THE HISTORICAL EVOLUTION OF TURBOMACHINERY

by

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ABSTRACT

This paper presents a comprehensive treatise of the antecedents, evolution, developments, and inventions relating to turbomachinery from early paddle wheels to modern turbojets emphasizing the constant challenge, failures, and problems faced by engineers as they strived toward developing higher performance turbomachinery. Both normal technology and radical innovations are covered. Radical innovations or technologies are those that allow quantum leaps in turbomachinery technology. Particular emphasis is paid to the turbojet revolution that occurred before and during the Second World War, which ended the dominance of the reciprocating engine for aircraft propulsion and spurred technological advancements, leading to today's advanced turbomachines.

INTRODUCTION

From antiquity to the present day, there has been a constant quest for the mastering of power. From man's beginning to 1700 AD, all the motive power was provided by men or animals. Thereafter, there has been a rapid growth of technology encompassing hydraulic turbines, steam engines, and steam and gas turbines, culminating in the modern turbofan engine that represents the state-of-the-art of turbomachinery engineering today.

In any technical development, it is of critical importance to examine the historical antecedents that preceded it and examine the underlying causes creating the technology. George Santayana pointed out in his famous dictum: *"Progress, far from consisting in change, depends on retentiveness….those who cannot remember the past are condemned to repeat it."*

In the design of a new and complex turbomachine such as a gas turbine or compressor that pushes the envelope of technology, it is not always possible or realistic to design it perfectly the first time. Encompassed within the history of turbomachinery development are several instances of problems that had to be solved at great personal and financial cost. Petroski (1992) has studied the area of the role of failure in engineering design and points out the importance of how history can help in avoiding past mistakes. Another excellent reference is a book by Whyte (1975), entitled *Engineering Progress Through Trouble*, which presents case histories covering a wide range of equipment, including the Whittle turbojet, the famous QE2 steam turbine blade failures, and the failures of the Comet Aircraft.

In an age of unprecedented technological growth, we are often told that technology and knowledge are accelerating in an exponential fashion. We must recognize, however, that on a historic time scale, we are examining an exceedingly tiny period of human development as depicted in Table 1. This table represents a compression of the elapsed time from the Big Bang event to the present day and puts in perspective the fact that on a cosmic scale, our knowledge is still in its infancy. In a few decades, the technology that we now are so enthralled with will, in all probability, be a thing of the past in the same manner that steam engines, once mankind's dominant prime mover, are now relics. We will not even be able to comprehend or understand some of the technologies that will be present in a few hundred years.

Table 1. Time Compression from the Big Bang to the Present Showing Technology Development.

EVENTS	TIME- COMPRESSED AND SCALED TO 1 YEAR
Big Bang	Jan 1st
Origin of (Our) Milky Way Galaxy	May 1st
Origin of the Solar System	Sept 9th
Formation of the Earth	Sept 14th
Jurassic Period	Dec 27th
First Humans	Dec 31st, 10:30 PM
Invention of Agriculture	Dec 31st, 11:59:20 PM
Bronze metallurgy, Trojan wars, invention of the compass	Dec 31st, 11:59:53 PM
Iron Metallurgy	Dec 31st, 11:59:54 PM
Euclidean Geometry, Archimedean Physics, Roman Empire, Birth of Christ	Dec 31st, 11:59:56 PM
Renaissance in Europe, experimental methods in science	Dec 31st, 11:59:59 PM
Wide developments in science and technology, power, turbomachinery, flight, space flight , computers,	**Last second of the year** i.e., NOW

This paper provides a historical trace of the technological background and the incentives that were present for developments leading to modern day turbomachinery. Due to the constraints of space it is impossible to deal with all the contributors to turbomachinery engineering and there are, consequently, large gaps in the history ahead, with many famous names and inventions going unmentioned. Considerable emphasis has been placed in this paper on gas turbine technology and evolution and the early jet engine work in Britain, Germany, and the US. There are two basic reasons for this emphasis:

- Modern day gas turbine and turbojet engines represent the state-of-the-art of turbomachinery design and are the most sophisticated turbomachines available today. Many of the technological advancements and design techniques in the gas turbine area permeate down to industrial compressor and steam turbine applications.

- Development of gas turbines and the subsequent turbojet revolution required antecedent developments in the areas of hydraulic turbines, thermodynamics, steam turbines, compressors, aerodynamics, and rotordynamics. Hence, in covering gas turbines, one can also focus on these antecedents.

Technology Changes and Development

Technology can be categorized into "Normal Technology" and "Revolutionary Technology."

Normal Technology Development

The most prevalent change has been normal (incremental or gradual) technological change, which consists of innovations that improve the efficacy and efficiency of technology. A lot of development in the turbomachinery arena has been of this nature.

Characteristics of such normal change include:

- Engineering refinements as the result of careful testing and experience
- Manufacturing process optimization
- Development of new metallurgy (stronger, higher temperature)
- Development of new configurations (variations and optimizations of existing schemes)

An example of normal change is the growth in power of reciprocating aircraft engines in the 1925 to 1945 timeframe where power increased tenfold, from under 350 hp to over 3500 hp. This development came at great cost and effort but would still be considered normal technology as no step changes occurred. The introduction of the prony brake, which allowed the scientific testing of hydraulic machines and a consequent improvement in their efficiency, was an important step in technology but would also be considered a normal technology change.

Technological Revolutions

Radical or revolutionary change on the other hand, involves a step jump in technology. Kuhn (1962), has documented the dynamics of scientific revolution in his classic book, *The Structure of Scientific Revolutions*. A classic example of such a revolution is the introduction of jet engines, which within a few years rendered reciprocating aircraft engines essentially obsolete.

There are some common factors that occur in technological revolutions:

- They occur *outside* the affected sectors and are often instituted by outsiders. For example turbojet development in both Great Britain and Germany was *not* initiated by any major engine manufacture but was initiated by "outsiders."
- They are initially opposed or treated with contempt by the ruling establishment who, after the concept is proven and established, embrace it with great enthusiasm often taking control of the ongoing developments and displacing the innovator.
- Entities that continue to resist change cease to exist. An example being Curtis-Wright, which resisted jet engine technology till the 1950s before it reduced itself from the greatest aeroengine company to a subcontractor that ultimately left the aeroengine business.
- Upon establishment of the new technology, control often passes from the innovator to the more traditional companies. For example, Sir Frank Whittle's Power Jets Limited, was asked to stop work on new gas turbine engines and concentrate on research.
- The innovators often (but not always) had some knowledge of history and previous attempts that were made along the lines of their inventions.
- There is always an underlying dynamic that "forces" the radical invention, i.e., there is, at least in the mind of the innovator, a clear technological need for the invention. Both Whittle and von Ohain, for example, clearly saw the need for replacement of propellers in the quest for high-speed flight.

To indicate how technological change is strongly opposed, it is interesting to note the following pronouncements (Augustine, 1983):

- "As far as sinking a ship with a bomb is concerned, it just can't be done." –Rear Admiral Clark Woodward, 1939, US Navy.
- "I have not the smallest molecule of faith in aerial navigation (flight) other than ballooning." –Lord Kelvin, circa 1870.
- "The energy produced by the breaking down of atoms is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine." –Ernest Rutherford, circa 1930.
- "Fooling around with alternating currents is just a waste of time. Nobody will use it." –Thomas Edison, circa 1880.
- "X-rays are a hoax."–Lord Kelvin, circa 1880.
- "That is the biggest fool thing we have ever done…. The atomic bomb will never go off, and I speak as an expert in explosives." –Admiral William Leahy, US Navy, to President Truman, 1945.
- "Space travel is utter bilge." –Sir Richard van der Riet Wooley, Astronomer Royal, 1956.

We will see statements such as these made by eminent scientists and engineers in the course of the evolution of turbomachinery development. For example, opposition to Sir Frank Whittle, when he proposed the turbojet concept, delayed turbojet development for years. There is some conjecture that had the British government supported Whittle, the balance of air power at the onset of World War II may have been radically different, possibly affecting the course of the war. To compound the institutional challenges and resistance, Whittle also faced significant *technical* challenges including developing centrifugal compressor pressure ratios of 4:1 from the prevailing technology level of 2.5:1, increasing compressor efficiencies from 65 to 80 percent, and designing for combustion intensities that were 10 times the prevailing state-of-the-art in boiler technology.

Another factor in a technological revolution is that the group or person that creates the new development must have the skill to sell it. There is an interesting anecdote (Chandrasekhar, 1987) relating to Faraday who discovered the laws of electromagnetic induction, which then led him to development of theories of lines of force and force fields that were, at that time, totally foreign to the prevailing modes of thought. When Gladstone, who was the Chancellor of the Exchequer, impatiently interrupted Faraday's description of his work on the generation of electricity by the inquiry, "But after all, what *use* is it?" Faraday's response was, "Why Sir, there is every probability that you will soon be able to tax it." This is an excellent example of presenting the benefits of a new technology in terms that the recipient appreciates!

HISTORICAL ANTECEDENTS TO TURBOMACHINERY DEVELOPMENT

One of the earliest developments of turbomachinery is attributed to Hero of Alexandria, circa 100 BC (other sources place the time as 62 AD), where, in his book *Pneumatics*, he described a device known as the Aeolipile, shown in Figure 1, which could rotate using the reaction principle. The bowl held a supply of water and served as a boiler. Two hollow tubes extended from the boiler and entered a sphere that had two jets, which caused the sphere to spin. This was just one of several innovative inventions attributed to Hero. The Romans introduced pure impulse type paddle wheels in around 70 BC used for grinding grain.

Figure 1. Aeolipile Developed by Hero of Alexandria 120 BC. (Sawyer, 1945)

The concept of reaction for propulsion allowed rockets to be constructed as early as 1232 AD, both for use in war and for fireworks. There is a story of a Chinese scholar, Wan Hu, who devised a rocket-based sledge, but reportedly the attempt failed when the rockets exploded and obliterated the brave pilot.

In approximately 1500 AD, Leonardo Da Vinci described a "chimney jack," shown in Figure 2. In this device, hot air passed over fan-like blades that acted as a turbine and rotated the spit by the use of crude bevel gears.

In 1629, there is a mention by Giovanni Branca, an Italian engineer, of an impulse turbine that was used to power a stamping mill. This was a device where steam was generated and directed via a nozzle on a horizontal wheel containing blades. The rotary motion was converted to stamping action by means of bevel gearing, as depicted in Figure 3. It is reported that Branca built this device but, upon explosion of the boiler, was locked up on the plea that he must be mad!

In 1687, Sir Isaac Newton formulated his laws of motion, which were fundamental to the development of all kinds of turbomachinery. A "Steam Wagon" that utilized a reaction jet to provide forward movement was proposed later and has been loosely named "Newton's Steam Carriage." This device, shown in Figure 4, was a four wheel carriage with a spherical boiler mounted over a fire, with a nozzle designed to provide a reaction jet.

By 1690, mechanics became capable of forming cylinders, rods, and plates making it possible to fabricate heat engines. In 1690, Dennis Papin created a cylinder and piston arrangement that was a rudimentary heat engine.

In 1791, John Barber in England patented a design utilizing the thermodynamic cycle of the modern gas turbine. The turbine was equipped with a chain-driven reciprocating type of compressor and had a combustor and turbine. Barber proposed the use of charcoal, gas, or other suitable fuel to produce inflammable gas. The gas from the producer went into a common receiver and then into the combustion chamber where it mixed with compressor air and was ignited. The resulting hot gasses were allowed to impinge on a

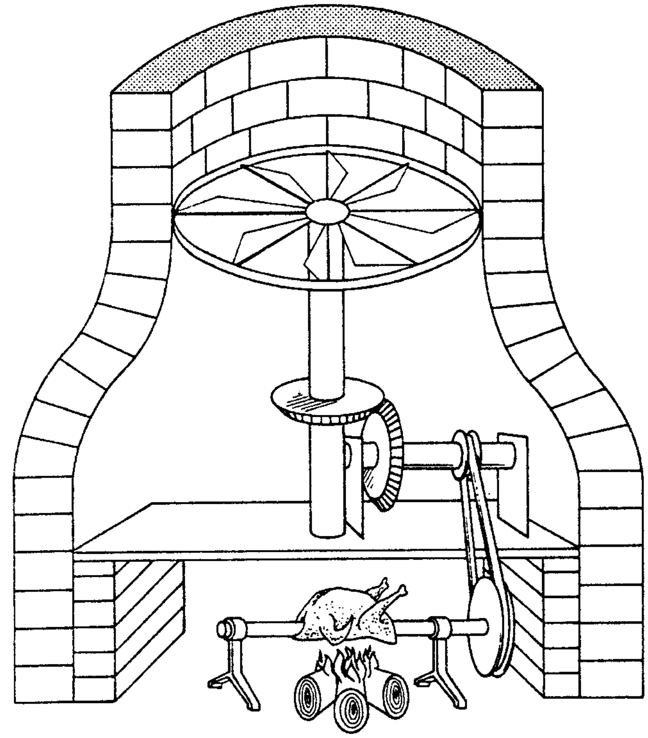


Figure 2. Chimney Jack Conceived by Leonardo Da Vinci (1500 AD).

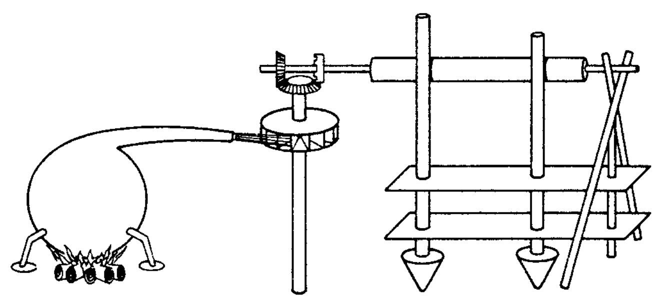


Figure 3. Impulse Turbine of Giovanni Branca Used to Power a Stamping Mill, Circa 1629—Possibly the Earliest Steam Turbine.

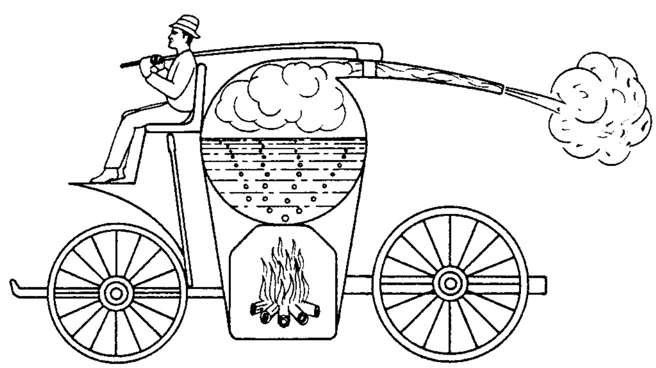


Figure 4. Newton's Steam Carriage—Developed by Jacob Graves. Speed Control by Steam Cock.

turbine wheel. To prevent overheating of the turbine parts, provisions to cool the gas by means of water injection were incorporated. There is no record of this engine being built but, in any event, it is unlikely that it would have self-sustained because of the large power requirements of the reciprocating compressor. A patent drawing of Barber's device is shown in Figure 5.

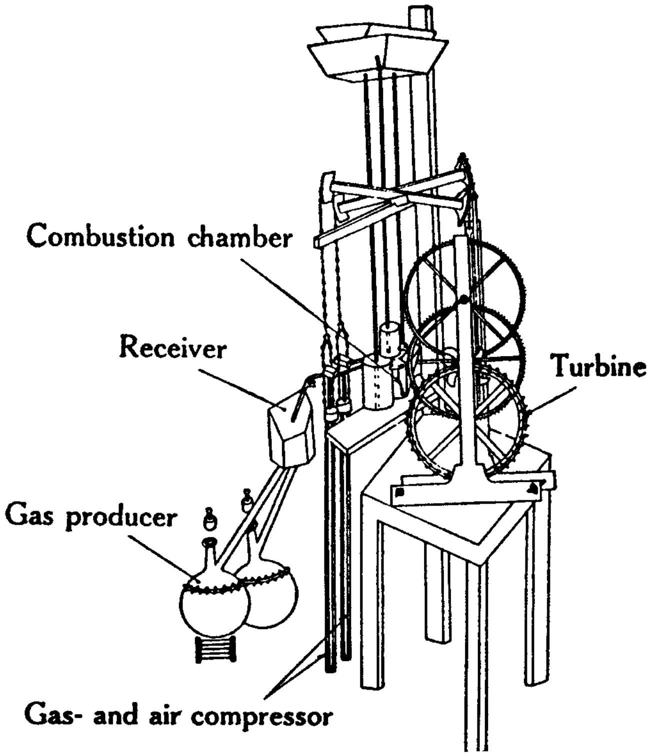


Figure 5. Patent Drawing of John Barber (1791) of Gas Turbine Cycle Utilizing Reciprocating Compressor, Combustor, and Turbine.

The APPENDIX provides a pictorial history of the sequence of developments and interactions therein that led to the modern turbomachine of today. A general overview of turbomachinery history may be found in Sawyer (1945), Constant (1980), Geoffrey Smith (1946), Garnett (1906), Strandh (1979), and Wilson (1982).

HYDRAULIC TURBOMACHINERY DEVELOPMENT

The history of hydraulics is of fundamental importance to the study of turbomachinery development as hydraulic theory and hydrodynamics formed the basis for design concepts used for steam turbines. The principles of minimizing incidence losses and concepts of the U/C velocity ratio were derived intuitively by some of the early hydraulic turbine designers.

While water wheels had been used in antiquity, it was in the 1600s that some empirical knowledge was derived relating to hydraulic phenomena. Torricelli published a work in 1644 in which he stated that the rates of discharge from an orifice in a tank were proportional to the fluid level. It was also known at this time that the force exerted by a jet was proportional to the square of its velocity. Details on the historical development of hydraulic machinery may be found in Burstall (1963), Smith (1980), and Constant (1980).

Developments in the 1700s

Important experiments were conducted by John Smeaton in England, who published his findings in 1759. He used carefully constructed small-scale test apparatus, which permitted accurate measurements. His work was, however, overshadowed by the more theoretical and rigorous work of the French including the work of Bernoulli and Leonhard Euler. In 1750, Euler offered a memoir containing a hydraulic analysis and equations for hydraulic turbines. Later, in a classic memoir to the Berlin Academy, he presented his famous relationship of reaction turbines equating the torque to the change in the moment of momentum of the fluid as it passed through the rotating section. In 1767, Borda presented his analysis of ideal water wheels in which he enunciated that water should enter the wheel without shock (one of the earliest intuitive understandings of incidence losses) and leave without any relative velocity. Borda also introduced the concept of stream tubes.

Development in the 1800s—Pioneering Work of Fourneyron

In 1826, the Societe d'Encouragement pour l'Industrie Nationale offered a prize of 6000 francs for the design of a water wheel with the condition that it had to work under water without any loss of efficiency. One of the competitors, was Claude Burdin (1790 to 1873) who was the first to use the word "turbine" derived from the Latin word "turbo" (spins). The first application of this word is found in a 1822 paper he presented to the Academy of Science. The winner of this competition was Benoit Fourneyron (1802 to 1897) who won with a design shown in Figure 6. The design was a radial outflow turbine with inlet guide vanes and turbine blades carefully constructed to avoid shock and to produce zero relative velocity outflow. The fixed inner wheel had curved guide vanes, which directed water against the outer wheel or runner. The efficiency of this outward flow turbine wheel was about 80 to 85 percent. This design was subsequently refined and saw considerable application in Europe. Benoit Fourneyron was the first person who constructed a modern high-efficiency hydraulic turbine. Another important contribution of Fourneyron was his approach to the careful testing of his turbines using a prony break (dynamometer). He started work on hydraulic turbines in 1824 but did not announce results till he submitted his award winning design in 1827.

The prony brake was a device that was most important in the history of turbomachinery development, as it allowed careful testing and refinements of design that resulted in higher efficiencies. Baron Riche de Prony first proposed his dynamometer in a memoir published in 1822. The prony brake (Figure 7) was an important tool for the turbomachinery community, as it allowed development to proceed in a scientific manner with careful quantitative evaluations being made of different designs. Fourneyron must be credited with being the first in the turbomachinery community not only to improve the prony brake but also to formalize its use allowing the precise and replicable evaluation of turbomachine output.

In Europe, other hydraulic turbine designs were implemented including an axial flow reaction design by Jonval that was introduced in 1841. Jonval was the first person to introduce the use of draft tubes.

In the United States, two people well known for their hydraulic turbine designs were James B. Francis (developer of the Francis turbine) and Uriah A. Boyden. Francis was born in England but emigrated to the US and took a job with the Proprietors of Locks and Canals on the Merrimac River, becoming Superintendent in 1837. Part of his job was to optimize the power generation capability at the Lowell works. This resulted in his comprehensive examination and study of hydraulic flow and water turbines, the results of which became known as the Lowell Hydraulic Experiments. Later, Boyden joined Francis bringing his own turbine design, which was tested and refined by both of them. The Boyden turbine produced efficiency of 75 to 80 percent. Francis continued his studies toward minimizing losses, and finally developed an elegant inward flow turbine now known as a Francis Turbine that produced efficiencies of 80 percent. A Francis type turbine is shown in Figure 8.

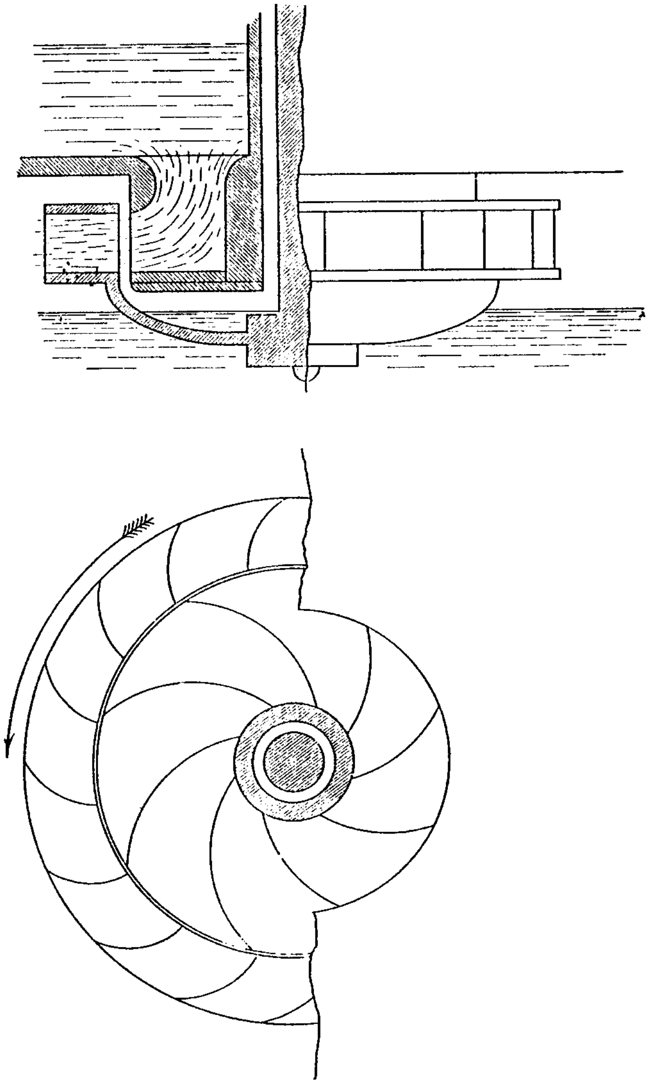


Figure 6. Fourneyron's Hydraulic Turbine-Radial Outflow Design with Inlet Guide Vanes. (Garnett, 1906)

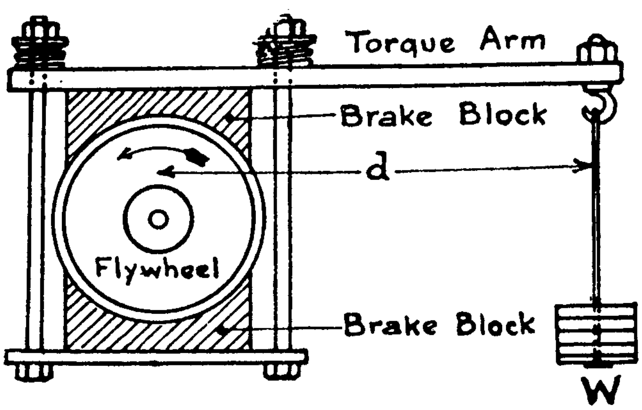


Figure 7. Prony Brake (1822) That Allowed the Scientific Testing of Turbomachines.

Development of the Pelton Impulse Turbine

While the development of the impulse Pelton wheel has the name of Lester G. Pelton associated with it, in reality it was probably co-invented by several others who had similar ideas at about the same time. The Pelton wheel is a pure impulse wheel and exploits the total conversion of head into kinetic energy in an efficient nozzle. The resulting high-speed jet is directed into a split bucket fastened around the rim of the wheel. In an ideal case, the water would leave with no relative velocity and the turbine peripheral velocity should be about 50 percent of the water jet. Prior to the introduction of Pelton wheels, there were several inefficient wheels in use known as "hurdy-gurdy" wheels.

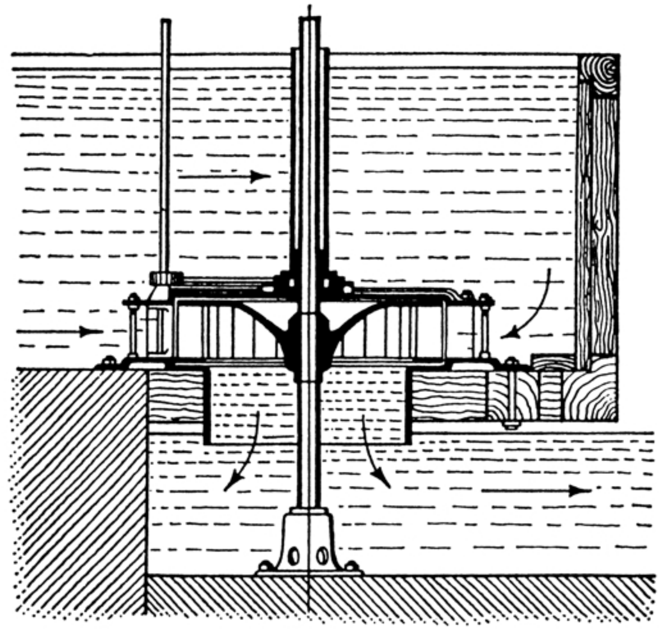


Figure 8. Francis Type Hydraulic Turbine. (Burstall, 1963)

Lester Pelton started experimenting with water wheels in 1878 and had read Francis' Lowell Hydraulic Experiments. Pelton conducted his experiments using a prony brake and a Francis type weir. He claims to have tested over 30 to 40 bucket designs and finally noticed that a curved bucket having a jet strike at the side instead of the center (which was the normal practice at that time) provided a big boost in power and efficiency. This approach however produced an end thrust on the bearing and, after experimenting with alternate side buckets, Pelton realized that one bucket could be constructed to split the water flow. He patented his wheel in 1880.

Today the Pelton wheel design with hydrodynamically correct ellipsoidal buckets can produce efficiencies of 90 percent and are widely used in industry. An early Pelton wheel is shown in Figure 9. In this wheel, the two disks can move axially on the shaft and are normally held together by springs. As the speed increased, an elegant centrifugal weight mechanism caused the disks to be forced apart, thus causing the jet to be directed into the tailrace. This mechanism allowed accurate speed control.

Hydraulic Turbine Development in the 1900s

As the size of hydraulic turbines increased and their application for large power plants became more common, the need for high efficiency, reliability, and better speed control became an imperative. Several approaches were tried, such as the use of multiple reaction wheels on the same shaft, but the resulting complexity and reliability problems caused designs to revert to large simple reaction turbines that were necessarily low speed. The availability of the following studies and concepts in the late 1800s allowed the rapid scaling up of hydraulic machinery and the application of data from scale models to full scale turbines:

- Osborne Reynold's work on dynamic similarity and on the transition between laminar and turbulent flow published in 1883.

- Lord Rayleigh's classic work in developing dimensional analysis in 1892.

