motor and compressor front bearing. The other pump supplied oil to the compressor rear bearing, and the two turbine rotor bearings. These oil pumps were located below the engine and driven by bevel gears through a nose casing strut.

4.6.2 Auxiliary Drive Case. The auxiliary casing was located above the engine and driven from the front compressor shaft. The casing drove the fuel injection pump, the RPM governor and the pump for the thrust regulator and the bullet servo motor. The accessories located above the engine are shown in Figure 17.

4.6.3 Instrumentation. The instrumentation consisted of the several gauges indicating the fuel injection pressure gauge, RPM[10], exhaust gas temperature, exhaust gas pressure and oil pressure.

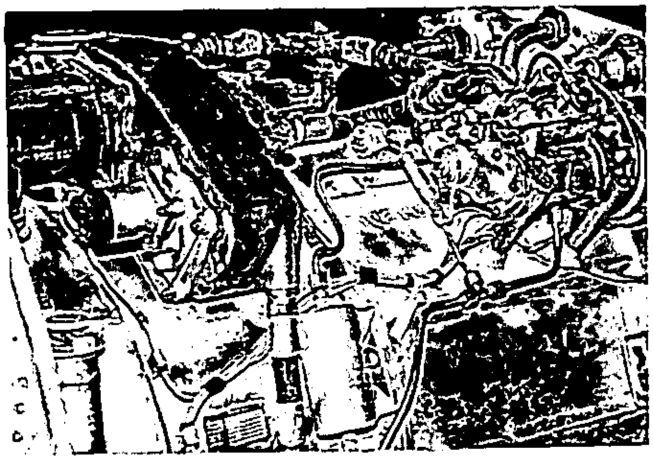

Figure 17. Auxiliary equipment located above the compressor section including fuel injection pump, speed regulator (governor) and bullet servomotor.

4.7 Comparative Analysis of the Junkers Jumo 004 and the Rolls Royce Welland.

It is of interest to compare a few salient features of the Jumo 004 and the Welland which was the power plant for the Meteor and the only other engine to go into production during the second world war. The Welland went into production in May 1944. The Derwent I went into production in November 1944 at approximately the same time as the BMW 003 in Germany. The Junkers Jumo 004B engine was frozen for production in November 1943. Table 3 shows a comparative analysis between the two production engines.

Parameter	Welland	Jumo 004
Lb/Thrust	0.53 Lb/lb	0.83
Max. Frontal Area, sq in/Lb thrust	0.94	0.46
Fuel Consumption	1.12 lb/lb thrust	1.4-1.48
Pressure Ratio	4:1	3.1:1
Compressor Configuration	Centrifugal Compressor	Axial Flow Compressor.
η Compressor	75%	78-80%
η turbine	87%	79-80%

Table 3: Comparison between the Welland and Jumo 004 Turbojets.

5.0 THE ME 262 JET FIGHTER.

5.1 Aircraft/Powerplant Development.

In 1938[11], the German Air Ministry awarded a design contract to Messerschmitt for the design of a radical jet fighter, the power plants of which were to be the BMW 003. The ME 262 was developed under Project No. 1065 and was conceived to be an interceptor fighter with swept back wings. After building a mockup in January 1940, a contract was awarded of three prototypes for flight testing[12].

Messerschmitt encouraged his designers to work in teams and created a climate which encouraged innovation. The design team settled for two engines and a tail wheel undercarriage. Because the wing was too thin to accommodate the landing wheels, they were designed to retract into the fuselage, giving the aircraft its characteristic shark-like triangular cross section.

Over time, changes in weight and dimensions in the power plants influenced the design. Engine problems with the BMW 003 engines resulted in low thrust[13] requiring a major redesign. In November 1941, BMW 003 engines now capable of only 1,015 lbs thrust, were fitted to a ME 262 prototype which included a 12 cylinder Jumo 210G piston engine in the nose. Fritz Wendel, a legendary test pilot took off and experienced flame out of both BMW 003 engines. After he managed to get the aircraft on the ground by virtue of his superb flying skill, BMW engineers found both engines had broken compressor blades. It was clear that another major engine redesign would be required.

