The development, history and future of the industrial gas turbine: Part 2 – The update

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Preamble

The first part of this paper was published by IDGTE in the 2011 Paper 582 [120] and this covered the first fifty years of the industrial gas turbine from 1939-1999. Part 2 brings the story up to date and includes developments up to 2017, the charts having been brought up to date. This account of the history of the industrial gas turbine documents the development of gas turbines for power generation, off-shore, locomotive, marine and other land based applications. A key part of preparing this history has been the documentation of manufacturers and gas turbine models produced each year since 1940. The aircraft engine is generally excluded from the scope of the work and only referred to, in so far as it is related to the development of industrial gas turbines, whilst aero-derivative turbines are included.

The author gratefully acknowledges the permission to publish the material provided, photographs, data, encouragement and assistance of all the companies and organisations referred to. Sincere thanks and appreciation is given to the many individual contributors for this work and all who have given significant support to the work and generously given of their time and experience, providing data and reference material thus making this historical account possible and full of past experiences.

This paper is a shortened version of the full history which the author is currently having published as a book.

1 Introduction to the industrial gas turbine

It is clear that in the 19th century the concept of the gas turbine became known to many engineers who were obviously encouraged by the success of the steam turbine. The efforts of all the early pioneers are in the main well documented. The story of the gas turbine began in the early part of the 20th century when a number of trials took place. Very early on it was recognised that this was a technological concept with huge potential, being limited only by the state of art of associated technologies and the materials available at the time. There were difficulties encountered in designing a practical and efficient axial compressor as centrifugal compressors were limited in scale and hence the power of the GT. By the late 1930s the concept of the gas turbine had already been around for decades with articles already having being published, patents applied for up to 50 years ahead of the realisation of the goal.

Figure 1 The author and Neuchatel turbine in Birr, Switzerland 2018

Experimental gas turbines were around in various forms from the early 1900s and in the following chapter the efforts of the pioneers are given the credit that they deserve. The question as to who came first is also addressed. Those early efforts to make the gas turbine work often resulted in disappointment as the poor efficiencies initially achieved meant that there was little incentive to take the idea further.

There was certainly no shortage of vision in the early 1900s, as is exampled by Captain H Riall Sankey[1] who, in his outstanding lecture on Heat Engines given to the Institution of Mechanical Engineers in November 1917 [1] predicted the future role of the gas turbine. Sankey could see the continued dominance and development of the steam turbine for some time to come, which at that time had already reached 45MW. In his discussion about the future of power generation he says "…… *steam turbines will hold the field for the large units ….… until a satisfactory gas turbine has evolved*". He also mentions that during the past 15 years (that is 1902-1917) "*a few experimental turbines have been produced but so far there has been no progress*".

Aegidius Elling was a Norwegian inventor who is considered in his homeland Norway to be the father of the gas turbine. In 1903 he designed and constructed the first constant pressure gas turbine. His first machine had a net positive output of 11hp and the second reached 44hp. The major challenge he faced was to find materials that could withstand the high temperatures developed in the turbine needed to achieve increased output power. It is clear that Elling deserves much wider recognition for his achievements. [38][89]

There is no doubt that it was Brown Boveri in Switzerland with their 4,000kW Neuchatel machine who are credited as

1 Inventor of the Sankey Diagram (1905)
2 The full versions of these biographies are published in the book
3 An extract from the Barber patent is published in the Gas Turbine Manual by R J Welsh in 1951 page 1

producing the first practical and commercial industrial gas turbine, which ran at full power on test on 7 July 1939. [5]

Moving on briefly after two decades something really quite amazing was the effort of the British Government in the early 1940s to promote the development of the gas turbine. This effort was applied in so many gas turbine related fields, industrial engines as well as aircraft engines. It was at this time that, Harold Roxbee Cox, later to become Sir, entered into the picture in his government role in charge of the Gas Turbine Collaboration Committee and then Chief Scientific Officer. The UK Government effectively created a race and pulled into the fold all the established engineering companies pushing this with great determination.

One contributor has said that all companies had representatives attending these meetings and ideas and progress were openly exchanged.

The first industrial gas turbine to run in the United Kingdom was the 500bhp experimental machine of C A Parsons, which first ran in 1945. The original Swiss machine is on display in Birr, Switzerland (Figure 1) whilst the original Parsons machine is in storage at the Beamish museum in County Durham, UK. [117]

2 The work of the pioneers

Tribute is given to all of the pioneers for their true dedication to the development of the gas turbine and working tirelessly to achieve success. There must have been so many disappointments through all the trials and efforts but perseverance eventually bore fruits (see Figure 2).

The claim to the invention of the gas turbine is something that has to date never been satisfactorily resolved. The concept was certainly set out by John Barber in the late 18th century and his 1791 patent.