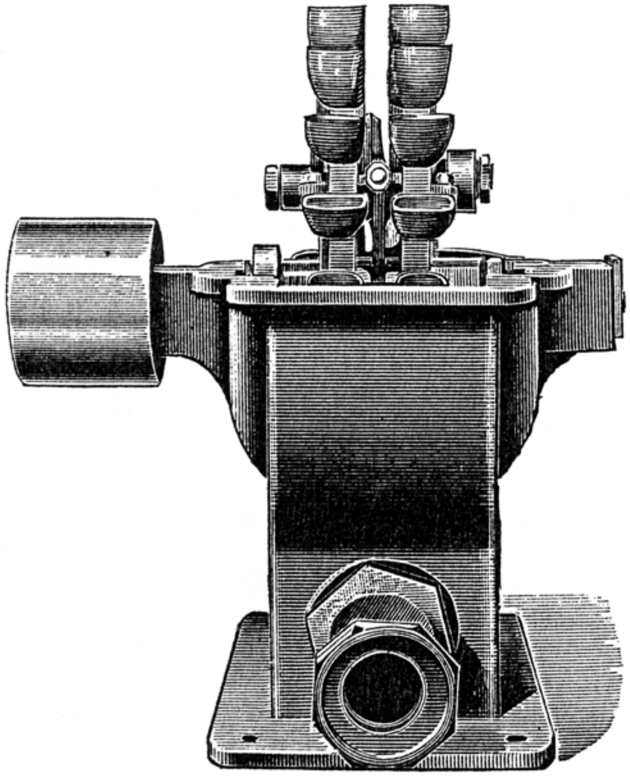


Figure 9. Pelton Wheel Design, Two Sliding Disks Mounted on a Common Shaft Normally Held Together by Spring Force. (Kennedy, 1910)

- Introduction of Specific Speed Concept in 1903.

Two solutions were proposed for high-speed turbines, one by Kaplan in Czechoslovakia and the other by Nagler in the US.

Dr. Victor Kaplan created an advanced turbine in 1912 utilizing a propeller type rotor in which the blade pitch could be controlled. This design could run efficiently at part load and could maintain accurate speed control over its load range. Kaplan devised an approach to link control of the wicker gates and the propeller pitch. While Kaplan applied for European patents in 1913 and for US patents in 1914, the intervening period of the First World War delayed commercial construction of the first turbine till 1920. Once introduced, it became a very successful design utilized to this day.

In the US, Forrest Nagler tried to reduce frictional forces, which he correctly deduced were the cause for limiting speed. In order to reduce the wetted area of the turbine, he eliminated the running band around the runners and made the runner radial, thus resulting in an axial flow design. Nagler's first commercial turbine was installed in 1916.

Turbopump Development

Denis Papin originated the idea of a centrifugal pump in the late seventeenth century and published detailed descriptions of a centrifugal pump and blower in 1705. Papin was a scientist well known for his demonstration of his Papin cooker (pressure digester) to the Royal Society. In the first half of the 1800s, there were several empirically designed pumps offered, and in 1846 Johnston in the US and Gwynne in England proposed multistage designs. Most of the early pumps did not employ a diffuser and were used for comparatively low heads (4 to 15 ft) with efficiencies being between 40 to 60 percent (Constant, 1980).

The first turbine pump employing a diffuser was invented by Osborne Reynolds, who would later be famous for formulating the law for hydrodynamic flow similarity and introduction of the now famous Reynolds number. In 1875, he patented a set of turbines and pumps including the idea of multistage pumps, and the use of movable guide vanes with divergent passages in the pumps. The patents indicated applicability for liquid or gaseous media. His work represented a significant improvement in science and technology. As an outcome of the patent, Osborne Reynolds constructed and operated a small experimental axial steam turbine running at 12,000 rpm. Clearance leakage losses between the blade tips and the casing were however very high, and Reynolds concluded that this device could never be competitive with existing steam engines. As Constant points out, it is ironic that Reynolds, a scientist who within 10 years would formulate the laws of hydrodynamic similarity, did not realize that clearances would be proportionately smaller as the turbine became bigger and that clearance losses would therefore be less. Reynolds would later in 1885 also mathematically describe the convergent-divergent nozzle that was independently discovered by De Laval.

The first Reynolds turbine water pump was built in 1887 by Mather and Platt. The design was later built by Sulzer Brothers, which up to that time had built diffuserless pumps. In 1900, Sulzer entered into a patent agreement with Mather and Platt. As a result of their cooperation, several other firms entered the market including Rateau's company and Byron Jackson Company in California. In the early 1900s, De Laval Steam Turbine Company, Allis-Chalmers, and Worthington began manufacture of multistage turbine pumps.

STEAM TURBINE DEVELOPMENT

The first steam turbine conceived by Hero of Alexandria operated on the reaction principle. James Watt actually considered a reaction steam turbine but felt that the rotational speeds would be too high to be practical. William Avery in the US built several reaction turbines for use in sawmills. His designs were, however, noisy and dangerous. There were several steam turbine patents, but most of them were unsuccessful because of a lack of knowledge in the area of materials and steam thermodynamics.

In 1853, Tournaire in France proposed a multistage reaction turbine. Tournaire recognized that a single-stage design would have to operate at an exceedingly high speed and consequently proposed a gradual expansion of vapor through several stages. His ideas did not, however, receive much attention. During this time, the common feeling was that reciprocating steam engines could do the job better without the problems of high rotative speed.

There are four people who may be considered to be pioneers of steam turbine technology (Constant, 1980):

- Carl Gustav De Laval (Patent date, 1883)
- Sir Charles Parsons (Patent date, 1884)
- Auguste Rateau (Patent date, 1894)
- Charles Curtis (Patent date, 1897)

Steam turbine history and construction are detailed in Constant (1980) and Stodola (1927).

Steam Turbine Developments of Gustav De Laval

Carl Gustav De Laval was born in 1845 and graduated from the technical University of Upsala in Stockholm in 1866. While working in Germany at the Kloster Iron works, he began experiments with centrifugal machinery and blowers for Bessemer converters. He conducted a novel set of "cane experiments" that allowed him to understand the rotordynamic behavior of high-speed shafts. This experience led to the design of a successful centrifugal high-speed cream separator. At that time, reciprocating engines were used to provide power with the speed increase to the separator (which required 7000 to 9000 rpm) being derived by unreliable belt drives.

In 1870, De Laval, who had researched flow through nozzles, turned to a steam turbine to power his cream separator. In 1887, he utilized a convergent-divergent nozzle to efficiently transform steam pressure to a high velocity jet. This resulted in an efficient impulse turbine running at 30,000 rpm that had efficiencies comparable to steam engines at that time. Tip speeds were approximately 1200 ft/sec with nozzle exhaust velocities of 3000 to 5000 ft/sec. A valve and nozzle used in a De Laval turbine are shown in Figure 10. Details of a De Laval turbine wheel and nozzle are shown in Figure 11. A 150 kW De Laval turboalternator is shown in Figure 12. A cutaway of a De Laval steam turbine is shown in Figure 13, in which the slender shaft and flexible bearing can be seen on the left. Double helical gearing can be seen in this figure. Details of a bearing utilized by De Laval are shown in Figure 14. A De Laval turbine and gear are shown in Figure 15.

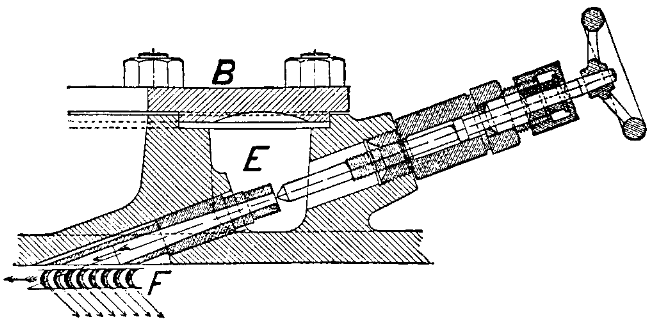


Figure 10. De Laval Steam Turbine Nozzle and Vane. (Kennedy, 1910)

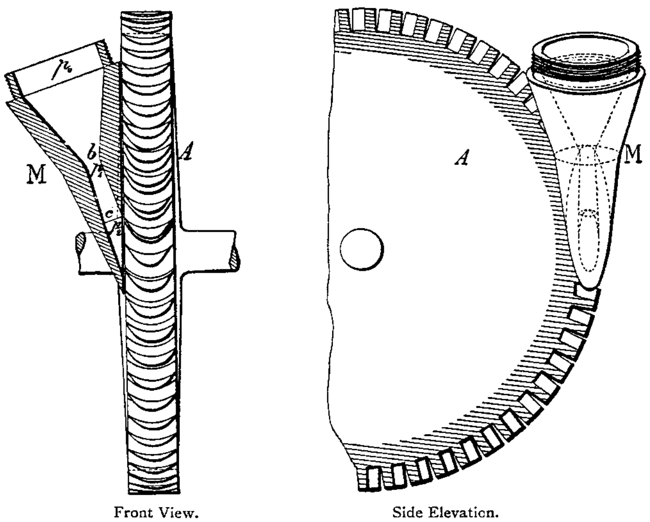


Figure 11. De Laval Impulse Turbine Wheel and Steam Expansion Nozzle. (Kennedy, 1910)

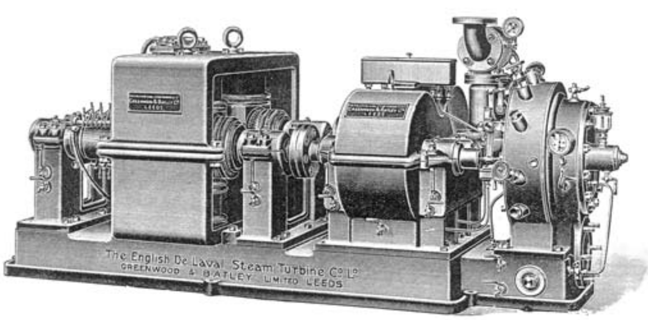


Figure 12. 150 KW De Laval Steam Turbine Turboalternator Skid. (Garnett, 1906)

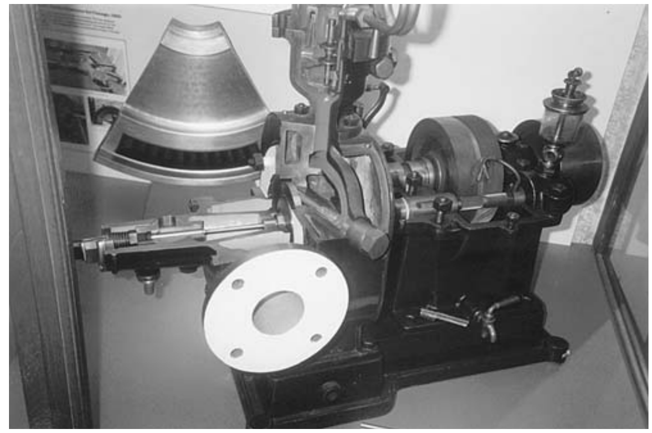


Figure 13. High-Speed De Laval Turbine Sectioned View Including Reduction Gearing.

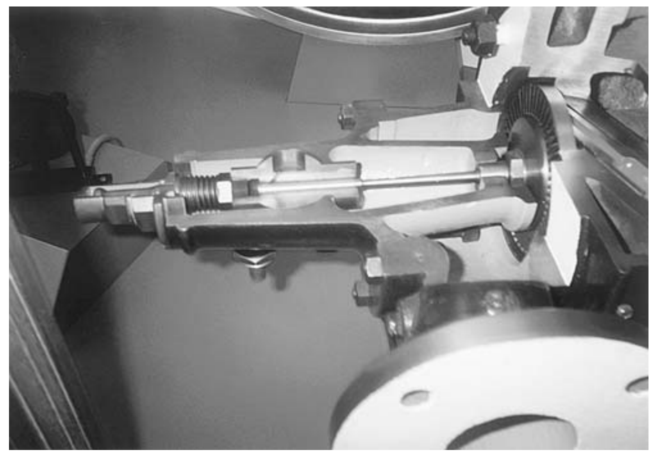


Figure 14. Detail View of De Laval Steam Turbine Showing Flexible Shaft and Bearing Arrangement.

In 1889, De Laval introduced a two-stage velocity compounded impulse turbine that allowed lower speeds and better efficiencies. These turbines were applied to pumps, blowers, and for electric power generation. De Laval was responsible for the development and refinement of double helical gears, which were needed to lower his high turbine speeds. Details of the developments of De Laval may be found in Garnett (1906), Kennedy (1910), and French (1908).

Steam Turbine Developments of Sir Charles Parsons

Charles Parsons was born in 1854, nine years after Gustav De Laval. He came from a well-known family in England, his father being President of the Royal Society. Charles Parsons grew up in a scientific and intellectual household and was tutored at home. He attended Cambridge University during 1873 to 1877 where he was, in all probability, exposed to a background in mathematics, science, thermodynamics, and mechanical engineering. Details on the pioneering work of Sir Charles Parsons may be found in Bowden (1964), Garrett Scaife (1985), Harris (1984), and Parsons (1936).

After graduating from Cambridge in 1877, he took up an apprenticeship at W. G. Armstrong Company, which was a leading naval ordnance supplier. In this position, he designed and built a high-speed compound, four cylinder rotary 10 hp piston engine. Parsons also worked on torpedo propulsion and shrouded propellers and rocket propulsion for torpedoes. The results of some of his experiments, which resulted in loud explosions under the Board of Directors luncheon room, resulted in his moving to

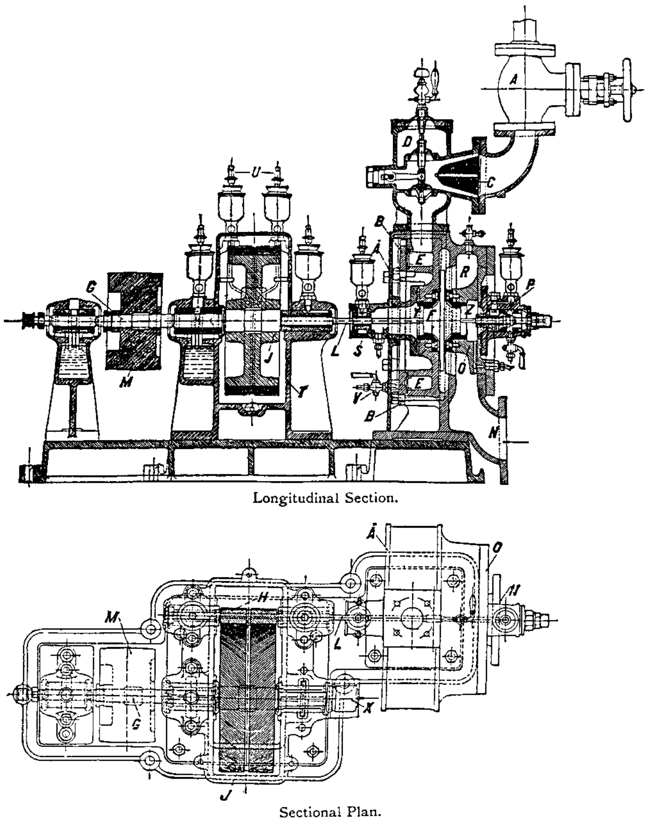


Figure 15. Longitudinal Section and Plan View of De Laval Steam Turbine Including Double Helical Reduction Gearing. (French, 1908)

Messrs. Kitson and Company to continue his torpedo investigations. In 1884, Parsons joined Clarke Chapman and Company where he was placed in charge of high-speed generator sets for ship lighting.

In 1884, Parsons designed and built his first steam turbine. Rather than utilizing the single-stage impulse design, he chose to follow the multistage reaction turbine route. Parsons cited the following reasons for his decision:

- Lower speeds—which would give his turbines a larger market as speed reduction gearboxes would not be needed
- Higher efficiencies
- Avoidance of steam erosion problems

It seems that Parsons was not aware of De Laval's work with convergent-divergent nozzles or with the theoretical description that was done by Osborne Reynolds. He therefore concentrated on reaction turbines that were focused on the power generation and ship propulsion markets that he wished to penetrate.

Parsons steam turbine blades initially used straight (flat) blades but later used curved blades. On his early turbines he used successively larger blades in each stage. His later designs used an increasing drum diameter and multiple compounded turbines in series. The first Parsons Turbine, shown in Figure 16, produced 10 hp at 18,000 rpm. His early machines used brass blades attached to steel disks. Parsons used an ingenious self-centering multiple washer bearing that was later superceded by a concentric tube design. Parsons fully utilized steam condensers, as his low-pressure stages could extract energy very effectively with small pressure differentials. Over 300 marine turbogenerators were sold by Parsons before he dissolved his partnership with Clarke Chapman in 1889 in a dispute that resulted in Parsons not being allowed to market his own reaction turbine. Therefore, after founding C. A. Parsons and Company, he worked on a compound radial outflow turbine that he patented. A radial flow compound turbine designed by Parsons is shown in Figure 17. A photograph of blade details is shown in Figure 18.

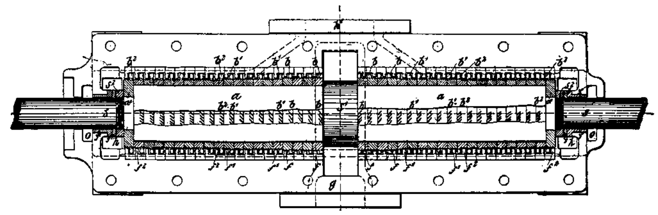


Figure 16. Sectional View of First Parsons Axial Steam Turbine Rated at 10 HP, 18,000 RPM. (Parsons, 1926)

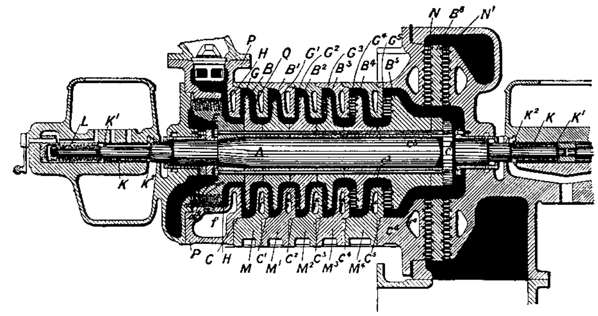


Figure 17. Parsons' Radial Flow Compound Turbine. (Kennedy, 1910)

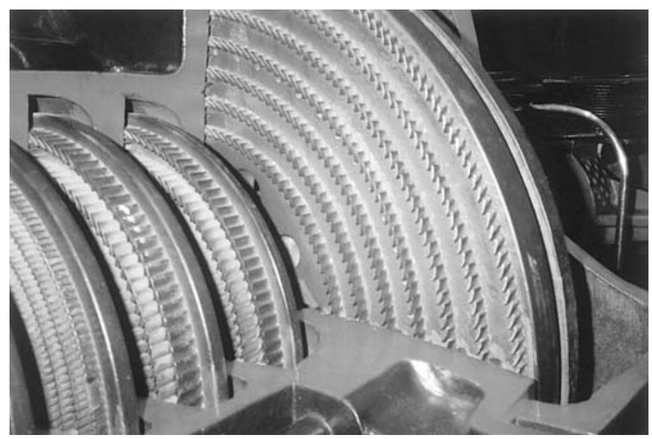


Figure 18. Blade Details of Parsons' Radial Flow Turbine.

After considerable difficulty, Parsons finally got the power industry to buy into his steam turbine turbogenerator designs and soon his turbines started to displace reciprocating engines at central stations. In 1893, he repurchased his original patents and again offered his multistage axial reaction design. Soon his multistage designs were producing 25,000 kW and became the norm for central power stations all over the world. By 1923 Parsons had installed a set up to 50,000 kW. A 600 hp Parsons multistage turbine is shown in Figure 19, and a Parsons turboalternator is shown in Figure 20.

Parsons Contribution to Naval Propulsion

Sir Charles Parsons revolutionized the Naval propulsion market making the steam turbine the world standard. In 1893, he began work on a small turbine-powered demonstration ship called the Turbinia. This small 100 ft long ship displaced 44 tons and had a single radial outflow turbine engine turning a single screw. After recovering his axial flow turbine patents, Parsons re-engined the ship with a three-stage axial flow design. The engine developed 2300 hp and allowed the Turbinia to attain a speed of 34 knots.

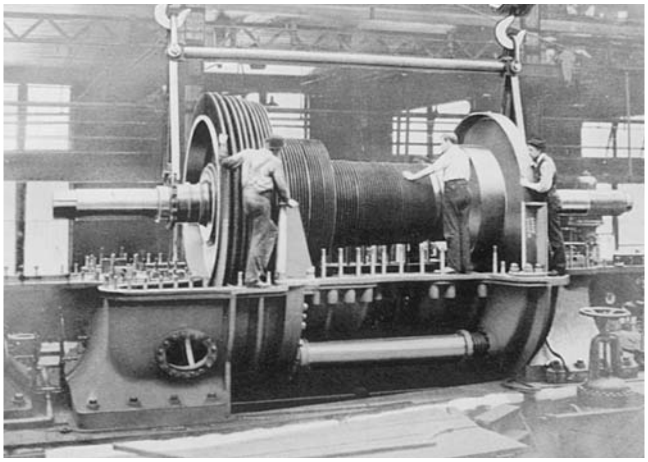


Figure 19. Parsons Axial Flow Steam Turbine Opened for Inspection. (Parsons, 1926)

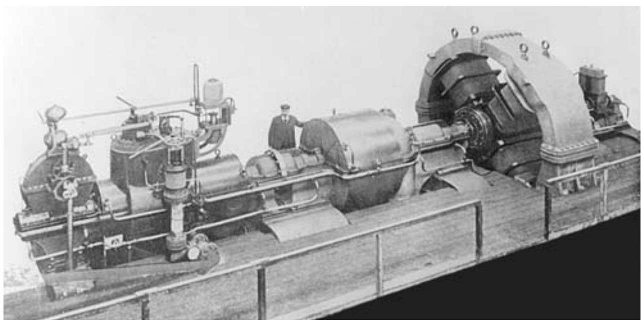


Figure 20. Photo of Parsons Turboalternator. (French, 1908)

Because of the opposition to new ideas from the very conservative British Admiralty, Parsons staged a daring demonstration. In 1897, which was Queen Victoria's Diamond Jubilee, the Royal Navy had organized a huge review of its nation's and other nations' naval vessels, which was held in Spithead. Parsons gate-crashed the event with his Turbinia and raced it up and down the ranks of the great ships at speeds of over 30 knots. A photograph of the Turbinia is shown in Figure 21. Confronted by this amazing and audacious demonstration, the Admiralty issued a contract for a turbine-powered destroyer, the HMS Viper. Following the construction of HMS Viper, Parsons built a series of larger turbines including turbine engines for the famed battleship HMS Dreadnought and the 70,000 hp Mauretania and Lusitania.

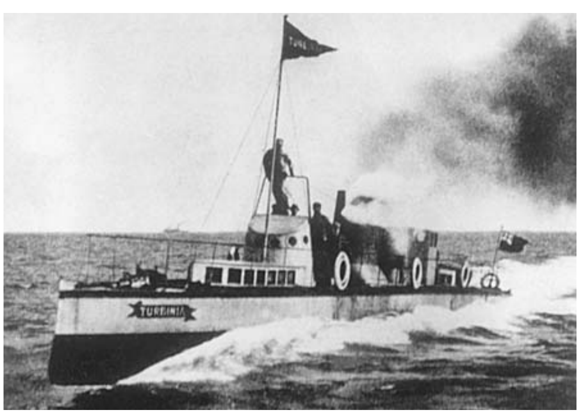


Figure 21. The 34 Knot "Turbina" at Spithead Naval Review in 1897—First Demonstration of Steam Turbine Propulsion. (Parsons, 1926)

Steam Turbine Developments of Auguste Rateau

Auguste Rateau was born in France in 1863 and graduated from Ecole Polytechnique in Paris in 1883. Rateau began his steam turbine experimental work in 1894 trying to modify a De Laval turbine with Pelton buckets—an experiment that was not successful. In 1900, he designed a pressure staged impulse turbine that bears his name today. In 1903, Rateau formed his own company. With his publication of "Treatise on Turbomachines," Rateau established himself as a preeminent authority on steam and gas turbine design. Rateau also pioneered developments of turbo-superchargers and air compressors. A cross section of a Rateau turbine is shown in Figure 22 and a photograph of 60 bhp, 6000 rpm Rateau steam turbine is shown in Figure 23.

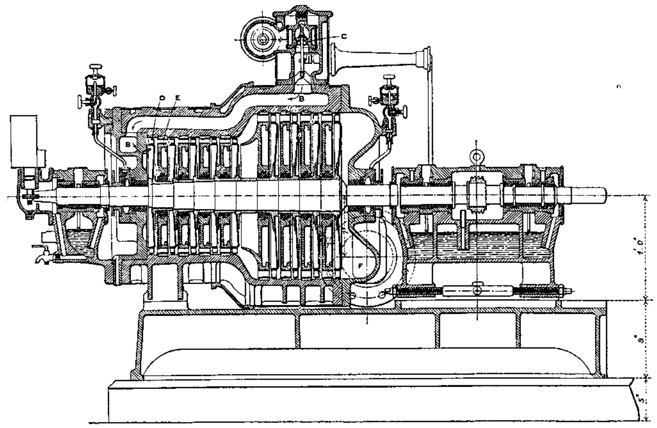


Figure 22. Cross Sectional View of Rateau Steam Turbine. (French, 1908)

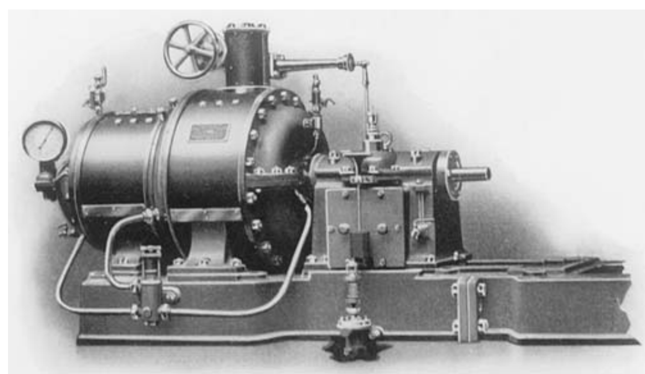


Figure 23. 60 BHP Rateau Steam Turbine. (French, 1908)

Steam Turbine Developments of Charles Curtis

Charles Curtis was born in Boston in 1860 and earned a Civil Engineering degree from Columbia in 1881. In 1886, he and two partners started a firm to manufacture electric motors and fans. In 1888, Curtis left the partnership to establish his own company called the Curtis Electric Manufacturing Company. Curtis developed his velocity-stage turbine in 1896 and sold his rights to General Electric Company in 1901. GE subsequently refined the turbine and it competed with the Parsons designs for central station and marine applications.

Licensing Agreements for Steam Turbines

By 1920 almost every major manufacturer had established licensing contracts and was making stream turbines (Constant, 1980).

- Westinghouse Corporation, USA, worked out a licensing agreement with Parsons in 1895.

- Allis-Chalmers, after trying several domestic designs, took out a Parsons license in 1905.
- Escher Wyss and Company undertook the design of their chief engineer, Zoelly, that was essentially similar to the Rateau design. The Zoelly turbine was also, in turn, licensed to Krupps and Maschinenfabrik Augsburg-Nurnberg (MAN).
- Orliken of Switzerland acquired the Rateau license.
- The Czech Skoda works evolved their own turbine design from the Rateau design.
- Brown Boveri, which was founded in 1892, began development of a Parsons' based turbine.
- Thysen in Germany produced a turbine, which included both Parsons and Curtis features.
- Fraser and Chalmers (an affiliate of GE USA) produced a Curtis type machine.
- British Westinghouse Electric first built Parsons turbines but later, on becoming Metropolitan Vickers Electrical Company, turned to the Rateau design.
- English Electric Company manufactured a Rateau-Curtis design.
- British Thompson-Houston (BTH) produced Curtis turbines.

Ongoing Evolution of Steam Turbines

In the century after the introduction of the steam turbine, there was significant evolution in inlet steam pressures and temperatures. According to Bannister and Silvestri (1989), from 1900 to 1950, inlet steam pressure and temperatures increased on average 43 psi and 13°F per year. During the 1930s, higher temperatures and pressures made a 3600 rpm (60 Hz) machine more attractive. There were several modifications made to the fundamental Rankine steam turbine cycle. In 1876, Weir patented a regenerative feedwater heating cycle in which a small portion of the steam was used to externally heat the water to its boiling point prior to introduction to the boiler. The reheat cycle added further efficiency benefits. The widespread adoption of reheat in the early 1950s resulted in a rapid increase in throttle pressure from 1450 to 2400 psig. Throttle and reheat temperatures were 1000/1000°F or 1050/1050°F. Double reheat units introduced later caused an even greater rise in efficiency. Most of these double reheat units had throttle steam conditions of 3500 psig, 1000/1000°F. Philadelphia Electric Company's supercritical Eddystone 1 unit operated at 5000 psig/1200°F conditions. The steam turbine did not experience any problems but because of problems in the boiler and superheater, conditions were derated to 4800 psi/1130°F.