By this time, Franz had developed the Jumo 004 to a point where it could be flown on the ME 262. During taxiing trials, Wendel found that in order to raise the tail wheel, he had to touch the brakes at approximately 112 mph. The cause of this problem was the the attitude of the aircraft (tail wheel configuration) and the ground turbulence caused by the jet engines, which caused the elevator to be ineffective. At 8:40 am on July 18th, 1942, Wendel completed a successful test flight and described in section 1 of this paper and reported that the engines "ran like clockwork". Later, the fourth prototype ME 262 was also flown by a distinguished fighter pilot ace Adolf Galland. Anslem Franz recalled (Jones, 1989) that he was on the wing trying to advise the impatient Galland about the delicate control limitations of the jet engine when Galland told him "OK, OK, I understand please get off- I want to go!" After the flight, Galland was most enthusiastic and even recommended that all fighter production be restricted only to ME 262s and Focke Wulf 190s.

5.2 Deployment of the ME 262.

The deployment of the ME 262 was delayed by bureaucratic problems and Hitler's insistence that that it be retrofitted as a bomber. A few days after the Normandy landings, he issued an order permitting *testing* of the ME 262 as a fighter but insisting that the bomber deployment not be delayed. Galland's vehement and vocal opposition to this finally resulted in his dismissal, though he was later recalled to form and lead a group of fighters (Fighter Group JV44)[14] as the war drew to a close.

[10] This gauge had an inner (0-3,000 rpm) scale for startup and outer scale (2,000-14,000 rpm) for flight.

[11] Almost one year before the outbreak of WW II.

[12] This was approximately the same time when Heinkel obtained his contract for the HE 280.

[13] The 003 engine was designed to give a thrust of 1,320lbs at 560 mph and a turbine entry temperature of 1652°F. This temperature was too high and was consequently lowered in late 1939 to 1382°F. When the engine was first run in 1940, it produced a thrust of only 570 lbs due to the mismatching of components.

[14] The JV44 Unit was based at Munich from March 31st, 1945. Galland choose an elite group of 50 pilots. Galland was shot down on August 26th, 1945 and his squadron fought on using the Autobahns to avoid strafed airfields. The squadron was then transferred to Salzburg where, on May 3rd, 1945, it was overrun by US forces. Adolf Galland died in Oberwinter, Germany at the age of 83 on February 26th, 1996.

From mid 1944, both fighter and bomber versions rolled of the production line. The supply of Jumo 004 engines really started in quantity in Spring 1944. On July 25th, 1944, a RAF reconnaissance Mosquito flying at 29,000 ft near Munich encountered, for the first time in history, a jet powered interceptor.

5.3 ME 262 Operation

The ME 262 is widely acknowledged to be superior (at least in terms of performance) compared to any fighter that the Allies had during 1946 and 1947. The ME 262 had a maximum speed of 524 mph (at 20,000 ft), a service ceiling of 37,565 feet and a rate of climb of 3.937 ft per minute at sea level. It had an endurance of one and a quarter hours. The aircraft had a high wing load (66 lbs/sq ft) and had a take off speed of 190 mph requiring a long takeoff run of 3,200 feet into a 15 mph wind. The landing speed was correspondingly high , just under 200 mph. This made the ME 262 vulnerable to attack during takeoff and landing.

The aircraft was a low wing, 41 foot wingspan, all metal monoplane with the wing having a leading edge sweepback of 18.5 degrees which delayed high speed compressibility problems (Mach effects) The engines were carried under the wings (underslung nacelle) and other than the first 4 prototypes, were fitted with tricycle landing gear. Two versions were built- the ME 262 Schwalbe (Swallow), a fighter and a fighter bomber called the Sturmvogel (Stormbird). The standard fighter was fitted with four Mk 108, 30 mm nose cannon. The fighter bomber was designed to carry two 550 lb bombs under the wings. Specifications of the Messerschmitt ME 262B are presented in Table 4.