COMPRESSOR DEVELOPMENTS

Turbocompressors co-evolved with steam turbines and several of the famous names associated with steam turbine technology also worked on blowers and compressors.

Rotary Positive Displacement Roots Blower

Rotary displacement compressors were widely used in the last part of the nineteenth century and the most famous was the Roots Blower. Constant (1980) reports on the development of the Roots Blower. In the middle of the nineteenth century, P. H. Roots and F. M. Roots, of Connersville, Indiana, owned a textile mill and needed a water turbine to drive the lineshafts by the fall of water from a canal. As a satisfactory water turbine was not available at that time, F. M. Roots designed and built a two-impeller device with a sheet-metal case and with wooden impellers. When this device was tried as a water turbine, swelling of the wood caused the turbine to jam. After considerable scraping of the wooden wheels, the device was connected to the lineshaft for a test. A local foundryman who was curious about the new machine looked into the top and his hat blew off, at which time he announced that this would make a better blower than a turbine. This reportedly was the birth of the Roots Blower in 1859. An early Roots blower used for mine ventilation is shown in Figure 24.

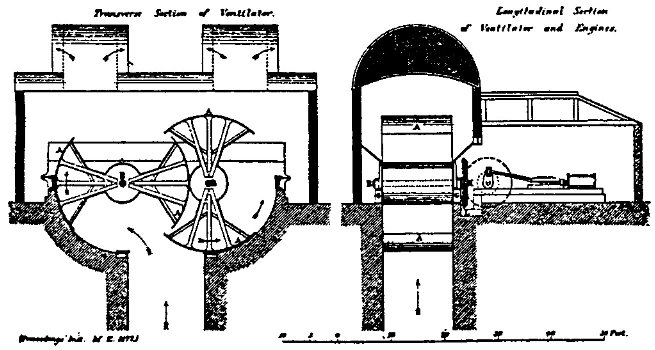
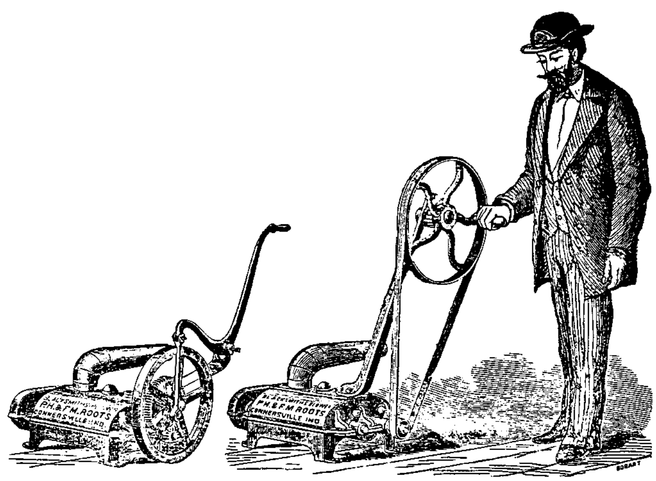


Figure 24. Early Roots Blower Used for Mine Ventilation. (Early Roots Brochure, Undated)

The Roots brothers were clever practical engineers but were not aware of the latest developments that were occurring in Europe. The Roots blower became the best device available for lower pressure operation and attained efficiencies of 35 to 40 percent. Initially it was also troubled by lubrication and sealing problems and thermal distortion. Figure 25 shows an early Roots hand blower.



IMPROVED HAND BLOWER OPERATED BY LEVER.

Figure 25. Early Roots Hand Blowers. (Early Roots Brochure, Undated)

Centrifugal Turbocompressors

The credit for the invention of the centrifugal impeller goes to Denis Papin in 1689. Euler's classic presentation in 1754 on an idealized theoretical application of Newton's Law to centrifugal impellers (now known as the Euler Equation) initially did much to help the development of hydraulic machinery, but did not initially influence centrifugal compressor development. Most of the early centrifugal compressor designs did not employ diffusers and were used mostly for low head and pressure ratio applications with efficiencies in the 45 to 65 percent range, with the compressors being driven by steam engines. Reynolds patented a vaned diffuser in 1875 (Engeda, 1998).

Rateau in France was a major contributor to the design of centrifugal blowers and compressors. In addition to developing the compressor itself, he published on the theory of turbocompressors and developed testing techniques. Rateau initiated the manufacture of these units in France and, by license, in other countries.

Based on his experience and expertise with axial fans and turbine water pumps, Rateau published a detailed paper on centrifugal blowers in 1892. He began design work on his first turbocompressor in 1898, which was a single-stage unit that was put on test in 1901 with test results being published in 1902. By 1900, Rateau realized that the availability of high-speed steam turbines would provide an excellent fit for his turbocompressors without the need for speed increase gearing or belts. By 1902 over 700 Rateau-design axial fans were in use for ventilation service and he had 200 centrifugal blowers in use for mine ventilation. By the turn of the century Rateau was working on his detailed treatise on turbomachinery and had the reputation of a scientist-engineer who was developing his compressors based on his theoretical studies. He was the first to use adiabatic efficiency for turbocompressor efficiency measurement.

In 1903, Rateau designed several single-stage units that were used in steel works and sugar factories. His first multistage compressor was installed in 1905. This unit had five stages and had a discharge of 4 m (13 ft) water head (5.6 psig) with a flow of 2500 m^3/h (88,287 ft^3/h). In 1905, he completed a compressor that developed a pressure ratio of 7:1 with a total efficiency of slightly less than 50 percent. This unit was the first compressor to include intercooling.

In 1904, Brown Boveri of Switzerland and several other manufacturers in Europe took out licenses for Rateau's compressors. In 1906, Brown Boveri manufactured a multicase compressor designed by Rateau for the Armengaud-Lemale gas turbine.

Axial Flow Compressors of Sir Charles Parsons

Sir Charles Parsons had patented an axial-flow compressor in 1884. In 1887, he designed and marketed a low-pressure three-stage centrifugal compressor for shipboard ventilation. He began extensive experiments in 1897 with axial flow compressors and two years later built an 80-stage axial-flow unit, which gave an adiabatic efficiency of 70 percent. In his early designs, the stator guide blades were flat on one side and curved on the other, with the enlarging passage between adjoining blades serving to change the kinetic energy to air pressure. By mid 1907 Parsons had made 41 axial flow compressors, but their poor aerodynamics caused them to be noncompetitive with centrifugal designs and so, in 1908, Parsons stopped manufacture. The fundamental problem was the lack of aerodynamic knowledge in that turbine blading was being used for axial compressor design. The challenge of diffusing flow and stability raised its ugly head here and would remain a problem for axial flow compressors well into the 1950s. A Parsons axial flow compressor design is shown in Figure 26. The arrangement of blading in a Parsons blower is shown in Figure 27.

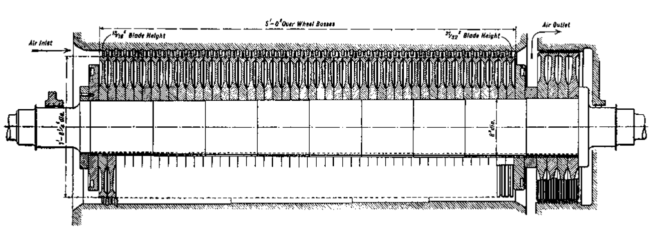


Figure 26. 48-Stage, Axial Flow Compressor Made by Parsons in 1904. (Flow rate 3000 cfm, Discharge pressure 8 to 15 psig, 3600 rpm.) (Parsons, 1926)

EARLY INDUSTRIAL GAS TURBINES

The first patent for a gas turbine was awarded to John Barber in 1791. According to Sawyer (1945), he may have been the first to coin the term gas turbine, as his concept used producer gas as the fuel. Between 1791 and the time the first practical gas turbine was

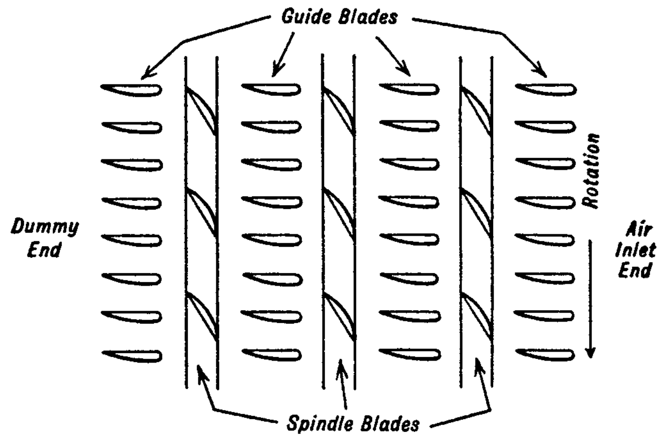


Figure 27. Arrangement of Blades in Parsons Axial Blower. (Parsons, 1926)

developed by Stolze, there were several inventions that included caloric or hot-air engines. The first was introduced by Sir John Cayley, and including the Stirling engine that was developed circa 1830. Sawyer (1945, 1947) provides a detailed description of the early industrial gas turbines.

Pioneering Work by Dr. Stolze

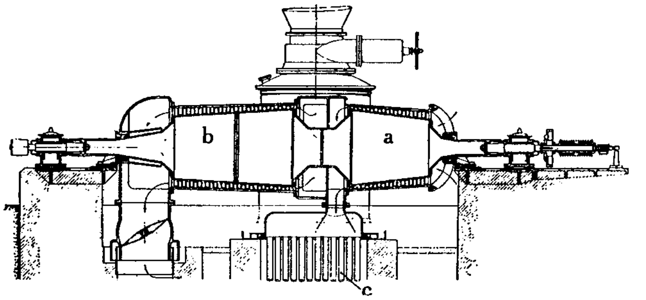
Dr. J. F. (Franz) Stolze developed the first gas turbine in 1872 with trials being made between 1900 and 1904 (van der Linden, 1977). This hot air turbine with a multistage axial compressor and multistage reaction turbine was not successful due to the limited knowledge of aerodynamics. It might be noted that even Sir Charles Parsons had to abandon the axial flow compressor at about the same time that Stolze was making his trials because of the complexities involved in axial compressor design.

Franz Stolze was born in March 1836 in Berlin and had a brilliant academic career with degrees in Philosophy, History, Geography, Physics, and Mathematics from the University of Berlin, and a Doctorate from the University of Jena in 1863 where he wrote a thesis on the design of a gas turbine. He filed for a patent in 1877 but, upon its rejection, moved on to other things including a study of Persopolis in Persia. In 1886, he was appointed to a Professorship at the University of Berlin. Reading a German patent awarded to Sir Charles Parsons for a steam turbine reawakened his interest in the gas turbine and he applied for and was granted a patent in 1899.

A view of the gas turbine is shown in Figure 28. It was a single-shaft unit supported by a bearing at each end and had a single silo combustor. Both ends of the shaft belt drove alternators that were rated at 150 kW. The axial flow compressor comprised 10 stages (pressure ratio of 2.5:1) and the reaction turbine had 15 stages. The machine operated at a turbine inlet temperature of 400°C (752°F). The compressor efficiency would have had to be over 70 percent for the unit to be self sustaining (Jeffs, 1986). Stolze's gas turbine utilized a reheater with the combustor being essentially a rudimentary coal gasifier. Some of the heated air from the recuperator was used to volatilize the coal. The recuperator was a U bank tube that connected to the compressor discharge plenum below the gas turbine. Gas turbine exhaust was routed under the machine to pass over 96 U tubes before discharging into the main stack. Details on the work of Stolze may be found in Jeff (1986).

Gas Turbine Patent of Charles Curtis in the USA

The first patent in the US (Patent No. 635919) covering a gas turbine was filed in 1895 by Charles G. Curtis. Curtis was well known as the inventor of the Curtis steam turbine at General Electric. Even though this patent was filed, he did not do much work on gas turbines, concentrating his efforts on steam turbines.



(a) Multistage Axial Compressor. (b) Multistage Reaction Turbine
(c) Heat Exchanger.

Figure 28. Stolze Gas Turbine Arrangement (Circa 1900)—10-Stage Axial Flow Compressor (Pressure Ratio 2.5:1), 15-Stage Reaction Turbine, and Silo Combustor. (Sawyer 1945)

Early Work by Dr. Stanford Moss in the USA

Dr. Stanford Moss, who would later become a legend at GE for his pioneering work on aircraft engine superchargers, completed his Master's degree in 1900 from the University of California with a thesis on gas turbine design. Thereafter, Dr. Moss continued toward his Doctorate at Cornell where he designed an experimental gas turbine. A combustion chamber was designed by Moss and a turbine from a De Laval steam turbine was used as the power generating section. The turbine drove a compressor that provided air to the combustor. The power requirements of the compressor were higher than the power delivered and consequently no net power was derived. The experimental runs did, however, yield sufficient data to enable Moss to obtain his Doctorate. This thesis was presented to Dr. Steinmetz of the General Electric Company and resulted in Moss obtaining a job at GE. He started working in the turbine development division at Schenectady and was later transferred to the Lynn, Massachusetts, works. In 1907, gas turbine work at GE was discontinued, but Moss continued work on compressor development and supercharger technology, soon attaining a reputation as one of the world's leading experts. It is this turbocharger expertise that made GE the first choice of the US Government for manufacturing the Whittle jet engine during the Second World War. Details of the contributions of Moss to early supercharger work may be found in Dalquest (1979).

Work of Charles Lemale and Rene Armengaud in France

In 1901, Charles Lemale obtained a patent for a gas turbine in France, and in 1903 he began an association with Rene Armengaud that resulted in a self-sustaining and positive output gas turbine. Their work represented some of the earliest comprehensive gas turbine experimental work. In this timeframe, several gas turbine proposals were made including concepts such as cooling by water injection, the use of hollow turbine blades, and the use of reheat combustors and intercooled compressors.

Between 1903 and 1906, the Societe Anonyme des Turbomoteurs in Paris built several experimental gas turbines. Figure 29 shows the turbine developed by Armengaud and Lemale. This was a large unit rated at 400 hp. The unit utilized the first centrifugal compressor built by Brown Boveri, which was designed by Auguste Rateau. The compressor was a three casing design with 25 impellers developing a pressure of 60 psia. The combustion chamber and turbine nozzle are shown in Figure 30. Test results of this gas turbine are presented in Table 2.

Explosion Gas Turbines and the Velox Gas Turbine

In 1905, Dr. Holzworth developed an explosion or constant-volume gas turbine. In this turbine, the fuel was fed to a closed combustion chamber that was filled with compressed air and the mixture was exploded, causing the pressure to rise approximately 4.5 times its original value. The combustion chamber, nozzles, and

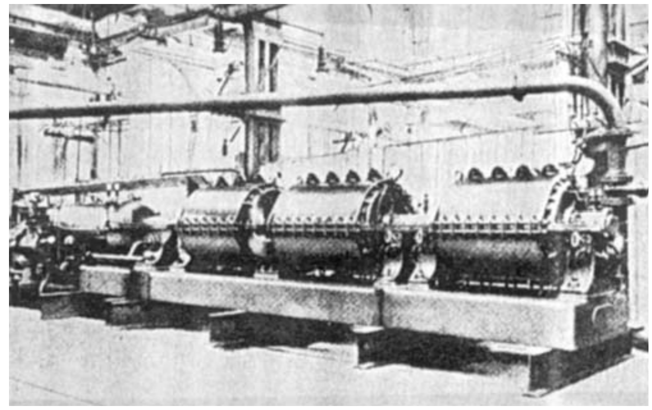
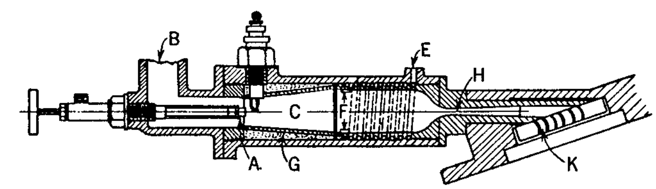


Figure 29. Gas Turbine Developed by Lemale and Armengaud, Circa 1905, Three Centrifugal Compressor Cases (25 Impellers) Designed by Rateau. (The turbine wheel diameter was 37 inches.) (Stodola, 1927)



A—Oil enters under pressure and is atomized.
B—Inlet for Air.
C—Combustion Chamber.
E—Inlet for Cooling Water: goes through coil and enters *C* at *F*.
G—Combustion Chamber Housing.
H—Nozzle.
K—Section of Turbine Wheel.

Figure 30. Combustion Chamber and Nozzles of Lemale and Armengaud Gas Turbine. (Stodola, 1927)

Table 2. Test Results of Gas Turbine of Societe Anonyme des Turbomoteurs, in 1905.

PARAMETER	VALUE
RPM	4250
Temperature before nozzle	1040 °F
Turbine exhaust temperature	788 °F
Combustion chamber pressure	56.6 psia
Compressor discharge temperature	189 °F
Ambient Temperature	64 °F
Water consumption per hour	65 cu. Ft
Oil consumption per hour	392 lb.
Net output	Practically Nil (just self sustained)
Thermal Efficiency	3%

blading were water-cooled. The power required by the compressor was a fraction of that produced by the combustion turbine. Only a small amount of excess air was required by the combustor since the cooling was done by water. The complexity and challenge in this scheme were the automatic valves that were needed for the combustor and the conversion of the combustor cooling water flow to steam that was used to drive the steam turbine for the compressor. The steam turbine had to be condensing and this further complicated matters. Brown Boveri built some of these units between 1909 and 1913. Several Holzworth gas turbines were built by Messrs. Thyssen between 1914 and 1927. In 1928, Brown Boveri developed a two-chamber two-stroke cycle, shown in Figure 31. The famed Dr. Aurel Stodola, who was a Professor at the University of Zurich Polytechnic, was involved in testing a Holzworth turbine at the Thyssen steel works and noted the high heat transfer in the water jacket around the turbine. He suggested that the waste heat be used in a steam generator, and from 1933 to 1936 Brown Boveri developed the Velox Boiler. The Velox boiler had an axial flow compressor supercharging the boiler in which gas or liquid fuel was burned, with the hot gases being expanded through a turbine that drove the compressor. Brown Boveri developed actual industrial gas turbines from 1939, but most of their sales were for the Velox boiler. Details may be found in Stodola (1927).

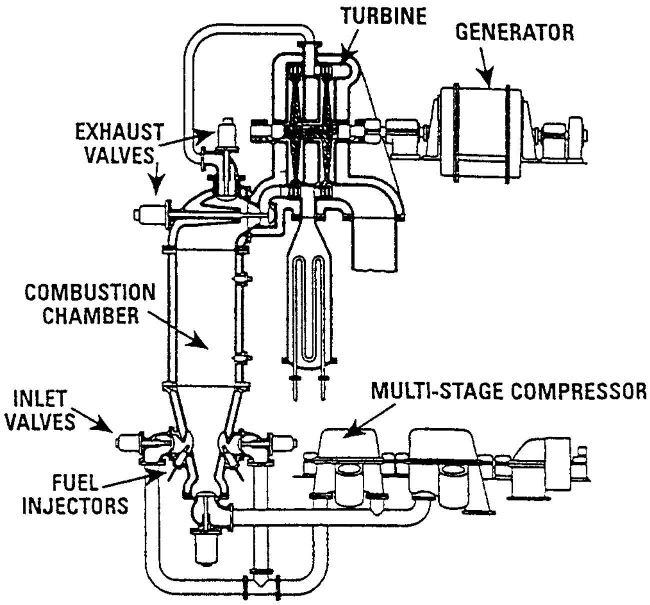


Figure 31. Holzworth Explosion Gas Turbine. (Sawyer, 1945)

In 1936, Sulzer studied and produced some gas turbine engines. A closed cycle gas turbine was designed at Escher Wyss by Jacob Ackeret and Curt Keller with the working fluid being air.

It might be mentioned parenthetically that Dr. Aurel Stodola's book published in 1903, called *Steam Turbines* (with later editions being renamed *Steam and Gas Turbines*), was truly a classic and detailed work in the art and science of turbomachinery engineering, containing both theoretical and practical aspects of thermodynamics, aerodynamics, rotordynamics, and mechanical design, with elegant theoretical treatments of several common problem areas such as turbine stresses, critical speeds, and overspeed problems. Sir Frank Whittle read this book when he was a student and it probably had a considerable impact on his pioneering turbojet development work.

In the early 1930s, A. J. R. Lysholm, who was chief engineer at the Ljungstrom Steam Turbine Company, started investigating gas turbine engines and built some experimental units that suffered severe surging problems with the centrifugal compressor. Because of this, he then turned to a Roots type blower but, as it could not make the pressure ratio required, Lysholm invented the helical screw compressor that is widely used in process industries today. Elliott Company tested a gas turbine incorporating a Lysholm compressor but the tests were unsuccessful. A screw compressor design is shown in Figure 32.

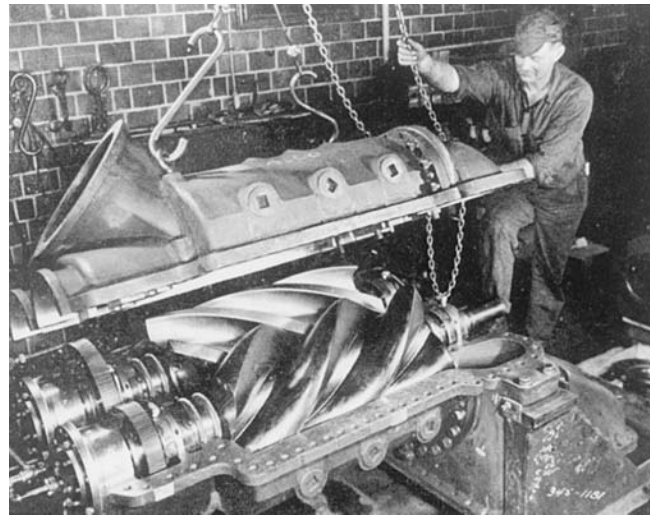


Figure 32. Lysholm Compressor.

BRITISH GAS TURBINE DEVELOPMENTS

The turbojet revolution was pioneered by Sir Frank Whittle in England and Hans von Ohain in Germany, their work being extensively documented by Constant (1980), Schlaifer (1950), von Ohain (1979), Scott (1995), Jones (1989), Gunston (1995), Meher-Homji (1996, 1997), Meher-Homji and Prisell (1999), and Neville and Silsbee (1948). Both these pioneers, who envisioned flight speeds in excess of 500 mph at altitudes of 30,000 ft, had their revolutionary ideas as students, and developed their engines without the help of the traditional aeroengine companies.

In 1919, when the gas turbine was an established prime mover, the British Air Ministry asked Dr. W. J. Stern to report on the prospect for the use of gas turbines for aircraft propulsion. His study was flawed in its assumptions and he concluded that the gas turbine was not a feasible proposition. Stern based his computations on industrial technology taking, for example, 1250 lb for fuel pumps and drive gears (Jones, 1989). This report was to have an adverse impact on Whittle's quest for support years into the future.

Dr. A. A. Griffith, a brilliant scientist who started work at the Royal Aircraft Establishment (RAE) at Farnborough in 1915 and had made fundamental contributions to airfoil theory, was also a gas turbine pioneer. He focused on an exceedingly complex model of an axial flow gas turbine (a turboprop) and could not appreciate the fact that Whittle's centrifugal design had an inherent simplicity that would help promote its success. Griffith did groundbreaking work on aerodynamic theory in the 1920s where he treated turbomachine blades as airfoils. Griffith played an important part in gas turbine development but, as seen later, initially rejected Whittle's concept, thereby delaying government assistance at a most critical juncture.

Whittle's Early Work

As a flight cadet attending the Royal Air Force College at Cranwell in 1928, Whittle wrote a thesis titled "Future Developments in Aircraft Design." In this thesis, he proposed a propulsion concept that utilized a piston engine-driven compressor to blow air over fuel jets, exhausting the high temperature air through a propulsion nozzle. In October 1929, he realized that he could increase the blower pressure ratio and replace the piston engine with a turbine. Whittle approached Britain's air ministry with his concept but was told that it was not feasible. This assessment was made by Griffith who was eager to pursue his own complex gas turbine scheme and failed to see the elegant simplicity of Whittle's engine.

On January 16, 1930, Whittle filed for Patent No. 347206 for "Improvements in Aircraft Propulsion" (Figure 33). This figure depicts a single shaft turbojet with an axial-centrifugal compressor, tubular combustor, and two-stage turbine. Between 1934 and 1936, he studied for his Tripos at Cambridge and, in 1935, allowed his patent to lapse because the Air Ministry would not pay the £5 renewal fee. Whittle however, doggedly pursued his goal and, in March 1936, a company called Power Jets Limited was launched with a nominal capital of £10,000, with Whittle acting as the Chief Engineer. On May 18, 1935, he filed for Patent No. 459980 for an experimental turbojet, which would be called the WU. Whittle proceeded to design a double entry compressor with a 19 inch diameter made of high strength aluminum alloy and having 30 vanes. The compressor was to be driven by a 16.4 inch turbine operating at 17,750 rpm. The mass flow rate was to be 26 lb/sec and the pressure ratio 4.4:1. Whittle recognized that the area of greatest technical risk was in the combustor where an exceedingly large heat release had to be achieved in a very small volume. Whittle's aim was to burn 3.3 gal/min in a volume of 6 cu ft. After talking to several burner manufacturers, Whittle was able to get the assistance of Laidlaw Drew and Company to work on a small research contract. Details pertaining to Whittle's pioneering work may be found in Whittle (1945, 1954, 1979) and Golly (1987).

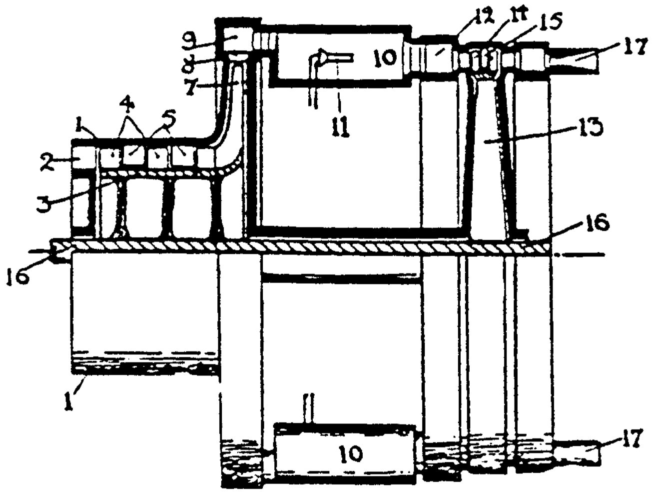


Figure 33. Whittle Patent Drawing (1930) Showing Two-Stage Axial Compressor, Centrifugal Compressor, Straight-Through Burner, and Two-Stage Axial Turbine on One Disk. (Meher-Homji, 1997; Courtesy ASME)

Design and Development of the WU Experimental Engine

In June 1936, the British Thomson-Houston Company (BTH) of Rugby was awarded the contract for the detailed design and construction of the WU. Due to severe financial constraints, Whittle could not afford component testing and therefore had to boldly take the risk and attempt to run a complete engine.

His initial experiments on combustion were run with very crude combustion test rigs and equipment. As reported by Jones (1989), these experiments produced deafening noise and thick clouds of fuel vapor and smoke. It was said that Power Jets' engineering drawings were recognizable by the smell of fuel oil with which they became impregnated!

On April 12, 1937, the first few runs of the WU engine were made. These were eventful because, in several instances, the turbine accelerated with a rising shriek to 8000 rpm even with the fuel valve closed. This uncontrolled and noisy acceleration caused considerable concern as it was usually accompanied by patches of red heat being visible on the combustor and large flames emanating from the jet pipe. Finally, it was determined that fuel pump tests conducted prior to engine light-off resulted in an accumulation of fuel in the bottom of the combustion chamber, which ignited causing the uncontrolled acceleration. Figure 34 illustrates the assembly of the first model of the experimental engine and the test stand on which it was to be used. The engine had a single large combustor of helical form. Tests showed that the compressor and turbine efficiencies were below design expectations. This engine also suffered from a series of mishaps including one in which the compressor impeller rubbed its casing at 12,000 rpm causing the engine to come to a stop in about 1.5 seconds.

After the testing on the first WU engine was completed in August 1937, BTH was given an order for a complete reconstruction in which the major changes were an improved compressor diffuser, a new combustion system, and modification of the turbine blading to

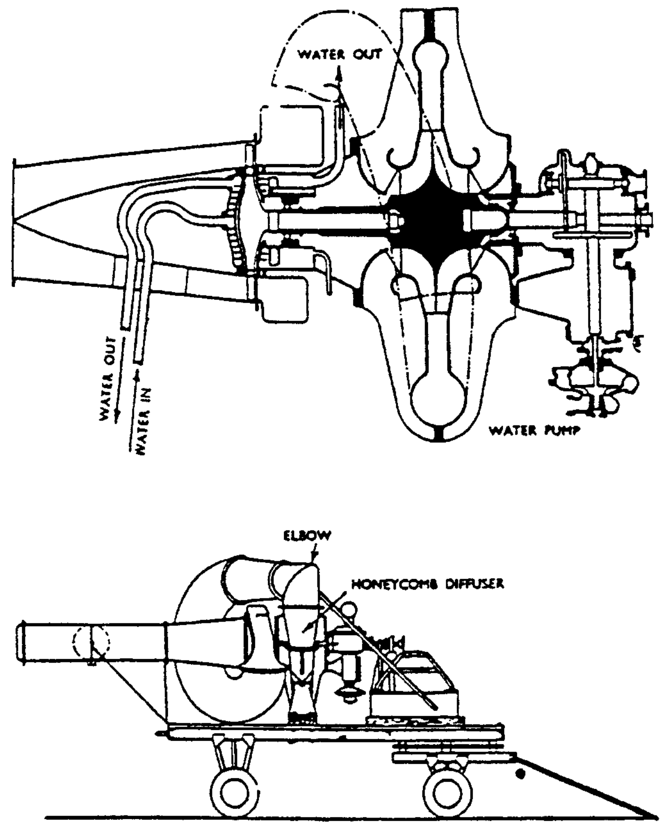


Figure 34. First Model of Experimental Engine and Test Stand, Water-Cooled Turbine Disk Jacket and Mass Flow Rate of 26 Lb/Sec. (Meher-Homji, 1997; Courtesy ASME)

conform to free-vortex design principles. Whittle had always believed in the importance of this type of blading and was amazed when he found that BTH turbine designers had not utilized it.

The second version of the experimental engine was tested in April and May of 1938, and demonstrated that the turbine designed by Whittle on free-vortex principles had an efficiency of 84 percent. The second version of the engine failed after only four hours of running. The major problem was still in the combustion system. In the third version of the experimental engine, 10 counter flow combustors were used instead of a single combustion chamber. The engine layout is shown in Figure 35. The use of multiple combustors allowed bench testing of a single combustor utilizing blowers existing at the BTH plant. From 1938 to 1940, most of the experimental work focused on combustion. Experiments were made on a system that vaporized the fuel before injection. In October 1940, an atomizer burner and flame tube were designed and used satisfactorily on the third experimental engine.

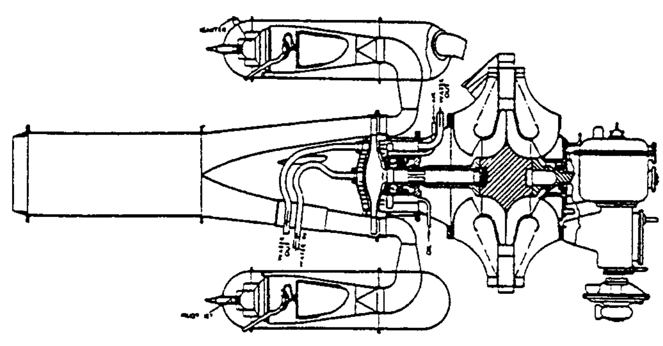


Figure 35. Engine Layout of Third Experimental Unit with 10 Reverse Flow Combustors. (Meher-Homji, 1997; Courtesy ASME)

Design of the Whittle W.1X Through the W.2B

In July 1939, Power Jets Limited was promised a contract for a flight engine designated as the W.1 and, in August 1939, Gloster Aircraft Company was awarded a contract for the design of an experimental aircraft that would be powered by the W.1. In late 1939, even while the development work was continuing on the W.1, the Government promised to pay for the development of a more ambitious W.2, which would power the twin engine Gloster Meteor fighter.

Whittle started the development of the W.1 engine in July 1939, with a design goal of 1200 lb of thrust. The aerodynamic design of the W.1 was similar to the WU third version. A comparison of the leading particulars of the WU engine and the W1 engine are presented in Table 3. The first W.1, called the W.1X, was put on test in December 1940. Experience on this engine was put into the design of the W.1 engine that powered the E28/39 jet illustrated in Figure 36. The first flight occurred on May 15, 1941. This historic flight, with test pilot Jerry Sayer at the controls, lasted 17 minutes. The successful flight provided an impetus for the British Government to lay definitive plans for the W.2B, which was to be the production engine for the Gloster Meteor. This flight made a significant contribution in speeding up jet engine development work in Britain. Rolls Royce, which had a program some time before 1939 when it hired A. A. Griffith from RAE, started to apply considerable resources to its development.

Table 3. Leading Particulars of the WU and the W.1 Engines. (Meher-Homji, 1997)

	W.U (first version)	**W.1**
COMPRESSOR		
Tip Dia., in.	19	19
Tip Width, in.	2	2
Eye OD/ID, in	10.75/5.5	10.75/5.5
No. of Blades	30	29
Material	Hiduminium RR 59	Hiduminium RR 59
TURBINE		
Mean Blade Dia., in.	14	14
Blade Length, in.	2.4	2.4
No. of Blades	66	72
Blade chord, in.	0.8	0.8
Material of Blade	Stayblade	Rex 78
Material of Disc	Stayblade	Stayblade
Max speed, RPM	17,750	17,750

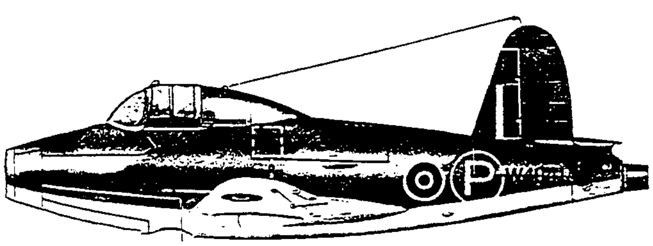


Figure 36. First British Jet to Fly—Gloster E28/29, Powered by Whittle W.1 Turbojet Designed by Power Jets Limited. (Meher-Homji, 1997; Courtesy ASME)

In early 1940, the Rover Company was given a contract for the production of Whittle engines as the Government did not feel that Power Jets had the experience or the personnel for quantity production. By April 1940, prototype drawings of the W.2, which was to be the production engine, were handed over to Rover. Shortly after the handover of the drawings, Whittle performed a detailed analysis of his design and became convinced that this design was liable to be a complete failure. This arose from an overambitious design where the exhaust velocity was too close to Mach 1, so that the component efficiencies were not achieved and exhaust velocities reached critical values at well below full speed. Surging of the compressor and high exhaust gas temperatures made it impossible to run at over 75 percent of the design rpm.

Whittle then began working on a revised design known as the W.2B. By the fall of 1941, Rover was almost ready to begin production of the W.2B and set up a special factory at Barnoldswick. Unfortunately, both technical and political problems relating to this design developed.

The first W.2B delivered surge at outputs over 1000 lb thrust and also suffered from turbine blade failures. In July 1942, GE sent Rover several sets of turbine blades made from Hastalloy® B, which were superior to Rex 78. A little later the British alloy Nimonic® 80 was introduced. On the political side, relationships between Power Jets Limited and Rover started to deteriorate rapidly, mainly over disagreements with respect to Rover's right to make independent design modifications to the engine. In the fall of 1941, Power Jets was deprived of authority over the design of the production engine and was limited to research and development activities. Rover was authorized to make design changes without Power Jets' approval. Rover proceeded with work on its version of the W.2B engine. By December 1941, it had put on test the W.2B Mark II, which incorporated a 10-vane diffuser, designed in consultation with Rolls Royce, and a new turbine with fewer and broader blades. The engine attained a thrust of 1510 lb without surging.

In March 1942, Power Jets Limited designed a new engine designated the W.2/500. This engine retained the new diffuser of the W.2B Mark II, and included a new blower case and a new turbine design. On its first run in September 1942, the W.2/500 attained 1755 lb thrust.

Rolls Royce as the Producer of Whittle Type Jet Engines

In late 1942, Rolls Royce, which had a long history of reciprocating aeroengine successes but had been struggling with Dr. A. A. Griffith's gas turbine designs, took over the jet engine effort at Rover, and, toward the end of 1942, the direction of Rover staff and works facilities were in the hands of Rolls Royce. As reported by Hooker (1984), Lord Hives and Hooker of Rolls Royce met at a pub for dinner with S. B. Wilkes of Rover. Hives is reported to have told Wilkes, "You give us this jet job and I will give you our tank engine factory at Nottingham." A decision was made on the spot and the deal was made.

Ultimately the W.2B/23 was put into production and named the Welland, the first of Rolls Royce "River Class" jet engines. On June 12, 1943, the Meteor, shown in Figure 37, was flown with two Welland engines. The Welland was put into production in October 1943, and deliveries were first made in May 1944. Production engines were rated at 1600 lb thrust, weighed 850 lb, and had a specific fuel consumption of 1.12 lb/hr/lb thrust. With this engine, the Meteor could attain speeds of 410 mph. The first production Meteors were delivered to Squadrons in July 1944 and were used against German V-1 flying bombs (Shacklady, 1962).

Based on experience with the Merlin engine's supercharger, Rolls Royce felt that the air flow through the Welland could be increased by 40 percent and changes were made ultimately resulting in the Rolls Royce Derwent. As blower casings that were already made for the Welland had to be used to facilitate rapid production, the increase in thrust was only 25 percent, achieved by the use of a new impeller adopted with some modifications from Whittle's W.2/500, a new diffuser designed by Rolls Royce and a scaled-up turbine. The Derwent I was first tested in July 1943, and, in 1944, it attained thrust of 2000 lb.

In 1943, the course of Power Jets' activities started to diverge from Rolls Royce. After the W.2/500 of 1942, Power Jets built the W.2/700 illustrated in Figure 38, which included important changes in the compressor, the introduction of a completely new

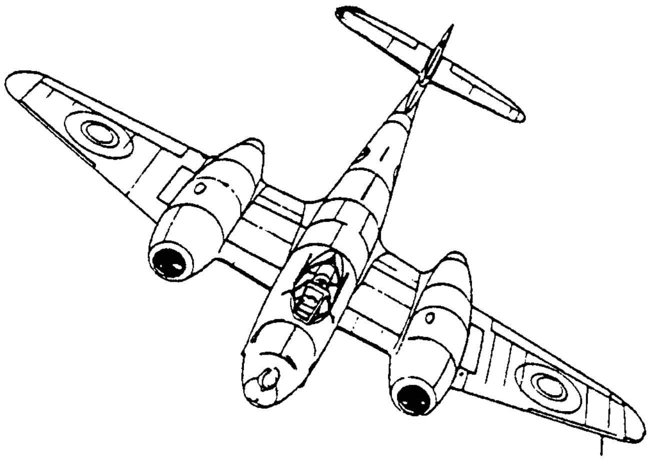


Figure 37. The First Operational Allied Fighter During WW II, the Gloster Meteor, Powered by Two Whittle W.2 Engines Built by Rolls Royce. (Maximum speed 410 mph at 10,000 ft.) (Meher-Homji, 1997; Courtesy ASME)

diffuser (known as the type-16 diffuser), and blower casing. With these modifications, the W.2/700 compressor finally attained Whittle's aim of 80 percent efficiency while deriving a pressure ratio of 4:1. In the four years that had elapsed since the first flight trials of the W.1 engine, Power Jets Limited had tripled the thrust of the engine with no increase in size and a 70 percent increase in weight (Whittle, 1954). The growth in engine capability is depicted in Table 4.

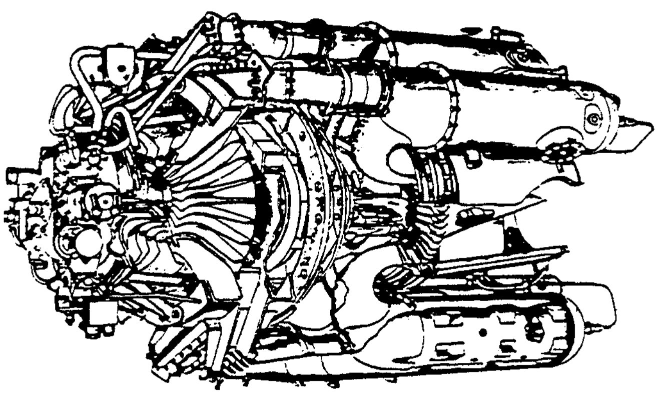


Figure 38. W.2/700 Turbojet, the Last Engine to be Built by Power Jets Limited. (Rated at 2500 lb thrust.) (Meher-Homji, 1997; Courtesy ASME)

Table 4. Growth in Whittle Engines, W.1 Through the W.2/700. (Engine speed for all engines was 17,500 rpm. Overall diameter was the same. W.2/700 data are for the final version, with Nimonic® 80 blading, blade height of 3.63 inches, and mass flow rate of 47.15 lb/sec.) (Meher-Homji, 1997)

ENGINE	Thrust, Lbs.	SFC, lb./hr/lb.	Jetpipe Temp, °C
W.1	950	1.37	597
W.2/500	1,755	1.13	606
W.2/700	2,487	1.05	647

In 1944, Power Jets Limited was nationalized. Engine development work continued with emphasis on the W.2/700 engine. Nationalization resulted in a serious drop in morale and the pioneering Power Jets' team started to lose heart with conflicts developing regarding the role of the company. Whittle felt that engine development should be a goal while others were content to view the organization as a research and development establishment. In January 1945, Whittle was invited to become a member of the board of Power Jets (R&D). It was at this time that the Gas Turbine Technical Advisory and Coordinating Committee was formed to direct the course of gas turbine activities in the UK. In April 1945, it started to become clear that Power Jets would not have the right to design and build experimental engines, and that it was expected to focus on fundamental research and component development. The company that boldly strode forth with technology with which no established company would invest resources in, was now stripped of the right to design or build jet engines. On January 22, 1946, Whittle submitted his letter of resignation from the board of Power Jets (R&D) Limited. As he predicted, the brilliant team of engineers that he had built and who had pioneered jet engines in Britain, finally broke up, and the engineers were hired by other firms working on gas turbines.

Whittle's basic engine design features lived on at Rolls Royce. The Nene, designed by Dr. Stanley Hooker and first run in 1944, had some new features but still retained 80 percent of the Power Jets' design ideas. The engine was rated at 4500 lb thrust. A scaled-down version of the Nene known as the Derwent V was made. Figure 39 shows a cutaway drawing of the Rolls Royce Nene. A photograph of a sectioned Nene Engine is shown in Figure 40. The small centrifugal compressor behind the main compressor is to supply bearing cooling air.

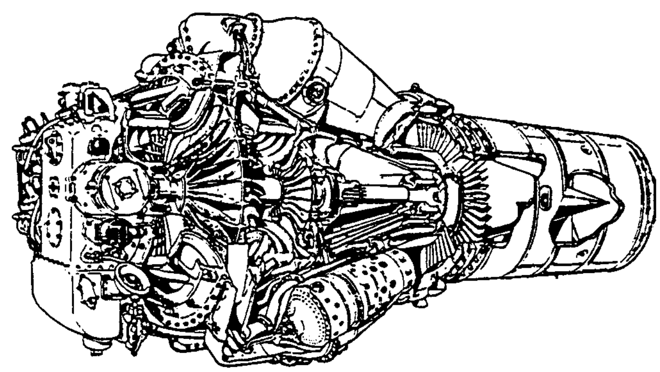


Figure 39. Cutaway of the Rolls Royce Nene Engine (5000 Lb Thrust, 80 Lb/Sec), Designed by Sir Stanley Hooker Incorporating Basic Whittle Design Features. (Meher-Homji, 1997; Courtesy ASME)

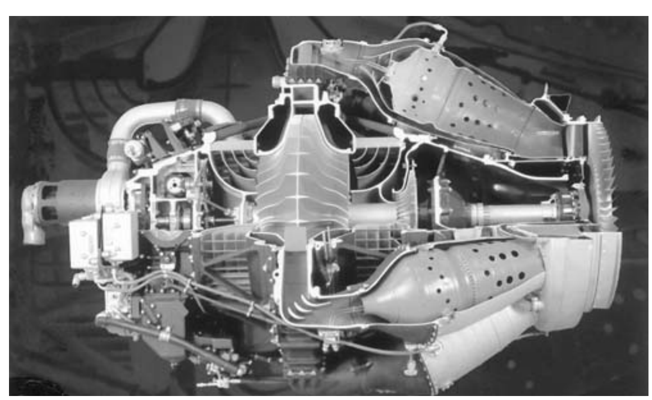


Figure 40. Sectioned Photo of Rolls Royce Nene Engine. (Courtesy Doug Nagy, Liburdi Engineering Limited)

It is interesting to note that all the major aeroengine manufacturers started their jet engine work based on Whittle's designs (Singh, 1996). The Rolls Royce Welland, Derwent, Nene, and Tay were based on the Whittle designs. Pratt and Whitney entered the gas turbine field after the war using the Rolls Royce Nene as a basis for their J-42 and J-48. General Electric started their jet engine work based on the Whittle designs and developed the I-A, J-31, and J-33.

Technical Features of Whittle's Engines

Whittle had the genius to know that to achieve success, his designs had to be simple, robust, and have the best chance for rapid development. Whittle's designs were masterpieces of simplicity in design and construction and low in weight. When Whittle pointed out the virtue of the simplicity of the engine to Lord Hives of Rolls Royce, Hives is reported to have dryly remarked, "Wait until we have worked on it for a while; we will soon design the simplicity out of it!" (Hooker, 1984). Looking at today's complex aeroengines, this was a prophetic statement!

Double Sided Centrifugal Impellers

Whittle's choice of a double-sided centrifugal compressor was made to obtain the maximum possible breathing capacity in proportion to size. The first experimental engine (WU) had a compressor tip diameter of 19 inches and had 30 blades. Whittle chose the largest number of blades possible based on manufacturing limitations in order to minimize the blade loading.

Reverse Flow Combustors

There were several reasons why Whittle elected to use reverse-flow combustors for his early developments. These included:

- To permit the use of a short shaft that required only two bearings and eliminated the need for a flexible coupling.
- To eliminate an expansion joint between the compressor and turbine.
- To provide for even air flow to the primary combustion zone.
- To screen the turbine blades from direct flame radiation.

Vortex Design of Turbine Blades

Whittle assumed that the BTH engineers were designing the turbines based on vortex theory. BTH engineers had not assumed vortex flow from the turbine nozzles and therefore had not designed the blades with adequate twist. Whittle's insistence on this design approach soured relationships with some BTH engineers who resented this young engineer instructing them on how to design turbines.

Design Problems and Failures

It is easy for one to gain the impression that the course of engine development was simple and logical. This was hardly the case, and there were numerous problems that had to be surmounted by Whittle and his team with minimal resources and funds and always under intense time pressure. Several problems were the result of pushing the state-of-the-art. Several setbacks were the results of bad luck, lack of funds that forced cannibalization of parts, or environmental factors. Whittle believed, for example, that several of the early bearing failures that occurred at the dilapidated Ladywood Works were the result of a "rain" of foundry sand derived from the roof of the workshop, which was formerly a foundry! Some of the serious problems faced are presented below.

Impeller, Turbine Blade, and Disk Failures

There were several problems pertaining to impeller vibration and cracks, which have been covered by Voysey (1945). Problems started with the W.2/500 engine. Whittle found out that, at 14,000 rpm, the engine produced a "howling" sound. Tests showed that even a short run at the howling speed would result in resonance cracks over the length of its junction with the impeller disk, as shown in Figure 41. A front view of a wrecked Power Jets engine caused by an impeller failure is illustrated in Figure 42. Several methods of fundamental importance in analyzing blade and impeller vibration were developed. Problems also plagued turbine blading, especially with later versions of the Whittle engines, specifically in the W.2/800 where the blade lengths had increased. A Campbell diagram for the W.2/800 is illustrated in Figure 43. A wrecked impeller due to fatigue failure is shown in Figure 44.

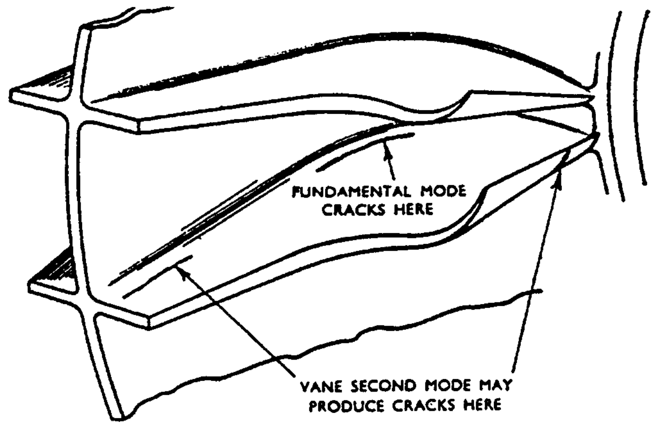


Figure 41. Position of Centrifugal Impeller Cracks. (Voysey 1945; Courtesy IMechE, UK)

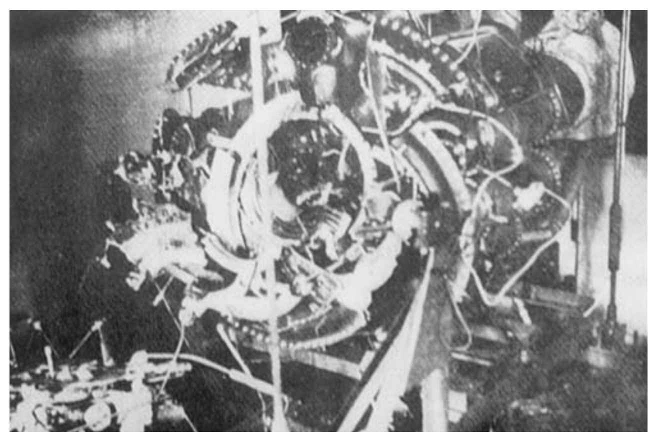


Figure 42. Whittle Engine Wreck Caused by Burst Impeller. (Development of the British Gas Turbine Unit, 1945; Courtesy IMechE, UK)

The initial disks that utilized the De Laval type fixation method were subject to failure as shown in Figure 45. This failure occurred on the WU engine in February 1941, at a run time of 168 hours. The use of a fir-tree arrangement and better blade materials resolved this problem on future engines. Cracking in the root serrations on the W1.A engine is shown in Figure 46.

In another case, the W.1 engine, which was putting in considerable time both on the E28 test aircraft and on the bench, suddenly encountered turbine blade failures. The mystifying factor in this case was that the location of the crack was not consistent (as would be expected by a fatigue type problem), occurring at times at the root, midspan, and at the blade tip. Whittle suspected that this was the effect of a thermocouple located three feet *downstream* from the turbine that was causing fluctuations in blade loading. Upon removal of the thermocouple, the blade failure problem disappeared (Whittle, 1979).

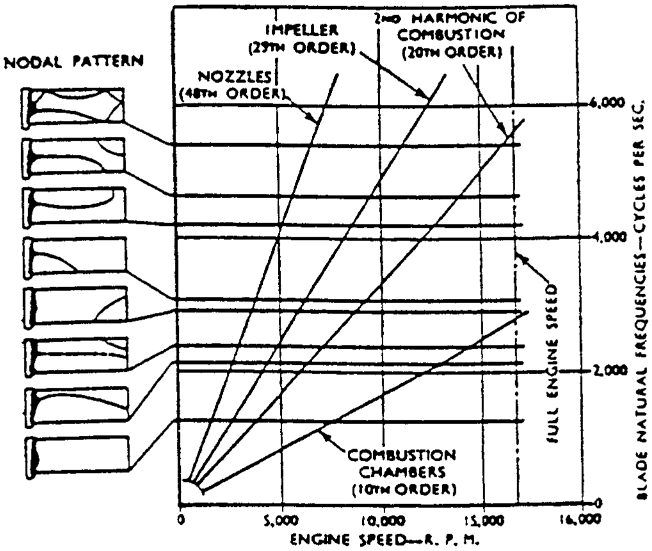


Figure 43. Interference Diagram for Turbine Blading. (Voysey, 1945; Courtesy IMechE, UK)

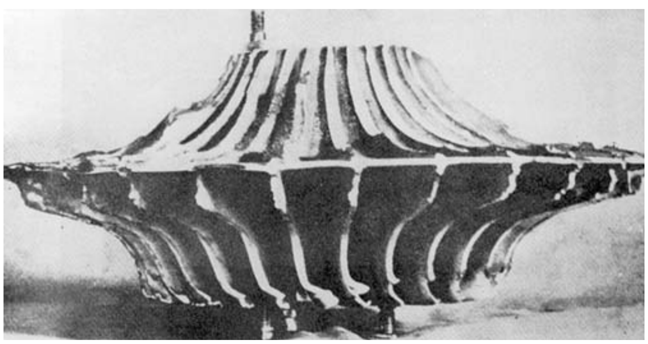


Figure 44. Impeller Failure Due to Fatigue. (Development of the British Gas Turbine Unit, 1945; Courtesy IMechE, UK)

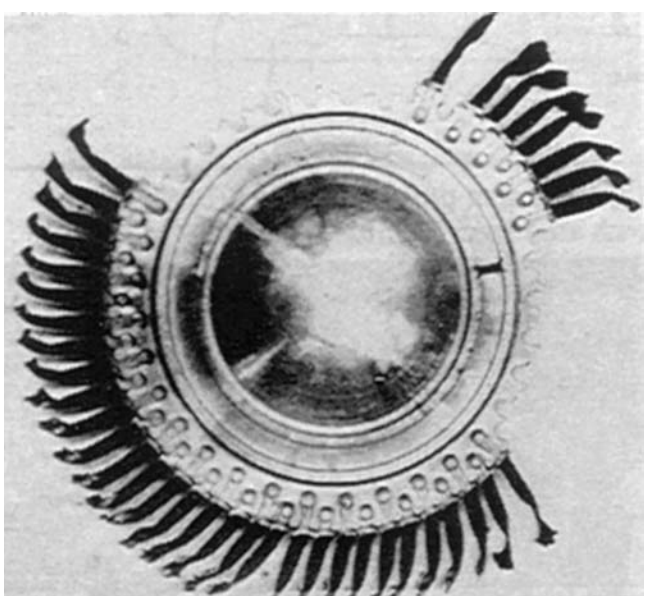


Figure 45. Disk Failure of Experimental Engine (De Laval Type Pin Blade Attachment) After 168 Run Hours. (Development of the British Gas Turbine Unit, 1945; Courtesy IMechE, UK)

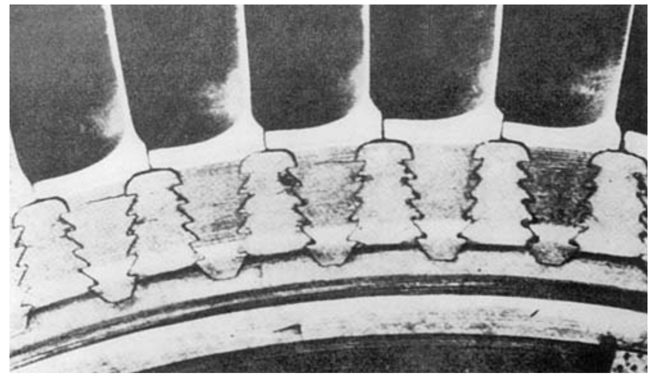


Figure 46. Cracking of Turbine Blade Root Serrations, W.1A Turbojet. (Development of the British Gas Turbine Unit, 1945; Courtesy IMechE, UK)

Combustion Problems

The first model of the experimental engine had severe problems with hot spots and improper heat distribution. Whittle made an attempt to utilize the primus principle and the single combustion chamber was fitted with a vaporizer. On this engine, poor compressor delivery pressure compounded the problem and diffusers were fitted to improve compressor performance. Numerous tests and modifications were attempted on the flame tubes, vaporizers, baffle systems, and spray patterns. Whittle (1945) states that in January 1939 alone, 10 types of vaporizers were tried in the combustion rig and nine flame tube modifications made. There were also problems with repeatability of results derived from the test rigs on the engine. Whittle struggled hard with the combustion problem until the fall of 1940 when Mr. Isaac Lubbock, head of Shell Fulham Laboratory who was advising Power Jets, developed and tested a combustor utilizing atomized spray injection. Power Jets continued development of this combustor, and from that point, the combustion problems diminished. A combustion chamber with a vaporizer as well as the Shell type combustion chamber are shown in Figure 47. The combustors and jet pipe end of the W.1X are depicted in Figure 48. More details of design related problems of the early jet engines may be found in Constant (1948).