Engines	Two, Junker Jumo 004B, each rated at 1984 Lbs (900 Kg) thrust
Span	40ft, 11.5 in. (12.48 m)
Length	34 ft, 11.25in (10.65m)
Wing Area	233.8sq. ft (21.72 sq. M)
Take off Weight	15,432 Lbs (7,000 Kg)
Maximum Speed	503 - 530 mph (810 Km/hr +)
Service Ceiling	34,450 ft, (10,500 m)
Range	559 miles (900 Km)
Climb to 26,000ft	11 minutes

Table 4: Specifications of the Messerschmitt ME 262B.

The first pure turbojet flight of the ME 262 took place on July 18th, 1942 using two pre-production Jumo 004 engines. Testing continued through 1942 and 1943. Potentially the ME 262 could have seen service early enough to prevent allied air superiority prior to the Normandy landing but priority for production was placed on bombers. Hitler also forbade production of the ME 262 until August 1943 when the decision was finally made to produce it in quantity. By then, Allied bombing had severely hampered production. Further, Hitler wanted all ME 262s converted into bombers for which the design was totally unsuited. It was at the end of 1944 when Hitler reversed his decision and the ME 262 was available in quantity for deployment as a fighter. However this decision was too late and even though a total of 1,400 aircraft were built, only 200 reached actual squadron service. During the Fall and winter of 1944 and 1945, a substantial number of ME 262s were put into operational use. There is no doubt that, had the ME 262 been deployed quickly and in quantity, it would have seriously hampered the Allied campaign.

Some insight relating to the engine operation of the Jumo 004 engines can be obtained from a direct translation of Messerschmitt's test pilot Fritz Wendel's flight notes presented in Boyne (1980). Excerpts pertaining to the engines have been presented in the Appendix. It is interesting to note the concern relating to surge (called "cavitation" by Wendel), during engine acceleration.

5.4 Other Applications of the Junkers Jumo 004 Engine.

The Junkers Jumo engines also propelled the world's first jet bomber, the Arado 234. The Arado was designed in 1941 and went into production in 1944. Several variants were built, the most common being the Arado 234 B which was an all metal single seat high wing aircraft powered by two Jumo 004 turbojets[15]. The Arado was a high wing, all metal aircraft. This aircraft had a maximum speed of 421 mph at 20,000 ft a range of 1,000 miles and a payload of 3,300 Lbs. The Jumo 004 was also used in the experimental forward swept wing Junkers Ju 287 four engine bomber. These aircraft are shown in Figure 18. After the war, the Jumo, designated the RD-10, was used in early Russian jets and powered the Yak-15, Yak-17 and the Sukhoi SU-9 (Morgan, 1994).

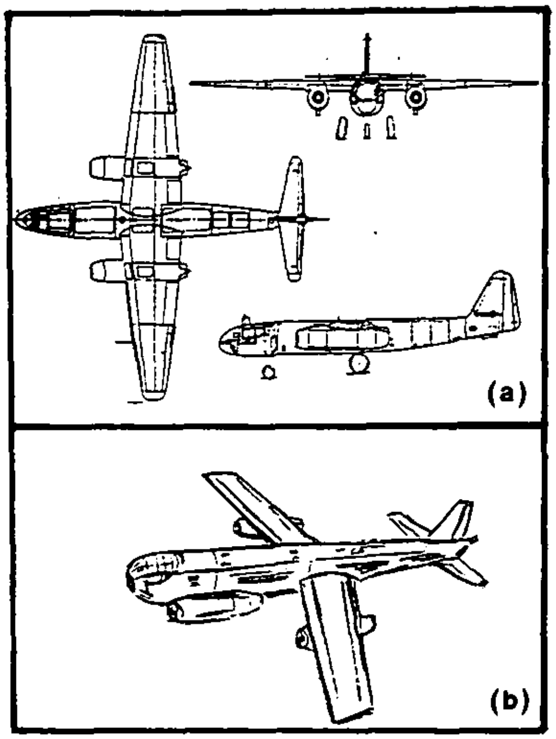

Figure 18 (a) The Arado 234 B, the world's first operational jet bomber powered by 2 x Junker Jumo engines. This aircraft was capable of 470 mph at 20,000 ft. (b) The Junkers JU 287 forward swept wing heavy jet bomber, originally powered by 4 X Jumo 004 turbojets. Capable of 527 mph at 16,400 ft.

[15] Later versions of the Arado 234 Bs were fitted with BMW 003 jet engines.

6.0 ANSLEM FRANZ- DISTINGUISHED JET ENGINE PIONEER (1900-1994)

Anselm Franz was born in Schladming, Austria in 1900. He studied mechanical engineering at the Technical University of Graz in his native Austria and received his bachelor's degree and master's degree. He obtained a Doctral degree from the University of Berlin. He was later awarded honorary doctorates from the University of Graz, and the University of Bridgeport.

Before World War II, Mr. Franz was a design engineer at Schwarzkopff Werke in Berlin where he developed Hydraulic torque converters. He joined the Junkers Engine Company (Dessau, Germany) in 1936 where he finally became Chief Engineer. He was head of supercharger development when, in 1939, he was put in charge of the design of the Jumo 004 turbojet. This engine was a success due to his brilliant leadership and astute choices in terms of design compromise.

Following the war, he came to the USA where he first worked for the U.S. Air Force and then, in 1951, joined Avco Lycoming where he was responsible setting up the gas turbine department and was instrumental for several successful engine development programs including the T53 (which powers the US Military's AH-1S Cobra, Grumman OV-1 Mohawk and Bell UH-1 helicopters) and the T55 series of turboshaft engines as well as the T55 high bypass turbofan (named the ALF502). In the 1960s, Anslem Franz led a team to design the 3 spool, 1500 SHP, AGT-1500 gas turbine which is the power plant for the US M1 Abrams Main Battle Tank. He retired as Vice President of Lycoming in 1968. Dr. Franz was a Fellow of the ASME and of the AIAA and received numerous awards including the 1967 Dr. Alexendar Klemlin award from the American Helicopter Society, the U.S Army Outstanding Civilian Service medal, the ASME R. Tom Sawyer Award and the Grand Decoration of Honor, in Gold with Star from the Austrian Republic in 1991.

He passed away at the age of 94 in Stratford Connecticut. Anslem Franz will forever be remembered as a jet engine pioneer and member of a select group of individuals who were responsible for the turbojet revolution.

7.0 CLOSURE

This paper has covered the background, design philosophy and development of the world's first production jet engine, the Junkers Jumo 004 turbojet. The development represented a historic achievement of Anslem Franz and his design team at Junkers. Approximately 6,000 engines were built at the end of the Second World War in the face of acute shortages of materials and damage to German industry. The Jumo was brought from conceptual design to production in a span of four years under the leadership of Anslem Franz, a pioneering achievement in the dawn of the jet age.

Acknowledgments.

Obviously, in a historical report of this kind, considerable use has been made of historical texts and technical reports and these have been referenced to the extent possible. A major source was, of course, Franz's paper (1979) presented at the 40 Anniversary of the Jet Engine as well as the excellent work of Jones (1989), Schlaifer (1950), Constant (1980), Boyne (1980) and Gunston (1995) which are highly recommended to those wishing to pursue this topic further. A good reference on the ME 262 may be found in Morgan (1994).

REFERENCES

Bentele, M., (1991) "Engine Revolutions: The Autobiography of Max Bentele," SAE Publications, 1991.

Boyne, W., (1980) "Messerschmitt 262: Arrow to the Future," Smithsonian Institute, Washington, 1980.

Boyne, W., Lopez, D., (editors), (1979) "The Jet Age: 40 Years of Jet Aviation," Smithsonion Institute, Washington, 1979.

Constant, E.W., II, (1980) "The Origins of the Turbojet Revolution," John Hopkins Univ. Press, 1980.

Ford, D.,(1922) "Gentlemen, I Give You the Whittle Engine," Air and Space, October/November 1992.

Foster, J, Jr, (1945, "Design Analysis of the Messerschmitt ME 262," Aviation, Vol 44, No 11, 1945.