Other Turbojet Engine Developments in England

In June 1941, The Bristol Engine Company undertook a survey of the gas turbine field and, by the spring of 1942, had completed the design for what would become the Theseus turboprop (Figure 49). Metropolitan Vickers worked on an axial RAE design that resulted in the F2 engine. De Havilland Aircraft Company worked on the development of the Goblin, which powered the Vampire fighter. The De Havilland Goblin is shown in Figure 50.

A detailed description of axial gas turbine development work in England is made by Constant (1945). A lot of careful development work was done on axial compressors by Constant and his group, including the pioneering work of Howell, whose contributions are detailed in Dunham (2000). A small 6 inch diameter axial flow test compressor designated "Anne" is shown in Figure 51. The British even experimented with water-cooled turbine blading in the early 1940s, as can be seen in Figure 52.

GERMAN JET ENGINE DEVELOPMENTS

Turbojet development in Germany initially included two independent programs that were not, at least initially, under the auspices of the German Air Ministry known as the Riechluftfahrtministerium, or RLM for short. As is typical of revolutionary technological changes, these two programs did not initiate at the traditional aeroengine companies, but started at Heinkel Airframe and at Junkers Airframe Company. Ultimately, both these

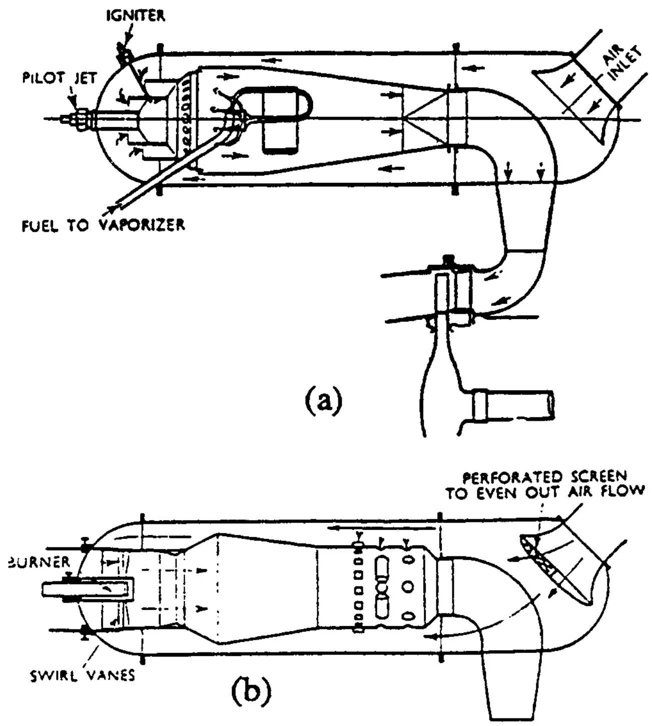


Figure 47. Vaporizer Type Combustor and Shell Type Combustor with Atomizer. (Meher-Homji, 1997; Courtesy ASME)

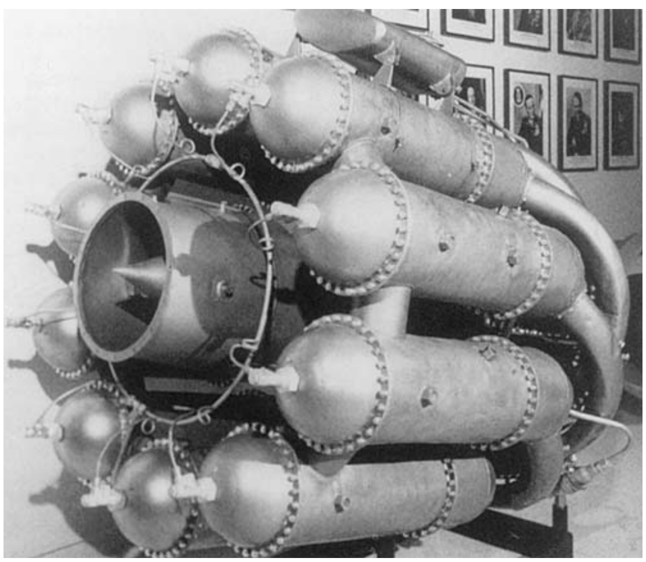


Figure 48. Combustor and Jet Pipe of Whittle W.1X Engine.

developments ended up under Heinkel, but as will be seen later, despite a preeminent position in the area of turbojet engine and jet aircraft development, Heinkel could not capitalize on his position as a jet age pioneer.

Engine Development Sponsored by Ernst Heinkel

Von Ohain developed the idea of his jet engine while he was a doctoral student at the University of Gottingen. The 25-year-old Ohain was hired by Heinkel and soon headed Heinkel's engine development work. His pioneering work allowed Heinkel to fly the world's first jet airplane. Heinkel proceeded with engine development on his own, but ultimately his programs came under government control.

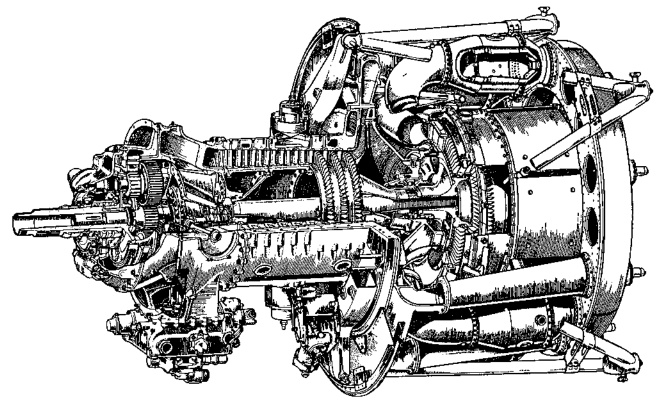


Figure 49. Sectioned View of the Bristol Theseus Axial Flow Turboprop Engine. (Geoffrey Smith, 1946)

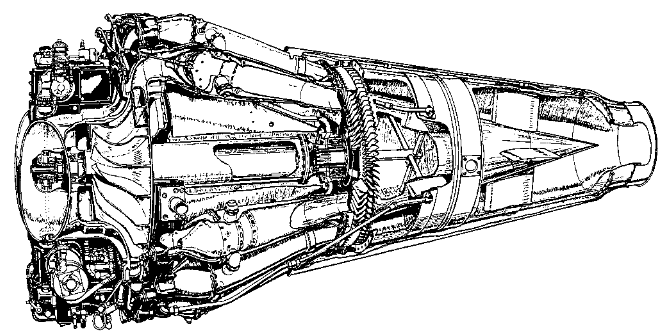


Figure 50. De Havilland Goblin Engine (Rated at 3000 Lb Thrust, 10,200 RPM, Weight 1550 Lb) Used on the Vampire Jet Fighter. Unlike the Whittle Designs, It Used a Single-Sided Centrifugal Compressor. (Geoffrey Smith, 1946)

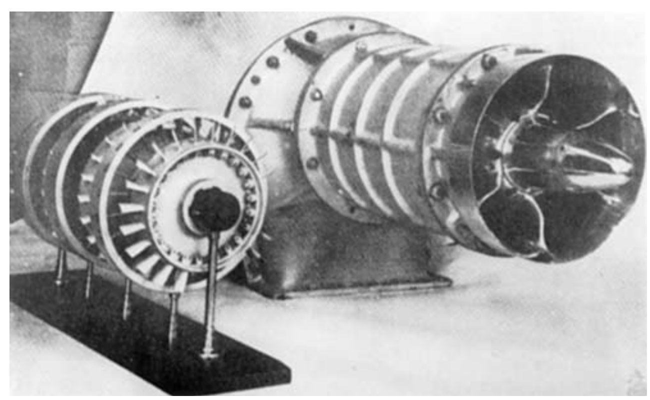


Figure 51. Six Inch Diameter Experimental Multistage Axial Flow Compressor, "Anne," First Run in 1938. (Tip speed 750 fps, 28,600 rpm.) (Constant, 1945; Courtesy IMechE, UK)

Turbojet Engine Development
Initiated at Junkers Aeroplane Company

During 1936 and 1939, engineers at another aircraft manufacturer, Junkers Aeroplane Company, were working on jet engines under the guidance of Professor Herbert Wagner. Wagner, a brilliant airframe designer, was well-versed in steam turbine design and wanted to develop jet engines that, he felt, would make Junkers a preeminent aircraft company. By 1938, Junkers had 30 designers and draftsmen working on the project at their Magdeburg plant and were in the process of developing a demonstrator, which

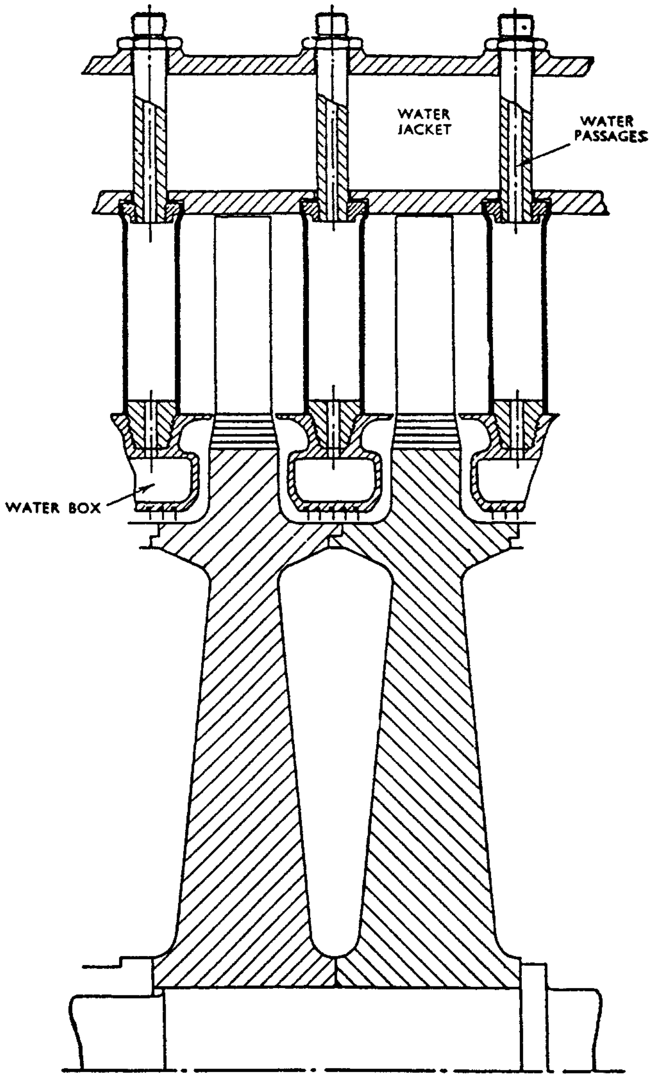


Figure 52. Details of Experimental British Water-Cooled Gas Turbine Developed in the Early 1940s. (Constant, 1945; Courtesy IMechE, UK)

had a 12-stage axial compressor, single combustor, and a two-stage turbine. This team included Max Adolf Mueller, who was at one time an assistant to Professor Wagner at the Technical University in Berlin and was now project manager for the Wagner jet engine studies. Later, the RLM insisted that engine development work be taken over by Junkers engine company (Junkers Motoren at Dessau). Mueller and 12 members of his team who objected to the organizational changes, left Junkers and were hired by Heinkel in the summer of 1939, thus bringing the Wagner engine program to Heinkel. Included in this team was Dr. R. Friedrich, an outstanding compressor aerodynamist.

Official Turbojet Programs of the RLM (German Air Ministry)

In 1938, Helmut Schelp and his senior, Hans Mauch, in the German Air Ministry (RLM) had ambitious jet engine development programs in mind and were trying to work with the aeroengine manufacturers to interest them in jet engine development.

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 Wagner's ongoing program at Junkers *Airframe* Company mentioned above. Daimler Benz refused Schelp's offer for funding. Bramo, fearful that they would soon face severe competition in piston engine orders from their rivals BMW, agreed to perform a study. BMW took on a study contract. Later, during the war, the BMW company developed the 003 engine under the leadership of Dr. Herman Oestrich.

Ultimately, all German turbojet development work came under RLM control. The RLM insisted that all engine development be done at engine companies. At the Junkers Aeroengine Company (Junkers Motoren, or Jumo for short), work proceeded on the deliberately conservative Junkers Jumo 004 engine under the leadership of Anselm Franz. This engine, which powered the ME-262, was the world's first high volume production turbojet (Meher-Homji, 1997). Heinkel was permitted to purchase the Hirth Corporation, which gave him access to engine manufacturing technology. Both the von Ohain and Mueller engine programs were moved to the Heinkel-Hirth Corporation essentially under RLM control. Further details are presented in Meher-Homji and Prisell (1999).

Von Ohain's Early Work

Von Ohain developed the idea of his jet engine while he was a doctoral student at the University of Gottingen, when he was working toward his Ph.D. under the renowned Professor Pohl. During a flight on a Junkers Trimotor aircraft, von Ohain was appalled by the high noise and vibration caused by the reciprocating engines and instinctively felt that the combination of aerodynamic aircraft would be more matched, in an aesthetic sense, with a continuous flow aerothermodynamic engine. Spurred on by this initial feeling, von Ohain, in the fall of 1933, started thinking about a steady aerodynamic flow process. With his design goal of simplicity for a working model, he chose a centrifugal compressor and radial inflow turbine layout to minimize matching problems. Even at this early date, von Ohain recognized the importance of minimizing frontal area by the use of axial flow compressors, but opted for the simpler radial design for the initial models.

By 1934, he had completed rudimentary design calculations that indicated speeds of 500 mph were possible based on a pressure ratio of 3:1 and a turbine inlet temperature of 1200 to 1400°F. Although the fuel consumption was high, von Ohain calculated that the turbojet's weight would be about a fourth that of a reciprocating engine. He initiated patent procedures and decided to build a working model of the engine at his own expense. Von Ohain developed a friendship with Max Hahn, an expert mechanic, machinist, and a natural engineer, who was the chief mechanic at the Bartells and Becker car repair shop in Gottingen where he used to have his car repaired. Von Ohain showed Hahn his initial sketches and Hahn made suggestions for simplification to enable manufacture. The prototype model was built by Hahn and funded by von Ohain with the initial estimate being 1000 marks. The engine is shown in Figure 53. This engine did not self sustain due to combustion problems but did result in unloading the starter.

Professor R. W. Pohl at Gottingen University was very supportive of von Ohain's extracurricular work and permitted experiments to be conducted in the backyard of his institute, supplying von Ohain with instrumentation and a starter motor. Convinced that von Ohain's theory was right and that this concept had a future, he recommended to von Ohain that industrial sponsorship would be needed for further development and indicated his willingness to write a letter of recommendation to an aeroengine company of von Ohain's choice. Von Ohain wisely chose the aircraft manufacturer Ernst Heinkel, as he was aware of Heinkel's obsession for high-speed aircraft and his reputation as a risk taker. Von Ohain intuitively recognized that the traditional aeroengine companies would resist the revolutionary design that he was proposing.

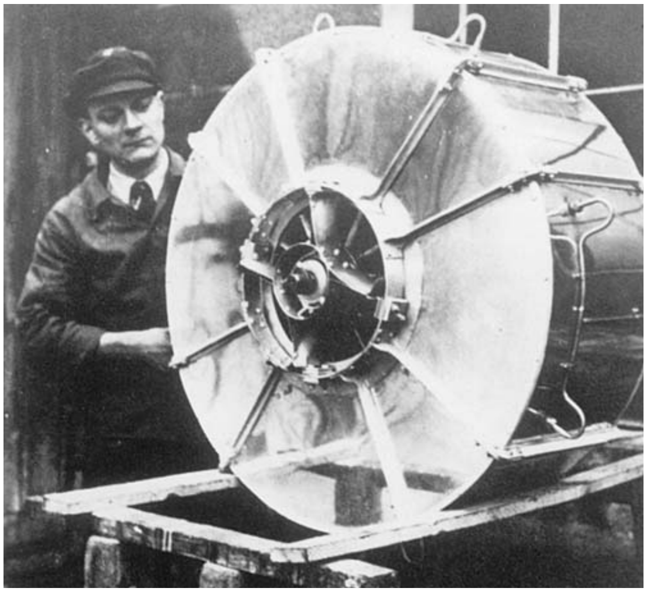


Figure 53. Von Ohain's Prototype Turbojet Built in 1934. (Bentele, 1991)

Turbojet Engine Development Work at Heinkel

In February 1936, Pohl wrote to Heinkel and as a result, the 25-year-old von Ohain was summoned to Heinkel's house on the Baltic Coast. Ohain met with the leading engineers at Heinkel and after a grueling one-day interview, in which he skillfully addressed all questions, succeeded in convincing Heinkel to hire him. Part of the reason for Heinkel hiring von Ohain was to prevent him from going to his arch rival, Messerschmitt. This rivalry continued throughout the war in the race to produce the first jet fighter. An employment contract was issued to von Ohain on April 15, 1936. Ernst Heinkel's perspective of jet and rocket propulsion work that he sponsored may be found in Heinkel (1956).

The HeS 1 Demonstrator Engine

Von Ohain and Max Hahn (whom von Ohain insisted be hired) started work under a shroud of secrecy in a special building in Marienehe and were given instructions to develop a jet engine as rapidly as possible with the stipulation from Heinkel that bench tests were to begin within a year.

The rather overambitious schedule stipulated by Heinkel forced von Ohain to deviate from his original plan, which was to systematically conduct studies and tests and solve the combustion problems. Recognizing the politics of the situation, von Ohain made the conscious decision that a simple engine run on hydrogen fuel would provide the impetus needed for such a project, quickly demonstrating a tangible running engine to Heinkel and buying him time for systematic combustion investigations. The HeS 1 layout is shown in Figure 54. It consisted of a back-to-back radial compressor and a radial inflow turbine. The rotor diameter was 12 inches and the centrifugal compressor was preceded by an axial entry stage. The hydrogen combustor consisted of a large number of hollow vanes with blunt trailing edges placed within the air duct between the compressor and the radial inflow turbine. Von Ohain's choice of hydrogen as a fuel was wise, as the combustor performed flawlessly because of the high flame velocity and the wide combustion range of hydrogen. Performance under off-design conditions and transient acceleration and deceleration was excellent.

Early one morning in the spring of 1937, the engine was demonstrated to Ernst Heinkel. This event had a major impact on von Ohain's position at Heinkel. Dr. von Ohain received a permanent contract and was named head of the Heinkel jet

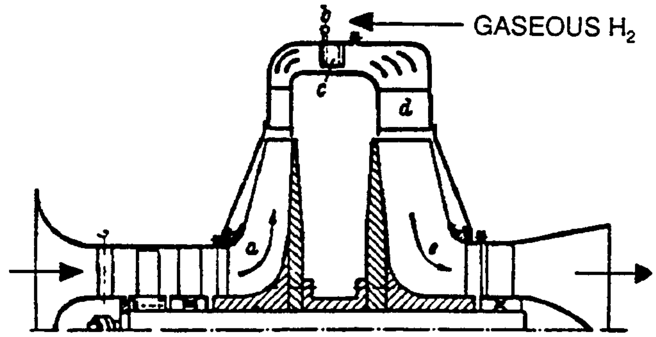


Figure 54. HeS 1 Hydrogen Fueled Demonstrator First Run in Spring 1937. (Thrust 250 lb, 10,000 rpm, and rotor diameter 12 inches.) (Meher-Homji, 1999; Courtesy ASME)

propulsion development. After this successful engine run, Heinkel pushed hard for a flight engine operating on liquid fuel, which led to the design and development of the HeS 2 engine and finally the HeS 3 engine.

Design and Development of the HeS 3A and HeS 3B Turbojets

Starting in May 1937, after the running of the HeS 1 engine, work was intensified on the combustor development. By 1938, a combustor with excellent operational characteristics was developed. This combustor used vaporized fuel, but there were difficulties with fuel atomization that had to be overcome.

The first HeS 3A was tested in 1938, but did not produce the design thrust required because a small compressor and combustor had been used to reduce the frontal area. The engine was, therefore, completely redesigned resulting in the HeS 3B. This engine increased the mass flow by having a high hub/tip ratio and von Ohain minimized the inlet losses by using an axial inducer stage that, in addition to contributing to an increased pressure ratio, also provided a counter swirl, thus decreasing the inlet relative Mach number and curvature of the inlet blade. The layout of the flight engine is shown in Figure 55. The inlet section of the HeS 3 is shown in Figure 56. The wraparound combustor is shown in Figure 57, and the radial inflow turbine is shown in Figure 58. The engine operated at 13,000 rpm, had a weight of 793 lb, and a frontal area of 7.31 sq ft.

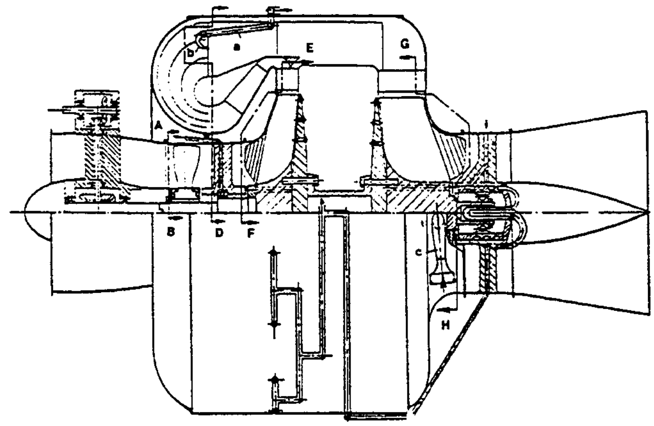


Figure 55. Layout of HeS 3B Flight Engine. (Engine speed 13,000 rpm, static thrust 1100 lb.) (Bentele, 1991)

The He 178—The World's First Jet Aircraft

The He 178 (Figure 59) was a small shoulder winged airplane having a wing span of 23 ft 7 inches (7.2 m) and a length of 24 ft 6 inches (7.48m). The wings were mostly of wooden construction with a small dihedral angle. Air for the single HeS 3B turbojet was

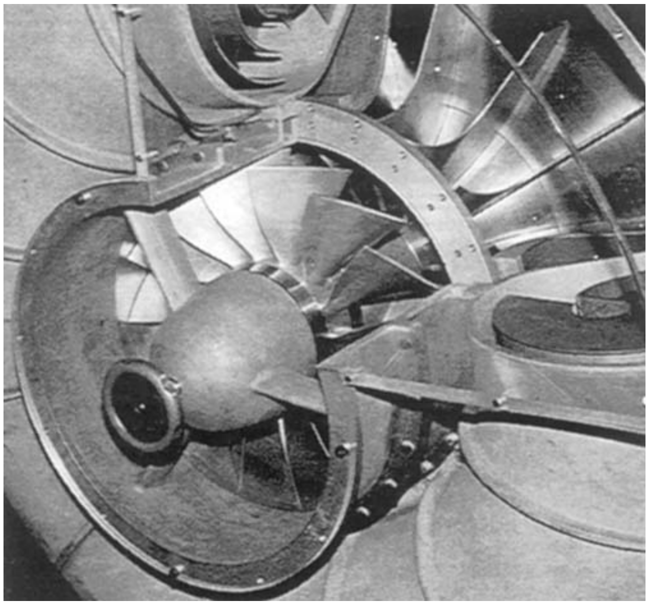


Figure 56. Inlet Section of the HeS 3B Engine Showing Axial Inducer and Centrifugal Compressor. (Meher-Homji, 1999; Courtesy ASME)

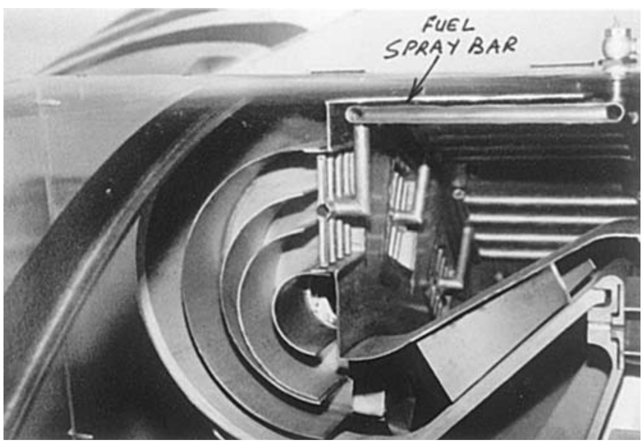


Figure 57. Wraparound Combustor of the HeS 3B Engine Showing Fuel Spray Bar. (Meher-Homji, 1999; Courtesy ASME)

drawn in from a nose intake and routed to the engine via a duct that went below the pilot's seat. The fuel tank was located behind the pilot's seat. The aircraft had a loaded weight of 4295 lb (1950 kg) and was designed for a maximum speed of 498 mph (640 Km/h) at sea level.

On August 27, 1939, the He 178 piloted by Erich Warsitz made a historic six minute flight from the Heinkel airfield in Marienehe at about 4:00 a.m. There was great jubilation after this historic event. Heinkel rushed to inform the RLM of this achievement, but met with indifference as the RLM had more immediate problems of gearing up for the war, which was to start within a few days. Later, Heinkel arranged for a demonstration of the He 178 that was observed by the German Air Ministry, but there was little enthusiasm displayed by the Air Ministry representatives.

This was the first aircraft in the world to fly utilizing a turbojet. To put the date into perspective, this flight was one year before the Italian Caproni-Campini CC2 (which used a ducted fan jet system but utilized a reciprocating compressor and consequently was not a true turbojet) and 20 months before the British Gloster E28/39 first took to the air powered by Whittle's W1 turbojet.

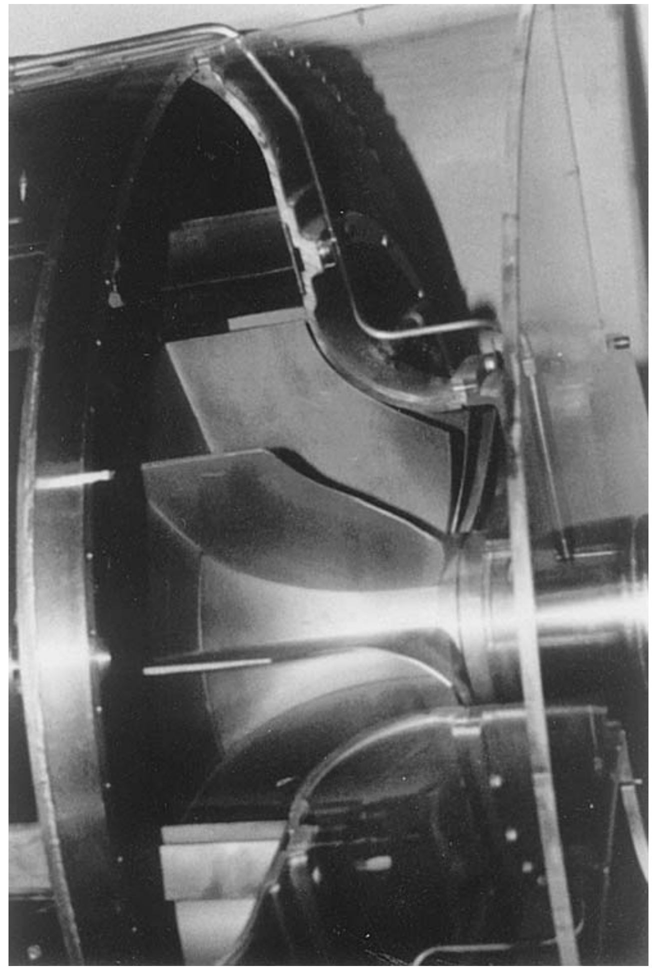


Figure 58. Radial Inflow Turbine of the HeS 3B Engine. (Meher-Homji, 1999; Courtesy ASME)

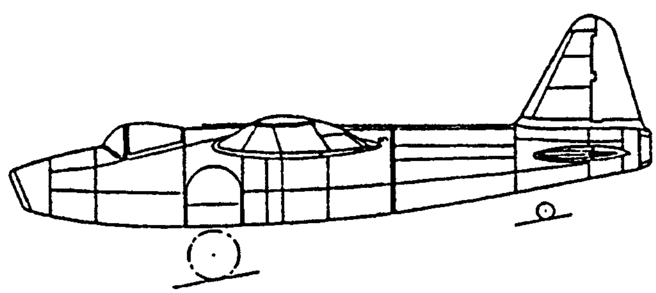


Figure 59. The World's First Jet Powered Aircraft, the Heinkel He 178, Powered by von Ohain's HeS 3B Turbojet. (First flight on August 27, 1939, a few days before declaration of WW II.) (Meher-Homji, 1999; Courtesy ASME)

HeS 8A Engine Development for the He 280 Jet Fighter

Shortly after the demonstration of the He 178 to the RLM, Heinkel started development of a twin engine fighter, which was designated the He 280. The aircraft could not use engines of the HeS 3B type because of the large engine diameter and low performance. At this time, however, the axial flow engine (designated the HeS 30) that was being developed by Mueller who had arrived at the Heinkel Rostock plant, was experiencing serious development problems. Recognizing that this engine would not be ready in time, von Ohain designed a backup solution designated the HeS 8, which would employ a radial rotor similar to the HeS 3B combined with an axial vane diffuser and a straight-through flow combustor. Only 14 months were available for this development, as the He 280 airframe was developed much faster than its engines.

The engine program was done under an RLM contract giving the engine the first RLM designation of a German turbojet, the 109-001. It was not without risks because the specification of the aircraft limited the engine diameter and therefore the axial diffuser function and efficiency together with the straight-through combustor became very critical. Luckily for Heinkel, von Ohain's HeS 8 engine managed to meet the minimum requirements and was ready in time for the first flight of the He 280, which took place in late March 1941. The HeS 30 program still suffered several problems including a mismatch between the compressor and turbine.

The HeS 8 (RLM designation 109-001) was based on the HeS 3 and HeS 6 engines. The reduction in diameter was accomplished by redesign of the compressor diffuser into an axial design and combustion chamber by making it a "straight-through" design, as shown in Figure 60. The leading particulars of this engine are shown in Table 5.

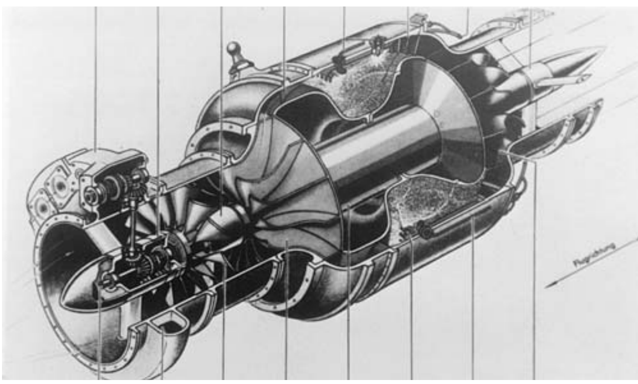


Figure 60. HeS 8 Turbojet Designed by von Ohain (13,500 RPM), Designed to Power the World's First Jet Fighter, the He 280. (Meher-Homji, 1999; Courtesy ASME)

Table 5. Leading Particulars of the HeS 8 Turbojet Designed by von Ohain. (Meher-Homji, 1999).

PARAMETER	HeS8 ENGINE
RPM	13,500
Weight	837 lbs, (380 kg)
Frontal Area	5.05 sq. f; (0.47 m2)
Specific Thrust.	1.89Lb thrust/Lbs; (18.5 N/kg)
Specific fuel consumption	1.6 Lbs/Lbs thrust hour; (0.163 kg/Nh)

Even though the HeS 8A was a good engine, its power was marginal for the He 280, and it lost out to the Jumo 004, which had been chosen for the production of the ME-262 jet fighter.

The He 280 was a graceful twin-engine fighter and was designed as an all metal mid-wing monoplane powered by two turbojets located in nacelles under the wings. The He 280 was itself a revolutionary design in that it had a tricycle undercarriage and a compressed air-operated ejection seat. On March 30, 1941, it took off for the first time powered by von Ohain's HeS 8 engines, with Heinkel's test pilot Fritz Schaffer at the controls. The He 280 is shown in Figure 61.

After the demonstration flight of the He 280, Heinkel finally received permission to purchase Hirth-Motoren, which was a reputable manufacturer of reciprocating aeroengines and turbochargers located at Zuffenhausen near Stuttgart. This acquisition was fraught with politics, with Heinkel's rival Messerschmitt reportedly delaying the acquisition for several months. With the acquisition of Hirth, Heinkel had access to the

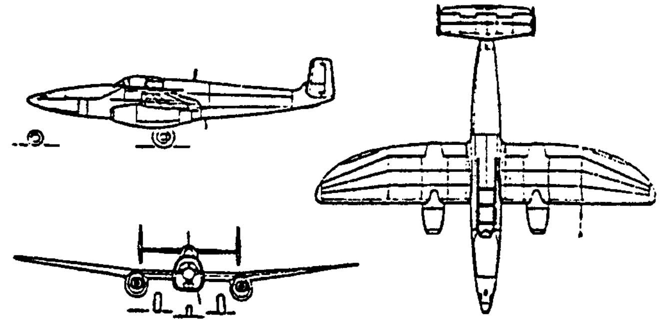


Figure 61. The Heinkel He 280 Jet Fighter Powered by Two HeS 8 Turbojets. (This fighter flew in March 1941, but production was canceled to focus on the Messerschmitt ME-262.) (Meher-Homji, 1999; Courtesy ASME)

engineering capabilities and manufacturing know-how of this small but well-known engine company.

The formal name of the company formed when Heinkel took over Hirth Motoren was Ernst Heinkel AG-Werk Hirth Motoren, and was called Heinkel-Hirth for short. It is interesting to note that when asked during a conference in 1978 what single item von Ohain needed the most during his early development days, he stated that the greatest need was for expertise in the area of blade vibration, which he said he got from the Hirth Company in the form of Dr. Bentele. Dr. Max Bentele was, at that time, a leading expert in Germany specializing in aeromechanics and blade vibration. In the fall of 1943, he had resolved a complex blade failure problem on the Junkers Jumo 004 engine.

Design and Development of the
Advanced Heinkel-Hirth HeS 011 Turbojet

In 1942, the RLM granted Heinkel-Hirth the contract for a second-generation engine known as the HeS 011 (RLM designation 109-011), which provided a quantum step in specific power and performance. The specifications of this engine were (Bentele, 1991):

> Max thrust 2863 lbs (12.75 kN) with a growth to 3307 lbs (14.7 kN), weight under 1985 lbs (900 kg), pressure ratio 4.2:1, altitude capability 50,000 ft (15 km), specific fuel consumption less than 1.4 lb/lb-hr

Dr. von Ohain was in charge of the development and Dr. Max Bentele was responsible for component development and managed the development on the compressor and turbine sections of the engine.

As reported by Bentele (1991) in December 1944, the best performance parameters attained for the engine were a thrust of 2940 lb at a rotor speed of 10,205 rpm. The leading particulars of the first generation Jumo 004B engine, which was in production, and this advanced engine developed at Heinkel-Hirth are compared in Table 6. A photograph of the engine is shown in Figure 62 and the layout depicted in Figure 63.

Details of the engine may be found in Meher-Homji and Prisell (1999). Of greatest interest was the diagonal compressor stage (mixed flow), an annular combustor, and the remarkable air-cooled turbine section. The compressor section of this engine is shown in Figure 64. The HeS 011 had a remarkable two-stage air-cooled turbine section (Figure 65) designed by Dr. Max Bentele. Two rows of hollow turbine nozzle blades were cooled by air bled off through the annulus after the final compressor stage. This nozzle cooling air was ducted between the combustion chamber and the rotor shaft, which was shielded by an annular insert. The two-stage axial turbine was cooled by compressor bleed air. Both of the disks had hollow vanes with air being routed to the second stage through holes bored in the first stage. The airflow exited the blades at the tip.

Table 6. Comparison between the Junkers Jumo 004B Engine and the Advanced Heinkel Hirth HeS 011 Turbojet. (Meher-Homji, 1999)

Parameter	**Jumo 004 B**	**HeS-011A**
Manufacturer	Junkers Engine	Heinkel-Hirth
Thrust, Lbs	2000; (8.927 kN)	2863 , (12.75 kN)
Weight, Lbs	1650; (750 kg)	1950; (885 kg)
T/W Ratio	1.21	1.44
Length	152” (3860 mm)	131.6” (3343 mm)
Frontal dia.	30”; (760 mm)	32”;(805 mm)
Air mass flow rate, lb/sec	46.7; (21.2 kg/sec)	64; (29 kg/sec)
Pressure Ratio	3.1:1	4.2:1
RPM	8700	10,205
Compressor configuration	8 stage axial flow	Diagonal stage +3 axial stages
Turbine Configuration	1 stage turbine	2 stage air cooled
Fuel Consumption Lb/Lb thrust	1.4-1.48	1.35
Turbine inlet temperature, ° F	1427°F; (775°C)	1427 °F (775°C)

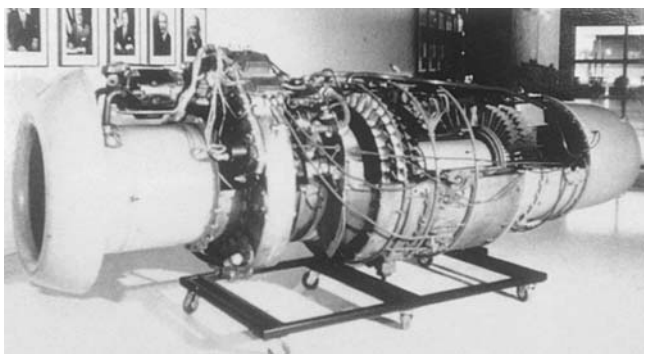
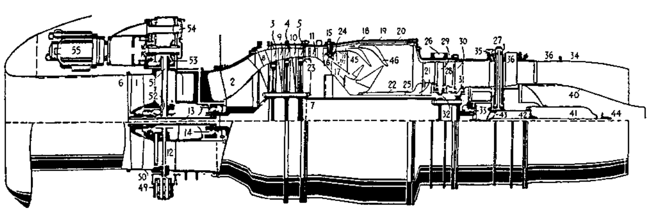


Figure 62. The Heinkel Hirth HeS 011 Engine Designed by Hans von Ohain and Max Bentele. (This was the most advanced turbojet at the end of the war, with a pressure ratio of 4.2:1, 64 lb/sec and thrust of 2863 lb.) (Meher-Homji, 1999; Courtesy ASME)



(1) Front axial rotor; (2) diagonal rotor; (3, 4, 5) third, fourth, fifth rotors; (6) air-intake hood; (7) main shaft; (8, 9, 10) guide grids; (11) triple grid; (12) pump drive shaft; (13) floating rod; (14) front main bearing; (15) connection for fuel pipe; (16) arrow-shaped ring (nozzle ring); (17, 18) air flows between compressor and turbine; (19) housing wall; (20) circular chamber; (21) guide grip in front of turbine wheel; (22) circular chamber; (23) annular cool-air gap; (24) injection nozzles; (25) cool-air passage to guide grids; (26) fastening flange; (27) connection for lubricant pipe; (28) guide grids between turbine rotors; (29, 30) turbine rotors; (31) cool-air holes; (32) cool-air holes; (33) rear main bearing; (34) thrust-nozzle housing; (35) cool-air connection; (36) ventilation tube; (37) pressure-measurement place; (38) (not shown—not identified); (40) thrust-nozzle sleeve; (41) piston rod; (42) pressure cylinder; (43) piston; (44) piston-rod bearing; (45) mixers; (46) scoops; (47, 48) (not shown—not identified); (49) lubricant pump set; (50) front compressor housing; (51) vertical shaft; (52, 53) bevel gears; (54) drive connection for turbine's extension shaft; (55) starter

Figure 63. Layout of the HeS 001 Engine. (Neville and Silsbee, 1948)

The development of the turbine section was most challenging. Initially solid blades were employed, and stress rupture occurred at the first stage and fatigue failures at the second stage. The resonance failure was traced to the location of four struts of the rear bearing support. These were eliminated by spacing the struts at unequal angles, thus minimizing the forced excitations that were in resonance with the second-stage rotor blades.

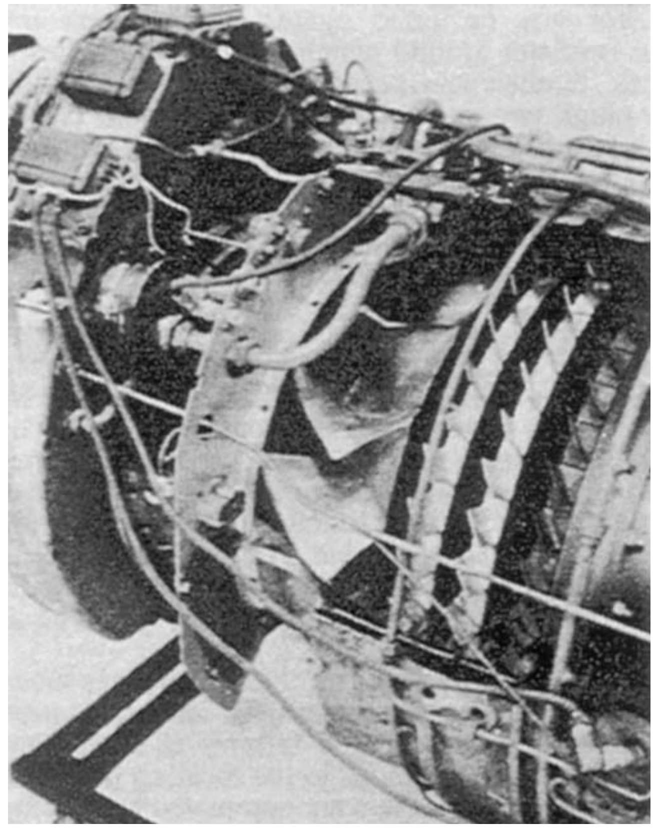


Figure 64. Compressor Section of the HeS 011 Engine Showing the Unique Diagonal Mixed Flow Compressor. (Bentele, 1991)

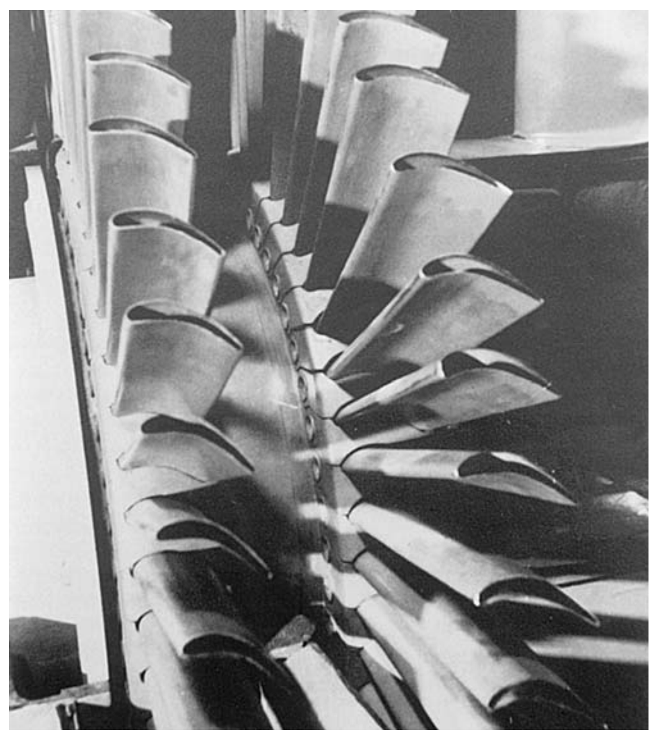


Figure 65. Details of the Advanced Air-Cooled Turbine Section Designed by Dr. Max Bentele for the HeS 011 Engine. (Bentele, 1991)

The final air-cooled blades designed by Dr. Bentele did not utilize any strategic materials and were called “topfschaufel.”

These blades were manufactured starting with a circular plate of austenitic chrome-moly sheet steel from which a closed end tube was drawn in several stages with intermediate heat treatments. As seen in Figure 66, wall thickness diminished from 0.079 inch (2 mm) at the root to 0.017 inch (0.45 mm) at the blade tip, so as to match the stresses with the prevailing radial temperature profile. The airfoil shape was then induced and finish machining done. Both the first and second turbine stages utilized this construction and contained an insert for the proper distribution of the cooling air and for damping blade vibration.

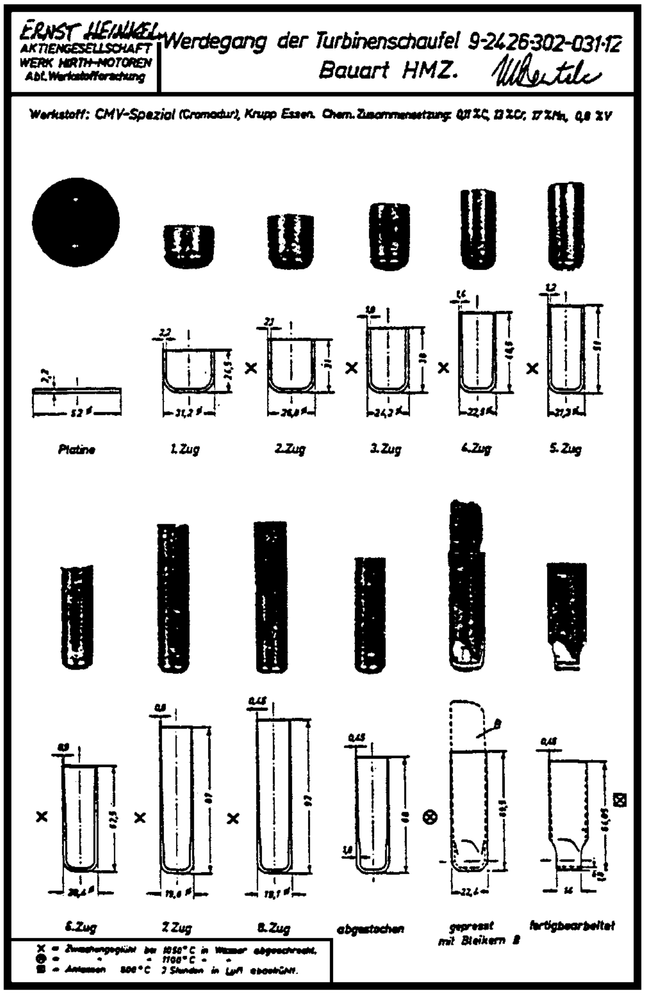


Figure 66. Ingenious Method of Developing Air-Cooled Turbine Blade Starting with a Circular Plate of 25 MM (.98 Inch) Diameter. (Hirth-Moteren Report 1944a, 1944b)

Dr. von Ohain had a distinguished career in the US after the war, rising to Chief Scientist at the Aero Propulsion Laboratory. He received the ASME Tom Sawyer Award in June 1990, and was inducted into the National Hall of Fame for Aviation in 1990. Von Ohain and Sir Frank Whittle were awarded the Charles Draper Prize in 1992 for their monumental contributions to aviation. This coveted award is considered the "Nobel Prize" for technology.

A photograph of Dr. von Ohain, Sir Frank Whittle, and Dr. Max Bentele is shown in Figure 67. This is the last known photograph of these jet pioneers together and was taken in 1978.

THE WORLDS FIRST PRODUCTION TURBOJET

No paper on turbomachinery history would be complete without some mention of the world's first production turbojet, the Junkers Jumo 004, which was the powerplant for the formidable

Figure 67. Photograph of Three Jet Engine Pioneers (1978). (Left to right: Sir Frank Whittle, Dr. Hans von Ohain, and Dr. Max Bentele.) (Bentele, 1991)

Messerschmitt ME 262 fighter. The development represented a historic achievement for Anselm Franz and his design team at Junkers. Approximately 6000 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. Details of this remarkable engine may be found in Meher-Homji (1996) and Franz (1979). A Junkers Jumo 004 engine is shown in Figure 68. In addition to powering the ME-262 fighter, the Junkers Jumo engines also propelled the world's first jet bomber, the Arado 234.

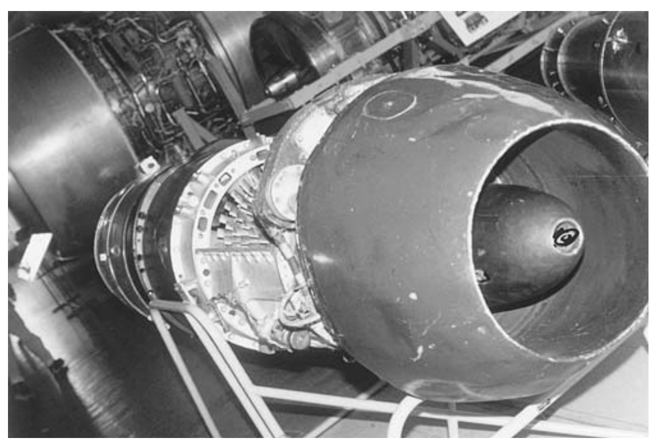


Figure 68. The Junkers Jumo 004 Engine. (1989 lb static thrust, pressure ratio of 3:1, air flow rate 46 lb/sec, 8700 rpm. Cable pull starter for the 10 hp Riedel starter motor can be seen in the nose cone.)

Design and Development of the Junkers Jumo 004 Axial Flow Turbojet

From the outset, Anselm 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.

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 shortest timeframe 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.

The compressor utilized pure reaction blading that resulted in a pressure ratio of 3.14:1 in eight compression stages. The engine airflow rate was 46.6 lb/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 six-can type combustor, as he knew that these would present less of a problem and permit bench testing with a single can. On July 18, the first flight of the ME 262 powered by two Jumo 004 jets took place and lasted for 12 minutes. The ME 262 is shown in Figure 69. Details on the ME-262 may be found in Morgan (1994).

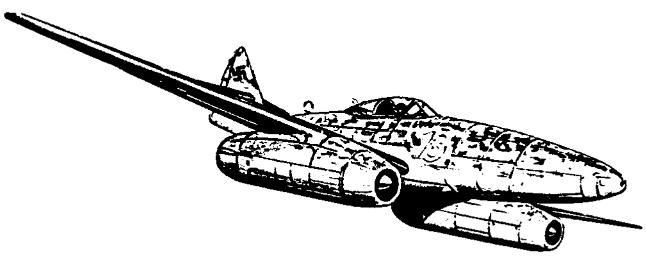


Figure 69. Messerschmitt ME-262 Fighter, the World's First Operational Jet Fighter Powered by Two Junkers Jumo 004B Turbojets. (The aircraft was capable of 550 mph and became operational in 1944.) (Meher-Homji, 1996; Courtesy ASME)

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 1850 lb, 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. 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 cutaway view of the Junkers Jumo 004 engine is shown in Figure 70.

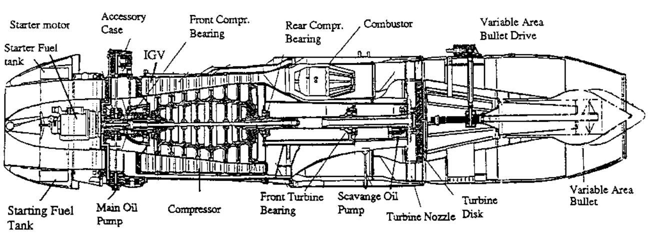


Figure 70. Cross Section of the Junkers Jumo 004 Turbojet Showing Eight-Stage Axial Compressor, Six-Can Annular Combustors, and Single-Stage Air-Cooled Turbine. (Neville and Silsbee, 1948)

Turbine Blade Failures

During the summer of 1943, several turbine blade failures were experienced due to a sixth order excitation (6 × number of 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 six 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 sixth order resonance occurred with the blade bending frequency in the upper speed range. The predominance of the sixth order excitation was due to the six 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 1 mm (.039 inch), and reducing the operating speed of the engine from 9000 to 8700 rpm.

TURBOJET DEVELOPMENT IN THE USA

The Whittle Engine in the USA

Upon declaration of World War II, Sir Henry Tizard, who was Chairman of the British Aeronautical Research Council, proposed sharing jet technology with the United States and started official talks. US military intelligence had, however, been filing reports about jet propulsion work in both England and Germany, and Major General Hap Arnold visited Britain to examine this technology. In May 1941, Arnold put in a formal request for jet technology. On July 21, 1941, Roxby Cox and Roy Shoults of GE visited the Power Jets Limited and the Gloster factory. A decision was made to mass-produce this engine in the US and GE was chosen to build the engine. As reported by Ford (1992), a GE delegation visited Washington on September 4, and was handed a sheaf of drawings with Hap Arnold stating, "Gentlemen, I give you the Whittle Engine." GE committed to build a working engine within six months. Bell Aircraft was commissioned to build a prototype jet fighter.

On October 1, 1941, the Whittle W.1X was flown to the US in a B-24 bomber and made its way to Building 34 North at the GE Lynn, Massachusetts, facility. On October 16, the W.1X was fired up. In a remarkable engineering effort, the GE team made some modifications to the design and within six months ran an engine on March 18, 1942. Later, Whittle visited Boston to help solve a problem with burning bearings. In August, GE delivered two engines (designated the I-A) to Bell Aircraft and the first flight of the Bell P-59 was made on October 1, 1942, exactly one year after the W.1X left Britain. An excellent description of the initial US jet engine work is made by Ford (1992).

Engine Development at Westinghouse

While most attention is traditionally focused on British and German turbojet development, it should be noted that a remarkable achievement was accomplished by a design group at Westinghouse led by Reinout P. Kroon. As a result of Kroon's visit to the Navy Bureau of Aeronautics on December 8, 1949 (one day after the bombing of Pearl Harbor), where he demonstrated that he could design such an engine on two sheets of paper, the Navy issued a contract in February 1942 (*IGTI Global Gas Turbine News*, 1993). Westinghouse was authorized to proceed with the construction of two 19A engines. The 19A was an axial flow design with a 19 inch diameter. The engine completed a 100 hour endurance test on July 5, 1943, only four months after its first run. The short time for the development for a new type of engine was truly a remarkable feat of engineering by Kroon and his design team. This engine with further refinements (Westinghouse designation 19B called the "Yankee" became the J30) was used to power the Navy's first all jet fighter, the McDonnell Douglas FH-1 Phantom. The engine had a 10-stage axial flow compressor with a pressure ratio of 3.8:1 and single-stage turbine. The engine was rated at 1560 lb static thrust at 17,000 rpm at sea level. The 10-stage axial compressor of this historic engine is shown in Figure 71. The annular combustor is shown in Figure 72, which also shows the coupling shaft. The single-stage turbine and nozzle guide vanes are shown in Figure 73. The production order of the J30 engine was given to Pratt and Whitney in 1944. A detailed description of aircraft gas turbine development in the US may be found in St. Peter (1999).

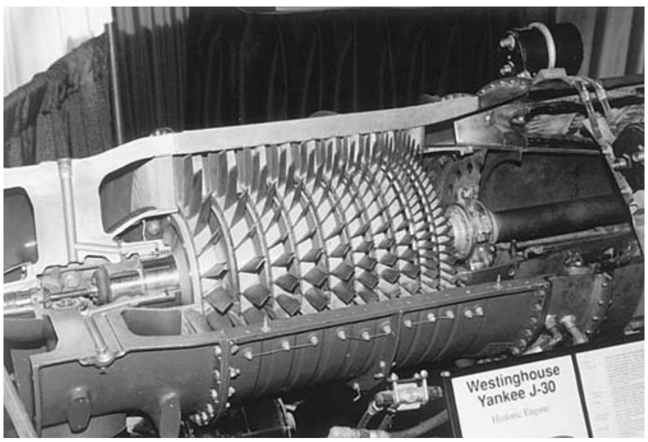


Figure 71. Westinghouse J-30 "Yankee" 10-Stage Axial Flow Compressor (Pressure Ratio of 3.8:1), Cutaway View.