Franz, A., (1979) "The Development of the "Jumo 004 Turbojet Engine," 40 Years of Jet Engine Progress, ed Boyne, W.J., and Lopez, D.S., National Air and Space Museum, Smithsonian, Washington, 1979.

Green, W. And Cross, R., (1980), "The Jet Aircraft of the World," Arno Press, NY, 1980.

Gunston, B., (1995), "The Development of Jet and Turbine Aero Engines," Patrick Stephens, Ltd., UK, 1995.

Gunston, B., (1995), "World Encyclopedia of Aero Engines," Patrick Stephens, Ltd., UK, 1995.

Jones, G.,(1989) "The Birth of Jet Powered Flight," Methuen, London, 1989.

Judge, A.W., (1950), "Modern Gas Turbines," Chapman and Hall Ltd. UK, 1950.

Lewitt, E.H., (1953) "Thermodynamics Applied to Heat Engines," Sir Isaac Pitman & Sons, London, 5th Edition..

Morgan, H., (1994), "ME 262 Stormbird Rising," Motorbooks International, 1994.

Munson, K., (1977), "Famous Aircraft of All Time," Arco Publishing Company Inc., 1977.

Neville, L.E., Silsbee, N.F., (1948) "Jet Propulsion Progress," Mc Graw Hill Inc, 1948.

Oakes, C.M., (1981) "Aircraft of the National Air and Space Museum," Smithsonian Institution Press, Washington, DC, 1981, pp 108,109.

Schlaifer, R., (1950) "Development of Aircraft Engines," Graduate School of Business Administration, Harvard University, Boston, 1950.

Scott, P.,(1995) "Birth of the Jet Engine," Mechanical Engineering, January 1995, pp 66-71.

Shepherd, D.G., (1949), "Introduction to the Gas Turbine," Constable & Company Ltd, 1949.

Smith, J.R., Kay, A., (1972)"German Aircraft of the Second World War,", Putnam, London 1972.

Stevens, J.H., (1953), "The Shape of the Aeroplane," Hutchinson and Company Ltd., London, 1953.

Von Ohain, H., (1979) "The Evolution and Future of Aeropropulsion Systems," 40 Years of Jet Engine Progress, ed. Boyne, W.J., and Lopez, D.S., National Air and Space Museum, Smithsonian, Washington, 1979.

APPENDIX

Wendel made the first flight in the Me 262 and was subsequently a major figure in the test program.
The following are some engine related flight notes excerpted from Boyne (1980).

PILOTS NOTES ON ME 262 BY FLUG KAPITAN FRITZ WENDEL:

"In addition to studying the condensed instructions for airframe and engines, a thorough knowledge of these notes, preferably before the first flight in an Me 262, is essential to the pilot.

1. *Taxiing*

Always accelerate the engines slowly. The gas temperature must never rise above the permitted value and the engine must not "roar" (*bullern*). In view of this, only take corners by using the brakes, never by using the engines. Always taxi gently and never make sharp turns, otherwise control of the aircraft will be lost.

2. *Take-off*

Switch on the fuel pumps in the main tanks. Hold the aircraft stationary by applying the brakes and then slowly run up the engines, especially slowly up to 7,500 r.p.m. The brakes must be so adjusted that they will hold the aircraft stationary up to 8,500 r.p.m.

After releasing the brakes, push the throttle lever right forward and then check over the engine. The aircraft makes so little demand upon the pilot at the commencement of the take-off run that he is easily able to carry out this check. The check is done by eye and ear, the engines must not "roar" and the instruments must show the same values as they did during running up or during previous take-offs. The gas pressure must be especially watched, and if it is more than five per cent lower than previously, do not take-off. In such a case, it is most likely that cavitation has taken place in one of the compressor stages, that is, by running up too quickly, the compressor has been overloaded and the smooth flow breaks up, exactly as it does when a wing stalls. Cavitation takes place so easily in many compressors as a result of small constructional faults or as a result of foreign bodies that they become entirely unserviceable. It the take-off is continued when cavitation has occurred in the compressor, then the quantity of air flowing through is too small, the quantity of fuel injected however is the same or sometimes even larger, as a result of which, the engine is overheated."