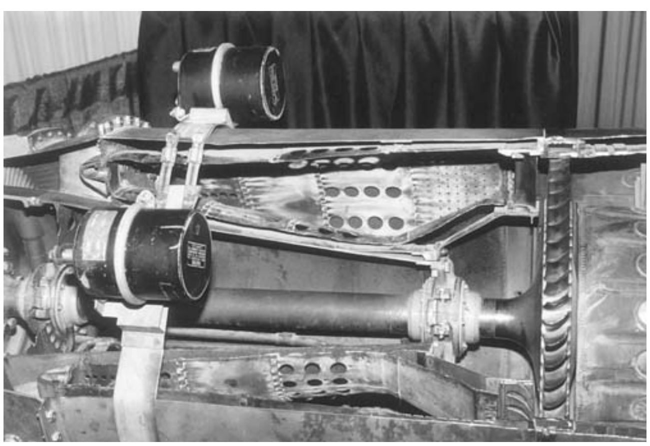


Figure 72. Westinghouse J-30 "Yankee" Annular Combustor.

HISTORICAL DEVELOPMENTS IN ROTOR BEARING DYNAMICS

Rotordynamics

A treatment of the area of rotordynamics and bearing technology is an important component in the history of turbomachinery development as several of today's high-speed machinery are the

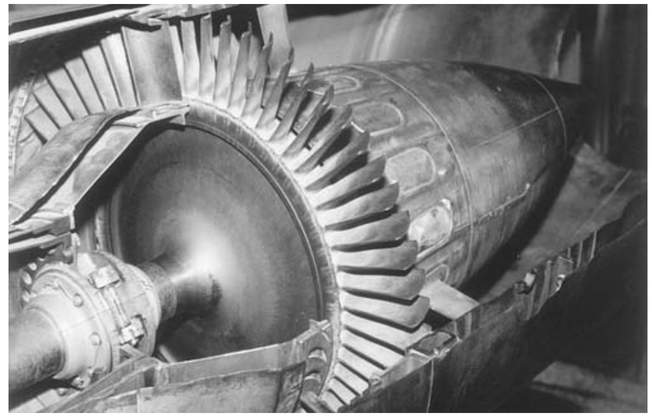


Figure 73. Westinghouse J-30 "Yankee" Single-Stage Turbine Wheel (17,000 RPM) and Jet Pipe.

result of the experimental and analytical work of the early pioneers. To this day, critical speed problems, aero induced instabilities, and other rotordynamic problems cause considerable distress to operating engineers. Details of the history of rotordynamics are provided in Gunter (1966), Jung (1973), and Traupel (1973), and a review of the literature is made by Bishop and Parkinson (1968) and Tondl (1965). A good overview of the historical development of balancing techniques is made by Rieger (1986).

The first recorded paper on rotordynamics was published in 1869 by Rankine (1869), where he examined the behavior of frictionless uniform shaft. Because of his neglect of Coriolis forces, he concluded that there were three operating regimes:

- Stable operation below the first critical speed
- "Indifferent" operation at the critical speed
- Unstable operation at supercritical speed

This analysis by the eminent Rankine led turbine designers to believe that operation above the first critical was impossible. In approximately 1892, Gustaf De Laval and simultaneously Charles Parsons in England proved this to be wrong. It took a period of 50 years after the publication of Rankine's paper for a definitive paper by Jeffcott (1919) to appear that established modern rotordynamics.

Gustaf De Laval made his first experimental turbine in 1883. This machine was a reaction design patterned after Hero's turbine and was designed for 42,000 rpm, which was an amazingly high speed for the time and too high for practical use. De Laval recognized that he would have to obtain a tip speed of approximately 250 to 350 m/sec (820 to 1148 ft/sec), i.e., around half the speed of steam (U/C $\approx$ 0.5). He conducted several experiments and developed reduction gearing and supercritical nozzles, circa 1880s.

In the course of his experiments, he found that violent vibrations that destroyed bearings resulted when he operated at speeds of 40,000 to 60,000 rpm. In January 1889, he had his first success with his "cane experiments," when he placed a disk on a cane and spun the cane in a lathe to observe its behavior. He made the important discovery that the vibrations diminished after passing through the critical speed and consequently concluded that the shaft had to be flexible. Figure 74 shows his patent drawings derived from his cane experiments.

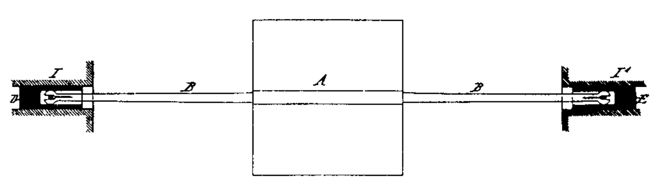


Figure 74. Patent Drawing (May 1889) of De Laval Flexible Shaft and Bearing.

De Laval ran into difficulties when attempting to patent his ideas in Germany, as the patent office did not accept the mathematics in the patent description. Because of this, De Laval had to build a hand-driven demonstration model for the German patent office that duplicated his cane experiments, but with a metal shaft. The model could show how the rotor ran smoothly despite being heavily unbalanced, after accelerating through the critical speed. Dunkerely conducted extensive studies in 1894, analyzing rotordynamic behavior considering the rotor as a flexible elastic body and bearings as simple supports.

In 1919, H. H. Jeffcott, a well-known English dynamist, started studies in rotordynamics to examine the effect of unbalance on whirl amplitudes and on bearings. His insightful paper entitled "The Lateral Vibration of Loaded Shafts in the Neighborhood of a Whirling Speed—the Effect of Want of Balance" (Jeffcott, 1919), forms the basis of what most rotating machinery engineers are taught today. The basic rotordynamic equation that starts many papers and texts of rotordynamics originated with him.

As a result of Jeffcott's superb analysis, turbomachinery designers started producing high-speed machinery. In the 1920s, several manufacturers went to flexible shaft designs with lighter rotors operating well above the first critical speed. This resulted in some severe instability problems. GE encountered a series of instability related failures in blast furnace air compressors. The blowers were seen by shop engineers to sustain "violent fits of vibration" and during these fits, the shaft would vibrate at low frequency, which shop engineers called "shaft whipping." The problems were initially attributed to poor balance but when it became evident that this was not the underlying cause, the investigation was put under Dr. B. L. Newkirk (1876 to 1964) of GE Research Laboratory. After a series of observations and experiments, Newkirk determined that during the violent whirling, the rotor centerline would precess at a rate equal to the first critical speed (Newkirk, 1924). If the rotor's speed was further increased above its initial whirl speed, the whirl amplitude would increase, leading to eventual rotor failure. After detailed experimental tests, he discovered the following facts (Gunter, 1966):

- The onset of whirling or whirl amplitude was unaffected by refinement of rotor balance.
- Whirling always occurred above the first critical speed.
- The whirl threshold speed could vary widely between machines of similar construction.
- The precession or whirl speed was constant regardless of the unit rotational speed.
- Whirling was encountered only with built up rotors (disk press fits).
- Increasing foundation flexibility would increase the whirl threshold speed.
- Distortion or misalignment of the bearings would increase stability.
- Introducing damping into the foundations would increase the whirl threshold speed.
- Increasing the axial thrust bearing load would increase the whirl threshold speed.
- A small disturbance was sometimes required to initiate the whirl motion in a well-balanced rotor.

A theory for the source of the vibration was provided by A. L. Kimball (1924), who suggested that the forces normal to the plane of the deflected rotor could be produced by the hysteresis of the metal undergoing alternate stress reversal cycles. Newkirk concluded that these forces could be caused by disk shrink fits. Thus started the study of shaft whirling or self-excited instabilities. Newkirk showed that the condition for rotor stability was dependant on several parameters such as bearing characteristics, bearing support, rotor flexibility, as well as external forces and torques acting on the system.

While modern analytical rotordynamic codes and techniques are highly sophisticated today, rotor instability still remains an elusive problem, especially with high-pressure ratio reinjection machines where the aerodynamic forces, rotating stall, and balance piston seal forces can have substantial influence on compressor stability and vibration.

Bearings

Associated with the history of high-speed turbomachinery were advancements of bearing technology. McHugh (1998) provides an excellent overview of the history of this field.

The industrial revolution (1750 to 1850) focused attention on the need for effective and reliable bearings. The widespread use of steam engines and railways made the study of lubrication more important. The most popular lubricant at that time was olive oil. James Watt recommended its use in his steam engines, and Osborne Reynolds' classic paper deals with olive oil.

As early as the 1400s, Leonardo da Vinci recommended the use of a bearing material alloy consisting of three parts (30 percent) of copper and seven parts (70 percent) of tin. The amount used in today's whitemetal is 80 percent. Isaac Babbitt (1799 to 1862) patented a tin-based material for steel shells in 1839.

Pioneering Experiments of Beauchamp Tower

In 1883, an English engineer by the name of Beauchamp Tower discovered full film lubrication. Tower was an established researcher and was chosen by the British Institution of Engineers to study friction in journal bearings. Tower constructed a special test rig to measure friction on a gunmetal half-bearing six inches long. The bearing rested on a horizontal shaft with a four inch diameter journal. A vertical load could be applied to the bearing to simulate loading. The test shaft was driven by a steam engine designed by Tower. The device was designed to measure the friction between the journal and the half-bearing by the restraining torque necessary to keep the half-bearing from rotating. As was the practice at that time, different kinds of lubricants were provided through a hole drilled at the top of the journal. Tower decided to place the lower half of the bearing in a bath of oil. He soon discovered that this arrangement produced a considerable hydrodynamic pressure and that the shaft was actually floating on a film of oil. Tower then proceeded to make accurate measurements to measure the oil pressure along the bearing length and circumference. His classic experiments clearly showed that the film of oil completely separated the journal and the bearing and carried the applied load. His seminal results were presented to the Institution of Engineers in a series of reports (Tower, 1883, 1885). It should be mentioned that Petrov in Russia independently developed similar findings during the same time. Some of Tower's results are shown in Figure 75.

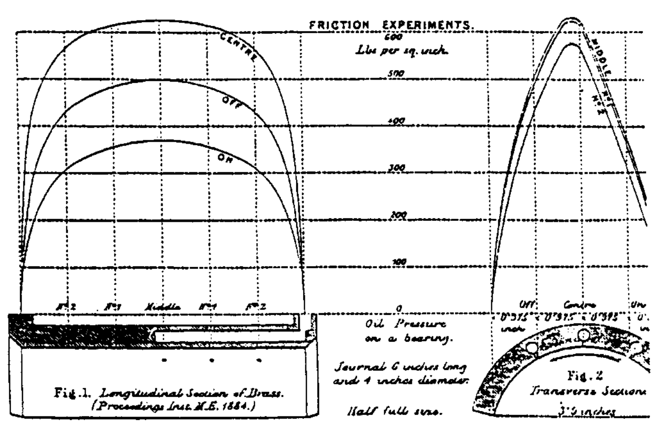


Figure 75. Beauchamp Tower's Experimental Results in Measuring Oil Film Pressure.

Work of Osborne Reynolds in the Theoretical Development of Lubrication Theory

While Tower's elegant experiments had tremendous practical value, there was still no explanation of the behavior noted. This explanation would come from the work of Osborne Reynolds. Osborne Reynolds was born in Belfast in 1842 and had served as a mechanical apprentice prior to entering Cambridge where he studied mathematics. In 1883 he published his classic paper on the flow of fluids in pipes and channels from which the term Reynolds number was derived.

In a meeting in Montreal in 1884, Reynolds first mentioned the classic hydrodynamic lubrication equation. Later, in a detailed 77 page paper, Reynolds (1886) provided his observations of Beauchamp Tower's work and laid the theoretical foundation of bearing hydrodynamic theory. In this paper, he showed that friction changes could be linked to changes in oil viscosity and changes in journal speed and load. He also considered the effect of temperature on the differential growth between the bearing and the brass liner.

The German physicist Arnold Sommerfeld, who was well-known for his work on atomic theory, provided tribologists with the famous Sommerfeld equation, which was a solution to Reynolds' equation. His solution showed that the displacement of the journal (i.e., its eccentricity ratio) could be characterized by a dimensionless combination of parameters including the load, the journal surface velocity, and the bearing clearance.

In 1952, Fred William Ocvirk, under the sponsorship of a NACA program, solved the Reynolds equation for a short bearing. Ocvirk accurately derived the load-bearing capacity and provided vital information as to how the journal center moved in a bearing and the lubricant flow required to supply it. He formulated the concept of a "capacity number" (also referred to as the Ocvirk number), which was the product of the Sommerfeld number and the square of the bearing length to diameter ratio.

Thrust Bearing Developments

The concept of tilting-pad bearings was independently developed by Kingsbury in the US and Mitchell in Europe—their designs being used to this day.

Albert Kingsbury entered Cornell University in 1887, but had to leave because of a lack of funds. Because of his experience as a machinist apprentice in Ohio, he was assigned the task of testing bearings provided by the Pennsylvania Railroad Company. It was during these tests that Kingsbury noticed the benefits of film lubrication. Several years later, while experimenting with a test device involving a six inch cylinder containing a piston, he noticed that spinning the piston caused the piston to float within the cylinder. He then conducted tests on this air lubricated bearing. This was an important step in his development of the tilting-pad thrust bearing that bears his name. He studied Reynolds' report dealing with the pressure that would be generated by a slight tilt of a flat surface and conceived of the idea of a tilt-pad thrust bearing. His concept involved a series of flat blocks arranged in a circle, each having a pivot on the back and facing a thrust collar attached to the rotating shaft. This allowed a dramatic increase in thrust load capability. Kingsbury filed for a patent for his bearing in 1907, even though he was testing tilt-pad bearings as early as 1898. His US Patents No. 247 and 242 were obtained in 1910.

Kingsbury, who was working at Westinghouse at that time, had considerable difficulty in getting his design accepted. In one case, he had to pay for the manufacture of the bearing that Westinghouse was willing to try. Finally when Kingsbury wanted to sell his patent rights to Westinghouse just for the cost of obtaining the patent, Westinghouse refused, at which point, Kingsbury started his own bearing company in 1912. In a few years, this type of bearing was very common, especially on vertical machinery.

CLOSURE

This paper has covered several centuries of development in the turbomachinery field and has traced the evolution of technology that has resulted in the high efficiency turbomachines of today.

Since the 1940s, turbomachinery development has been led by gas turbine and aeroengine development, and the growth in power within the past 60 years has been dramatic. The growth in thrust, turbine inlet temperature, and materials capability is shown in Figure 76.

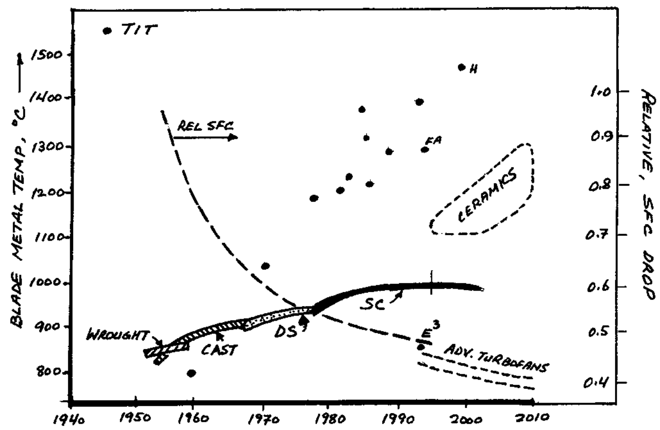


Figure 76. Turbomachinery Development for Aircraft Engines, 1940 to Present, Including SFC, TIT, and Material Capability.

Current fourth-generation aeroengines operate with very high bypass ratios and include the GE 90, the Rolls Royce Trent, and the Pratt and Whitney 4084. These engines have applied a host of state-of-the-art technologies including:

- Wide chord fans
- Full authority digital engine control systems (FADEC)
- Single crystal blading
- Active clearance control
- 3-D aerodynamic design
- Low emissions combustors

A current day fighter aeroengine has a thrust to weight ratio of about 10:1. Work is underway to increase this to 20:1 early in this new millennium.

In the industrial turbine arena, the high demand for power has caused a proliferation of combined cycle power plants including gas turbines operating at rotor inlet temperatures of 2600 to 2700°F. A 50 Hz GE Frame 9H gas turbine with an airflow rate of 1519 lb/sec is shown in Figure 77. This machine and its 60 Hz counterpart, the 7H, are offered in combined cycle configurations only and operate at pressure ratios of 23:1 developed in an 18-stage axial flow compressor. Rotor inlet temperature of these machines is 2600°F, with the nozzles and blades being steam cooled. Other OEMs have advanced technology machines including the GT 24/26, which is an intercooled reheat gas turbine operating at a 30:1 pressure ratio.

In a recent ASME talk, Povinelli stated that currently efforts are underway to study "breakthrough propulsion physics" (Povinelli, 1999). The concepts being investigated include the study of questions such as, "Are there forces that exist in the universe that we can utilize to push against?" "Are there clues in expanding dark matter that can lead to thrust or buoyance or lift forces?" and "Can the concept of cosmic energy or energy differential in space be utilized for providing large scale propulsive forces?" These concepts are attracting the attention of some leading physicists.

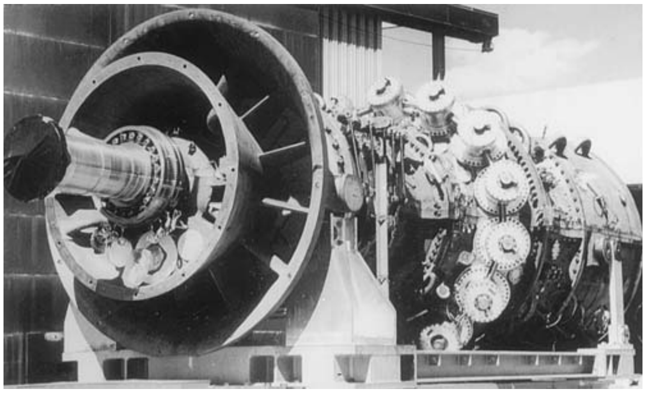


Figure 77. Advanced GE Frame 9H Gas Turbine (Airflow Rate 1519 Lb/Sec and Pressure Ratio of 23:1), Steam Cooled Nozzles and Blades. (Courtesy GE)

Perhaps in the near future, there will be some totally new power generation device that will emerge that could make turbomachinery obsolete. Most will dismiss this as being unrealistic and improbable. This is precisely what the reciprocating aeroengine specialists mistakenly felt in the 1940s. In the words of Edward Constant, *"Time, not reason, separates the real from the absurd."*

APPENDIX

TURBOMACHINERY DEVELOPMENT

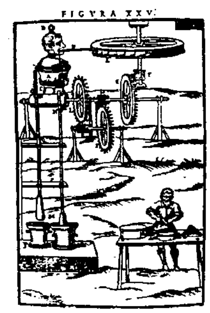
Hero's Aeolipile

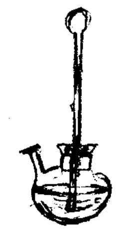
120 BC Hero of Alexandria builds aeolipile (wind ball)

1232: Reaction principle used for rockets for war and fireworks. Chinese scholar Wan Hu attempts use of rockets attached to a sledge.

1500: Da Vinci describes "Chimney Jack" utilizing fan like blades. He also recommends bearing alloy of 3:7 Cu to Tin. 340 years later, Isaac Babbit will introduce a similar tin based bearing material bearing his name. – Da Vinci also used the "lost wax " technique for reproducing repeated sculptures-a technique used for gas turbine blades today.

De Branca Turbine





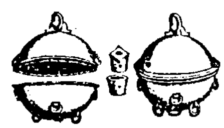
First Thermometer

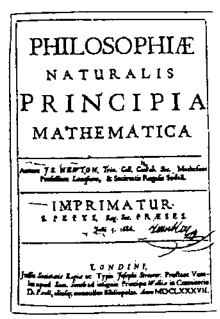
1512: Galileo experiments with a tube which held water and observed that the height changes with temperature. This was probably the world's first thermometer.

1629: Giovanni de Branca Develops Impulse turbine. Branca developed a steam turbine used for turning a spit. In this device, a jet of steam impinged on radial vanes (paddles) like a horizontal water wheel. A similar turbine appeared in China in 1669 (40 years later) in a toy three wheeled road carriage.

1642: Galileo dies and his student Torricelli invents the barometer in 1640 (Hg filled), and studies atmospheric pressure and deduces that a "vacuum" was produced by atmospheric pressure acting against a lower pressure in space. 14 years later was the classic Magdeburg hemisphere experiments conducted by Otto von Guericke.

Magdeburg Hemispheres





PHILOSOPHIÆ NATURALIS PRINCIPIA MATHEMATICA

IMPRIMATUR

LONDINI

1661: Robert Boyle, reading about the Magdeburg experiment, gets interested in the behavior of gasses and formulates Boyle's Law $V \propto 1/P$ It will take 100 years before Charle's Law is formulated . These laws are of fundamental importance in thermal turbomachinery.

1687: Sir Isaac Newton formulates the Laws of Motion. This formed the fundamental basis for much of turbomachinery theory.

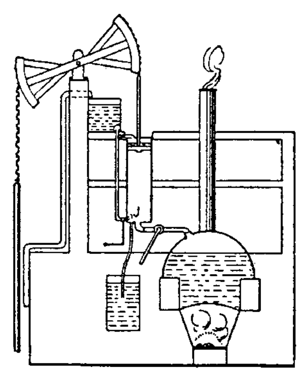
$$E = \frac{1}{g_c}(U_1 V_{\theta_1} - U_2 V_{\theta_2})$$

1700: Gabriel Fahrenheit devises the Fahrenheit scale.
In 1774, Celsius suggests a 0-100°C Scale.

1705: Denis Papin Publishes full description of Centrifugal Blowers and Pumps.

1712: A major step in the history of engines- Thomas Newcomen produces his full size atmospheric engine that is installed in a coal mine in England. This was a reciprocating steam engine and could operate at 16 strokes/minute. Over 100 engines were built.

Newcomen's Engine



1732: Henri Pitot announces his invention of the Pitot tube to the Royal Academy of Sciences in Paris. Pitot used his intuition that the ΔP measured by his instrument was proportional to the local flow velocity. The Pitot tube would prove invaluable in turbomachinery development and testing.

1738: Daniel Bernoulli (1700-1782) publishes "Hydrodynamica" covering fluid mechanics, kinetic theory, pipe flow. He defines the relation between pressure and velocity. Euler reduced Bernoulli's equation to popular form, years later.

1750: Leonhard Euler (1707-1785) while at the Berlin Academy of Sciences analyzes Hero's Turbine and conducts experiments. He applies Newton's Laws to turbomachinery and develops Euler's Equation which he published in 1754

1750-1850: INDUSTRIAL REVOLUTION

Circa 1750: James Watt boasts that one of his larger steam cylinders was *only 3/8" out of round.* This is indicative of the manufacturing tolerances of the day.

1763: James Watt discovers the phenomenon of the Latent heat of Evaporation,

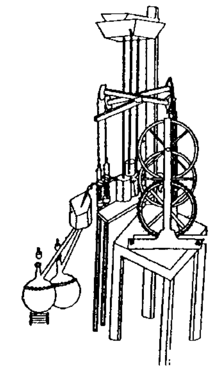
Meher-Homji P. 1 of 8

1765: James Watt patents his double acting steam engine with a separate cylinder and condenser that becomes the basis of all future engines.

1767: Stream Tube Analysis and study of ideal waterwheels conducted by Jean C. Borda. Borda enunciated that water should enter and leave without shock.

1791: John Barber patents a design utilizing the modern gas turbine cycle. The turbine was equipped with a chain driven compressor.

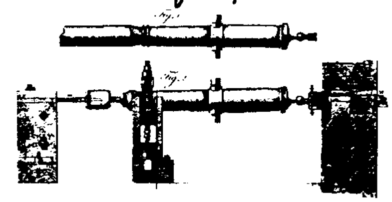
John Barbers Patent drawing



1798: Benjamin Thompson conducts his cannon boring experiments and finds a relation between heat and work. He is given the title of Count Rumford for his discovery. 45 years later James Joule will provide the conversion factor between work and heat.

1805: Gay -Lussac and Charles independently find relationship between gas Pressure and Abs. Temperature. This result, combined with Boyles's work 144 years earlier, results in PV/T= Constant or PV=RT a fundamental equation for turbomachinery processes.

Cannon boring experiments

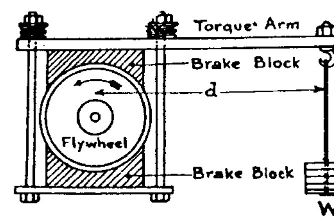


1807: Sir George Cayley invents the reciprocating hot air engine operating an the same cycle principle as the modern closed cycle gas turbine.

1822: Claude Borodin introduces the word "Turbine" from the Latin turbinis for "that which spins like a top"

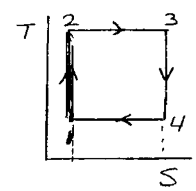
1822: Lazare Carnot identifies two principles for efficient turbomachinery- (1) fluid should enter rotor without shock (2) fluid should leave with as little energy as possible.

1822: Baron Riche de Prony develops the Prony break dynomometer. This will have a great impact on the future development of turbomachines as is permitted accurate testing.



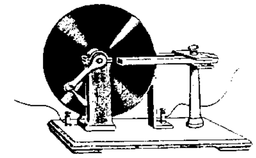
1823: Charles Babbage and English mathematician develops an analytic engine- a mechanical computer. 123 years later, von Neumann will detail the organization of an electronic computer that today is invaluable for detailed design of turbomachines (CFD, 3D analysis stress etc.). Babbage is also the first person who reportedly developed a condition monitoring device for measurement of rail road wheel problems.

1824: Nocolas Sadi Carnot introduces the basic idea of thermodynamic cycle and reversibility and describes the Carnot cycle in his book "The Theory of Heat."



1827: First commercially successful high efficiency hydraulic turbine developed by Benoit Fourneyron. The unit was a radial outflow turbine and used efficient blade angles and ran full rather than with partial admission (single incoming jet). A Prony brake was used to test he unit and Fourneyron boosted efficiency from 20-30% (pre 1800) to a maximum of 85%;

1831: Michael Faraday made major discoveries in the field of electromagnetism. His work first made possible the use of electrical power for industry.

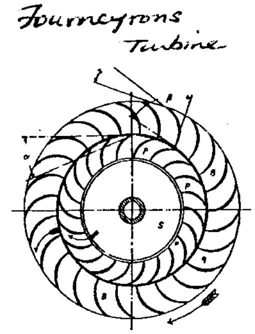


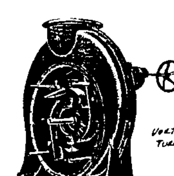
Faraday's Experimental generator

1839: Isaac Babbitt patents his bearing alloy.

1839: Equation of flow of a compressible gas through a nozzle (isentropic flow) given by St. Venant and Wantzel. These results go unnoticed for 28 years (till 1867) when Kloster and Rankine rederive the formula for critical pressure ratio.

Fourneyrons Turbine





1843: James Joule defines the relation between heat and mechanical energy, J = 778 ft-lb/BTU

1944: U.A. Boyden (USA) adds vaneless radial diffuser to a water turbine and adds 3% to efficiency increasing efficiency to 88%.

Vortex Turbine

1846: James Thomson (UK) (brother of Lord Kelvin) develops radial inflow turbine with variable IGVs. This was patented in 1940 as the "Vortex Turbine," and stayed in production for 80 years.

1849: Rankine and Clausius independently tabulate steam properties.

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Late 1850s: Works of Joule, Kelvin, and Carnot have established the essential principles of thermodynamics.

1853: Basic concepts of axial flow compressors presented to the French Academie Des Sciences by Tournaire.

1855: Publication of the classic "Lowell Hydraulic Experiments" by J.B. Francis, Boyden and Swain.

1866: Robert Napier demonstrates that for free expansion of a compressible fluid, through an orifice, flow rate did not increase above a pressure differential of approximately 2:1

1869: Scottish Engineer William J. Rankine investigates rotating elastic shafts and used the term critical speed. Rankine studied the eigenvalues of a simply supported shaft. He concluded that the system would be unstable at higher speeds. Publishes paper "Centrifugal Whirling of Shafts," in the Engineer XXVI (April 6th, 1869).

1872: Stolze obtains gas turbine patent. The unit had multistage axial compressor multistage reaction turbine. His design shows more stages in the turbine than in the compressor! This unit was tested in 1900.

1875: First mention of vaned diffuser made by Osborne Reynolds in patent for turbine pump. He also made a 12,000 RPM multistage steam turbine. Clearance leakage losses between the blades and casing were high and Reynolds felt that steam turbines could not compete with steam engines. He did not realize that clearances would be proportionately smaller for larger turbine sizes thus lowering clearance losses.

1875: Californian Gold Rush. Miners developed a water wheel known as a "hurdy gurdy". This turbine was made of flat plates bolted to a wheel rim. The high-pressure water was piped to a nozzle and the ensuing jets hit the plates to drive the wheel. One day, Lester Pelton was using his "hurdy-gurdy when the wheel became loose on the shaft and the jet hit the blades on one edge and discharged from the other edge. Pelton was surprised to see that the power and speed increased. His subsequent experiments resulted in Pelton wheel development in 1788 and subsequent Pelton Wheel Patents in 1880.

1876: N.A. Otto builds the first successful 4 stroke engine.

1878: De Laval makes high speed cream separator, impulse turbine with convergent-divergent (supersonic) nozzle that spun the turbine to 30,000 RPM (tip speed of 1,200 ft/sec). Both De Laval and Parsons were unaware of Rankine's work on high-speed shafts concluding that supercritical operation was not possible. De Laval also designed high speed gearing to reduce his steam turbine speeds.

1883: Buchamp Tower studies and discovers hydrodynamic load capacity in journal bearings.

1883: Osborne Reynolds establishes the foundation of flow similarity for laminar-turbulent transition in canals.

1884: C.A. Parsons runs multistage reaction turbine in reverse and obtains an axial flow compressor.

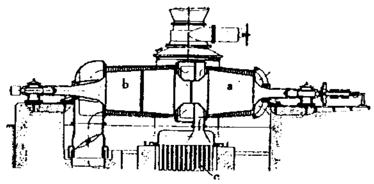
1886: Osborne Reynolds establishes mathematical formulation of hydrodynamics which allows calculation of bearing oil flow, temperature rise and load capacity

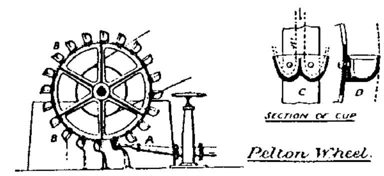
1889: C.A Parsons dissolves the partnership under which he successfully developed the axial flow reaction turbine. This action denies him access to axial flow patents and so he investigated radial inflow steam turbine (built in 1890) abandoned because of erosion problems and he then considered radial outflow turbines.

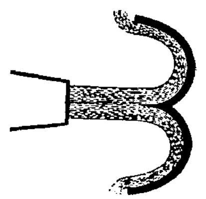
1892: Rayleigh introduces dimensional analysis.

1892: Rudolph Diesel constructs his first engine.

Stolze Gas Turbine

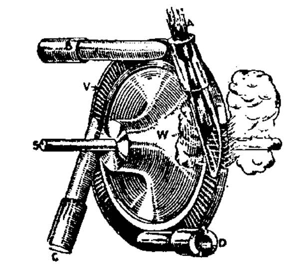


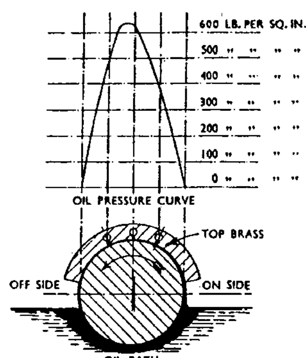




Pelton Wheel

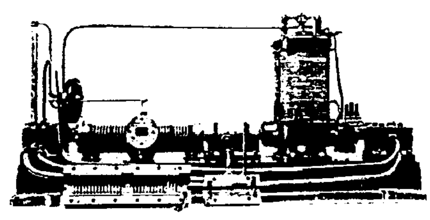
De Laval





$$Re = \frac{\rho V d}{\mu}$$

Tower's Study



Parsons early generator - Steam Turbine

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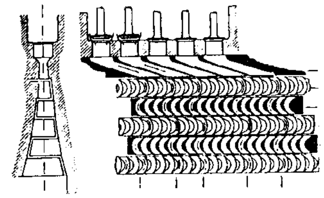
1892: Auguste Rateau publishes a major work on turboblowers. He designs compressor to give a pressure ratio of 1.5 at 12,000 RPM. This compressor when tested in 1902 yielded an efficiency of 56%

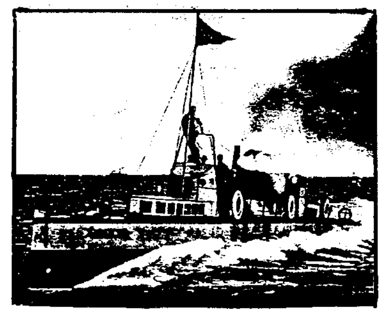


Curtis Stage

1897: De Laval develops double helical gearing for his high speed turbines.

1895: First US Patent on a Gas turbine given to Charles G. Curtis. Curtis patents his velocity staged turbine and sells rights to GE in 1901.

1897: Parsons demonstrates his "*Turbina*" at the great Naval review celebrating Queen Victoria's Diamond Jubilee. This ship was powered by a 2,300 HP, 2000 RPM multistage radial outflow turbine and operated at a speed of 34 Knots. This breakthrough was the start of steam turbine power being used for ship propulsion. Within 10 years (1907), the Mauritania was powered by a 70,000 HP Parsons turbine.

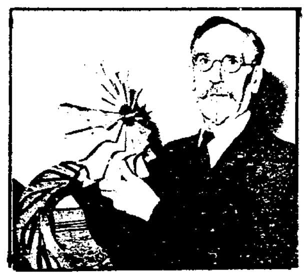


"Turbina"

1897: Charles Curtis, an American inventor born in Boston patents his first steam turbine and designs marine turbines for the British American, German and Japanese.

1900: Tests on Stolze's gas turbine begin. Unit rated at 150 MW, 10 axial stages and 15 turbine stages, TIT = 400°C, N=2,000 RPM, Pr Ratio = 2.5:1

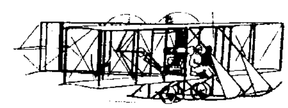
1900: Stanford Moss (USA) writes a Master's Thesis on engine design. After his Ph.D graduation at Cornell, he joins GE and experiments on compressor design at Schenectady and Lynn. GE ends work on gas turbines in 1907 as max thermal efficiency is 3.5%. Moss's turbocompressor designs were sold till 1925. Today, GE is amongst world's leading manufacturer of gas turbines and aeroengines.



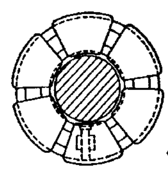
1902: Richard Stribeck investigates and explains bearing behavior during startup, operation and rundown.

1903: Prof Aurel Stodola publishes his classic work "Steam Turbines." Later revisions are called "Steam and Gas Turbines".

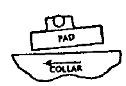
1903: Aegidus Elling in Norway designs and constructs the first constant pressure gas turbine. Net output = 11 HP. The machine had a 6 stage centrifugal compressor with variable angle diffuser vanes and water injection between stages. The unit had an axial impulse turbine (TIT=400°C). In 1904, Ellin made a second regenerated machine (TIT= 500°C) with an output of 44 HP.



Wright Flyer



Mitchell Bearing



1903: December 7, World's first powered flight by the Wright Brothers. 12 HP engine used. In the long term, flight will provide the impetus for engine development-reciprocating engines till WW II and jet engines thereafter.

1904: Arnold Sommerfield defines "Somerfield No." A dimensionless number including all the physical parameters for evaluating a bearing.

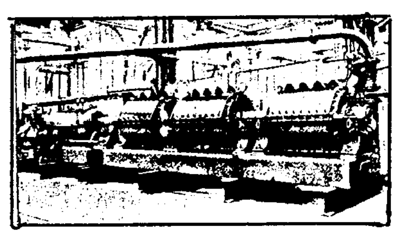
$$S = \frac{\mu N}{P}\left(\frac{R}{C}\right)^2$$

1905: Anthony Mitchell develops tilting pad bearings

1906: R. Cramer introduces the concept of "Specific Speed."

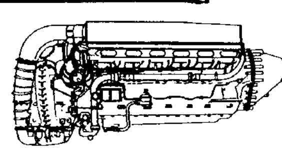
$$N_s = \frac{N\sqrt{Q}}{H^{3/4}}$$

1905/1906: The Societe Anonyme Des Turbometeurrs formed by Charles Lamale and Rene Armengaud commissioned Rateau to design a 25 stage centrifugal compressor in 3 casings (one shaft running at 4,000 RPM and absorbing 254 KW (328 HP) giving a pressure ratio of 3:1. This machine was made by BBC and achieved an isentropic efficiency of 65-70%. Normally this low efficiency would not permit self-sustaining operation but a very high TIT 1800°C (3272°F) attained in a coborundum lined combustor and a two-staged watercooled Curtis turbine. The Steam generated in the cooling circuit was led to nozzles and into the turbine wheel. This engine produced a positive power at a thermal efficiency of 3.5%.



1906: Rolls-Royce Partnership founded in England. This company will produce the famed Merlin engine during WWII and turbojets based on Whittle designs.

RR Merlin c.1943



1907: By 1907, the Parsons company has made or has on order 41 axial flow compressors but as they are plagued by aerodynamic problems he ceases production in 1908. Parsons utilized a high spacing /chord ratio and this led to

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stalling problems. Parsons continued work on centrifugal compressors. In 1909, he made a 16 stage radial flow tandem intercooled compressor.

1908: On January 13, a young Hungarian engineer witnesses the flight of a French Aviator that lasts for 1 minute and 28 seconds. This young engineer is mesmerized and his interest in aeronautics is captivated. This young engineer is Theodore Von Karman who will play a valuable role pertaining to turbomachinery and flight theory.

1910: On December 10, 1910, seven years after Kitty Hawk, 25 year old Henri Coanda claims to have a brief flight in a aircraft powered by his "turbopropulseur" engine. This engine incorporated the elements of a jet engine. It consisted of a centrifugal compressor driven by a water-cooled reciprocating engine. The compressed air was mixed with the engine exhaust and then routed to a duct into which gasoline was sprayed. Exhaust temperature during static tests was 2370°F. Coanda noticed that the jet tended to stick to the aircraft body an effect now known as the Coanda Effect.

1910: Albert Kingsbury patents Kingsbury axial thrust bearing having mechanical load equalization.

1912: Dr. Victor Kaplan, an Austrian engineer creates the Kaplan Hydraulic Turbine with mechanically adjustable pitch on blades. This turbine could operate efficiently at part load and could maintain constant speed over a wide range of flow conditions.

1914: World War I Begins.

1914: Prandtl establishes that the transition from Laminar Flow to turbulent flow specifically in the boundary layer and that the flow breakaway from a surface is a function of Re. No. With this, Prandtl makes it possible for hydrodynamic theory to be directly applied for aeronautical applications. Amongst Prandtl's students were Von Karman and Jacob Ackert who will,in due course impact turbomachinery development.

1915: US Congress forms NACA with an appropriation of $5,000/year for 5 years. This institution (later to become NASA) will have a tremendous impact on aerodynamics, turbomachinery.

1918: Prandtl provides complete theoretical theory of high aspect ratio wing. This permitted the scientific design of wings and airfoil sections. This theory represents an accumulation of insight to subsonic aerodynamics.

1919: First Flight of airplane using a turbine powered supercharger (Designed by S. Moss at GE)

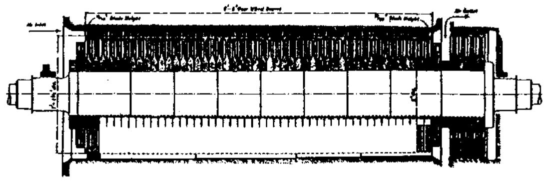
1919: Frank Whittle conceives the turbojet engine. As a student he had read Stodola's classic work on steam and gas turbines.

1919: Active work by eminent rotor dynamists such as Jeffcott, Stodola, Janis underway. The Royal Society of London commissions H.H. Jeffcott of Dublin University to investigate theory of rotating shafts. The publication of his classic paper in 1919 "Lateral Vibration of Loaded Shafts in the Neighborhood of a Whirling Speed- the effect of the want of Balance," sets the basis for modern rotor dynamics.

1921: In France Charles Guillaume patents an axial flow turbojet. His device shows a large manual crank protruding from the front o the engine.

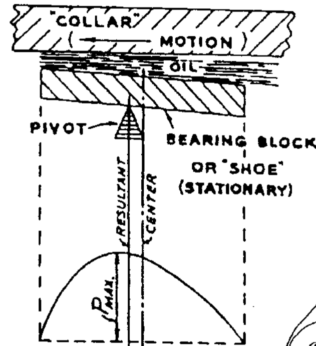
1926: A.A. Griffith (RAE) proposes a new airfoil theory. Previously, flow in compressors was treated as hydrodynamic flow in passages without blade medium energy transfer. Griffith proposes airfoil theory be utilized. He is probably the first to realize the implications of airfoil theory on turbomachinery. About 11 years later, Griffith prepares an icy evaluation of young Whittles jet engine concept. – Griffith also proposes a complex contra-rotating gas turbine concept that Rolls Royce attempted to develop.

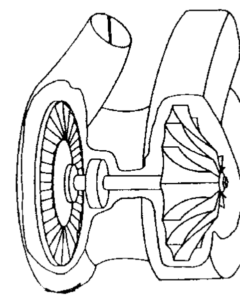
1927: Albert Betz and W. Encke conduct the most complete investigations into axial flow compressors. By 1930, they could get 2:1 pressure ratio from 5 wheels. By 1936, this pressure ratio was obtained in 4 wheels (Pr /stage≈ 1.2)



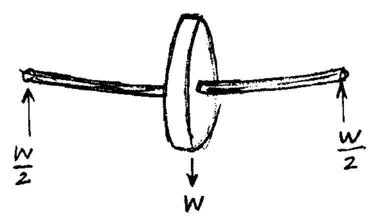
Parsons Axial Flow Compressor
43 STAGE

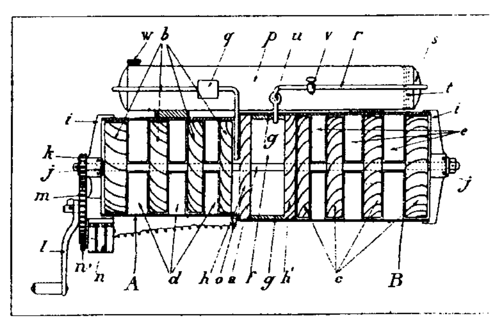
Kingsbury's Sketch





Aircraft Turbocharger





Guillaume's axial flow Turbojet

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1927: Stodola theoretically examines shock wave formation in a De Laval Convergent- divergent nozzle

1927: Jackob Ackert (Prandtl's student at Gottingen) applies airfoil theory to axial flow compressor design. He organizes an Aerodynamic Institute at the Swiss Federal Institute of Technology and designs a supersonic wind tunnel for which he designs a 13 stage axial flow compressor with PR of 2:1 and efficiency of 80% that was built by BBC.

1930: Frank Whittle submits his patent for Jet engine (axial +radial compressor and axial flow turbine) on Jan 30.

1932: First Velox Boiler turbine built by BBC but it needed aux power as Wcomp >Wturbine. Finally upon improvement, several of these were sold.

1932: Starting in 1932 through 1935, E.L. Thearle of the GE company describes Influence Coefficient method for balancing three bearing turbine generator sets.

1934: Hans von Ohain obtains turbojet patent and builds prototype

1935: Whittle's 1930 turbojet patent is due for renewal. Air ministry declines to pay the £ 5 renewal fee and Whittle lets patent lapse.

1935: Volta High Speed Conference held in Rome in October 1935. Was attended by the worlds leading aerodynamists and aeronautical practioners. Conference clearly showed the lead that German scientists have in high speed and turbocompressor theory and design. Upon return from this conference, von Karman urges NACA to accelerate work and build a supersonic wind tunnel. George Lewis of NACA rejects the idea.

1935: Escher Wyss in Switzerland does pioneering work on closed cycle gas turbines after 1935 patent by Ackert and Keller

1936: Whittle forms Power Jets Ltd.

1936: 25 year old Hans von Ohain interviews with Ernest Heinkel and is hired, starting work on jet engine development.

1937: Betz and Enke at Gottengen have developed the most unique and comprehensive theory of axial flow compressor theory and knowledge. The concept of supersonic compressors was recognized when Artur Weise publishes paper.

1937: Design work started at BMW (Germany) on the axial flow BMW 003 engine that would power the He 162 aircraft at the end of the war.

1937: First run of von Ohains HeS 1 demonstrator engine (April '37) using Hydrogen fuel. Upon this demonstration, Ernst Hienkel ordered accelerated engine and jet aircraft development.

1937: Whittle runs liquid fueled turbojet- dual entry radial compressor and axial turbine. This is the first run (April 12) of a turbojet on liquid fuel

1938: Whittle employs free vortex blade design for his engines.

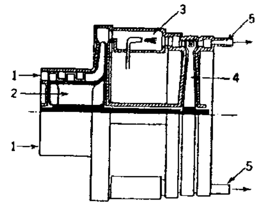
1938: Junkers Aircraft Company working on axial turbojet under Dr. Wagner

1938: P. Kapitza in Russia publishes first paper on a turboexpander for cryogenic applications.

1939: BBC build their first sizable power generation gas turbine with output of 4000 kW- demonstrated at National exhibition at Zurich in 1939 and commissioned at Neuchtal Power station in 1940. Stodola, aged 80 was invited by BBC to commission and test this unit. Results: Output= 3,057 kW, TIT= 988 °F, Thermal Eff = 16.4%

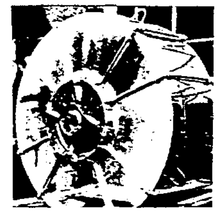
1939: BBC commissions the first closed cycle gas turbine.

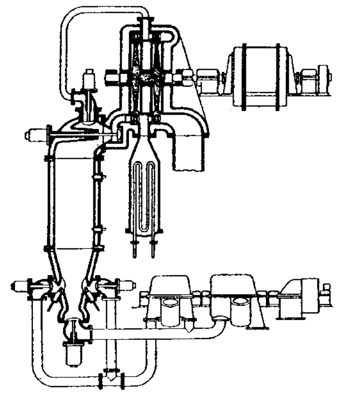
1939: August 27th- Worlds First Jet Powered Flight of Heinkel He 178 powered by von Ohain's HeS 3B engine (1,100 lb thrust, N= 13,000 rpm)



Whittle Turbojet Patent

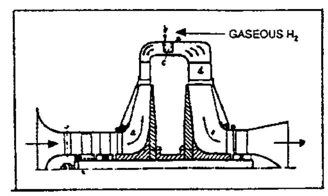
von Ohain's demonstrator

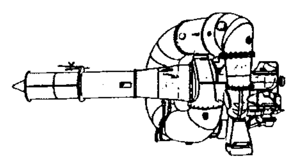




Explosion Gas Turbine

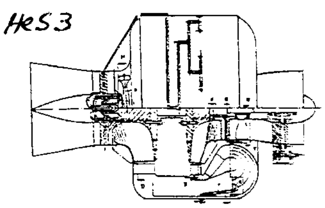
HeS01



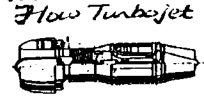


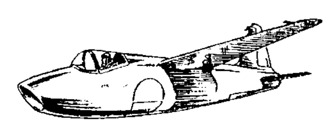
Whittle Turbojet

HeS3



Junkers Axial Flow Turbojet





Worlds 1st Jet Powered Flight.. He 178

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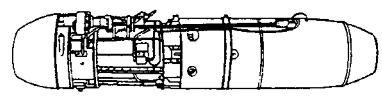
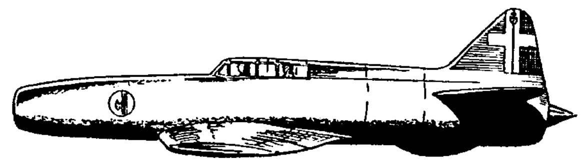
1939 August 30- START OF WW II



Junkers Jumo 004B

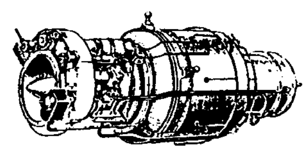
1939: All German aircraft engine companies working on jet propulsion. Messerschmitt starts work on - ME-262 jet fighter, Junker Aeroengine company developing the Jumo 004 engine, Hienkel Aircraft company (von Ohain) developing the HeS 8 engine.

1939: A.A. Griffith leaves RAE to join Rolls Royce to develop his contrarotating engine concept. RR who focused on the Whittle design later shelved this development.



1940: Engine designed by Sucendo Campini of the Caproni Company in Italy makes test flight. The "Jet Engine" relied on a 900 HP reciprocating engine compressor to run a 3 stage compressor. On Nov 1941 the Caproni-Campini N-1 makes first cross-country flight from Milan to Rome.

1940: November 1940- Junkers Jumo 004 engine put on test stand.



HeS8

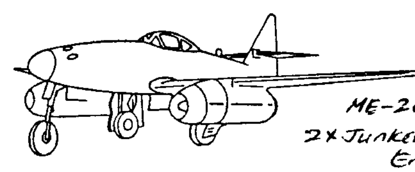
1941: April 2- Flight of Heinkel twin Jet fighter He 280 powered by von Ohain's HeS8 Engines. German Air ministry allows Heinkel to purchase Hirth Corporation for engine development thus acquiring the expertise of Dr. Max Bentele. Engine development at Heinkel Hirth was headed up by the young von Ohain.

1941: May 15th- First flight of British Jet aircraft- Gloster E28 powered by Whittle W-1 engine.

Gloster E28

1941: Westinghouse begins development of US designed axial flow Jet engine.

1941: GE starts manufacture of Whittle Turbojet (September '41). In an amazing feat of technology, they build and test first engine within 6 months.

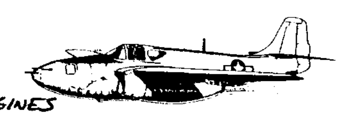


ME-262
2X Junkers Jumo Engines

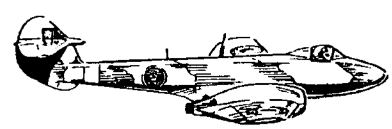
1942: First US Jet flight of Bell XP-59A with GE 1A (based on Whittle design) engines.- 13,000 lb thrust. Both the engine and airframe were designed in 1 year.

1942: July 12th- First Flight of Messerschmitt ME-262 jet fighter powered by Junkers Jumo 004 Engines.

BELL P-59
2XGE 1A ENGINES



1942: German Air Ministry awards contract to Heinkel Hirth for design of what would be the worlds most advanced turbojet at the end of the war- the Hienkel Hirth HeS 011 Engine. Designed by von Ohain and Max Bentle this engine has a T/W ratio of 1.44, pressure ratio of 4.2:1, and air flow of 29 lb/sec. 3 axial stage + Diagonal stage [Mixed flow stage] and an advanced 2 stage air cooled turbine section.

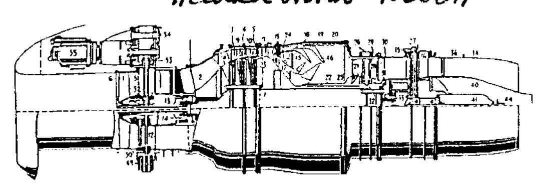


Gloster Meteor

1943: June 12- Gloster Meteor flown with Rolls Royce Welland Engines (Production engine based on Whittle design) Thrust = 1600 lbs

1947: Theodore Von Karman produces a comprehensive supersonic theory.

Heinkel Hirth HeOS011



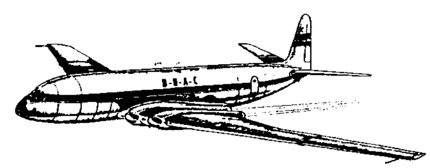
1947: First gas turbine powered naval ship –Royal Navy MGB 2009

1947: Chuck Yeager flies Bell X-1 faster than sound.

1948: Flight of the Vickers Viscount- worlds first turboprop (Dart engines, 1380 EHP each)

1949: July 27- First Flight of pure Jet airliner- de Haviland Comet 1, using the De Haviland Ghost Engine.

1949: First gas turbine used for gas transmission using gas turbine by Westinghouse (22 Pipeline of Mississippi Fuel Corp). GE commissions Belle Isle Station gas turbine power plant (3500 kW)



Comet

1950: First Automotive gas turbine demonstration by Rover (2 shaft engine)

1950: Westinghouse begins shakedown tests on No. 4000, a 4000 HP combustion turbine locomotive called the "Blue Goose". This locomotive once logged a speed of 125 mph while pulling 12 cars. Design TIT was 1350°F- used two W-21 turbine generator sets, and had waste heat recovery.

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1952: Rover (UK) introduces a gas turbine driven car.

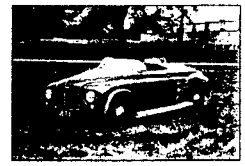
1967: Worlds first 3-shaft Engine- RR Trent. This experience formed the basis for the RB2-11.

1969: Concorde supersonic airliner (Mach 2.2) powered by afterburning RR Olympus 593 turbojets.

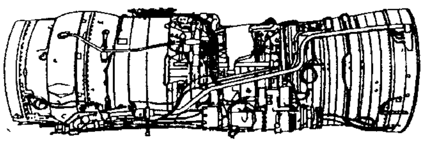
1970- 1980: Energy embargo, E3 program initiated, growth of plant size, growth of high speed turbomachinery size. Widespread use of aeroderivative gas turbines for indusrial, marine and pipeline applications.

1980- 1990: Introduction of large turbofans, larger gas turbines, profusion of large CCPPs, Widespread use of dry gas seals for industrial compressors, use of brush seals for aero and industrial units.

1990- 2000: Introduction of F, FA, H class gas turbines with TRITs of up to 2600 °F, steam cooling of blades. Intercooled reheat gas turbines, and 4th generation turbofans with thrust class of 100,000 lbs.

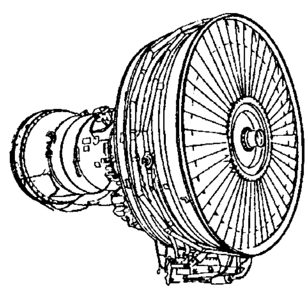


Rover Gas Turbine Powered Car

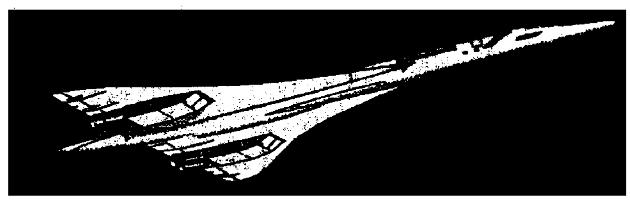


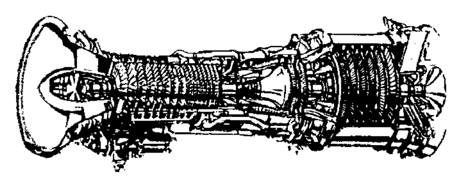
Rolls Royce Olympus 593 for Supersonic Concorde

2.2 Mach Concorde

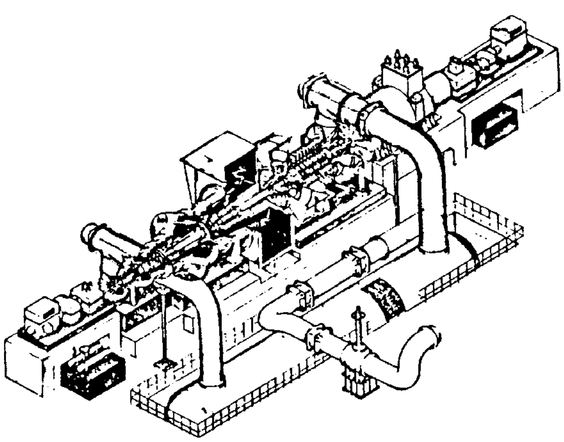


High Bypass Turbofan





LM 2500 Aeroderivative Gas Turbine



Large Intercooled Reheat Gas turbine

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