Then incredibly during the following 148 years so many attempts were made to solve the challenge. In this time so many other patents have been lodged and experimental machines constructed with varying degrees of success. Some of the problems encountered were due to the availability of suitable materials at the time, compressor technology and the construction of compressors of adequate efficiency. In truth the achievement of a practical industrial gas turbine is due to the work of many contributors. The following are brief and shortened summary biographies of each of the pioneer's on this roll of honour:

1 **John Barber** (1734-1801) – British. Born in Nottinghamshire and moved to Warwickshire in the 1760s to manage collieries in the Nuneaton area. He is at the top of the list as he patented several inventions, the most remarkable being one in 1791 "A Method of Rising Inflammable Air for the Purposes of Procuring Motion". This is the patent of a gas turbine.[3]

2 **John Dumbell** – British. Credited with patenting a device in 1808 having "a series of vanes, or fliers, within a cylinder, like the sails of a windmill, causing them to rotate together with the shaft to which they were fixed". [7]

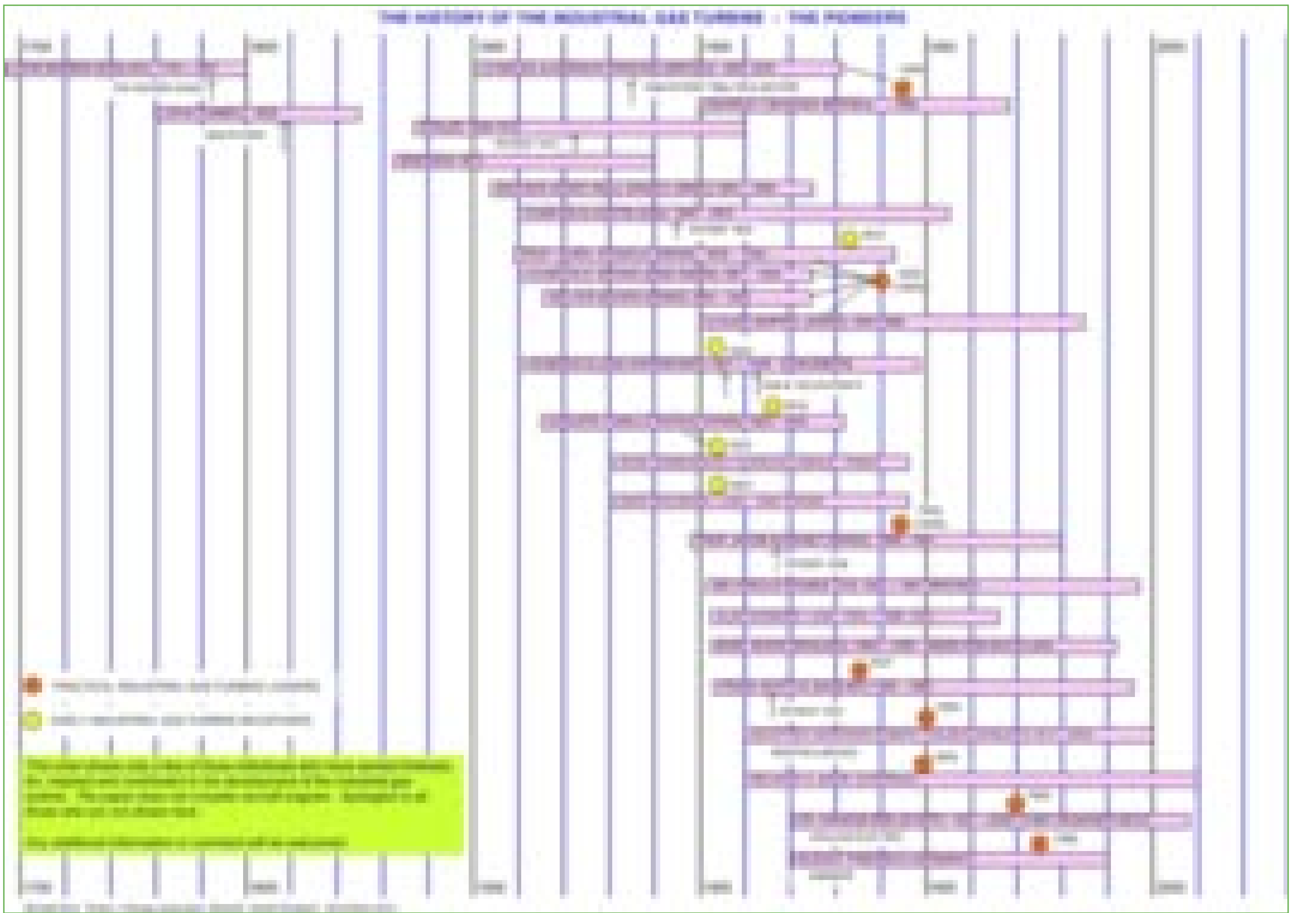

Figure 2 The pioneers

3 Bresson – French. In Paris in 1837 Bresson had the idea to heat and compress air then deliver this to a combustion chamber and to mix this with fuel gas and then burnt. The combustion products were to be used to drive "a wheel like a water wheel". [81]

4 Franz Stolze (1836-1910) – German. Dr Stolze took out a patent for a gas turbine engine in 1872. This engine used a multi-stage reaction turbine and a multistage axial flow compressor. He called this a "Fire Turbine". Tests were carried out in Berlin between 1900 and 1904 without success. [5][13][68]

5 Matthew Henry Phineas Riall Sankey (1853-1925) – Irish. He was an Irish engineer from County Cork who invented the Sankey Diagram. He became President of the Institution of Mechanical Engineers and was able to recognise the future role of the gas turbine as early as 1917. [1]

6 Sir Charles Algernon Parsons (1854-1931) – British. Along with his celebrated steam turbine patents, Parsons patented his idea for the gas turbine, which he called a Multiple Motor. By the early 1900s, in addition to steam turbines, Parsons was already designing and manufacturing industrial compressors. [115]

7 Rene Armengaud and Charles Lemale – French. In 1905 they built and successfully tested the first of several experimental gas turbines with internally water cooled disks and blades. Accounts at the time say that the machine had a very low efficiency and succeeded in producing a few kW for power by the addition of steam from combustor cooling.

8 Professor Aurel Boleslav Stodola (1859-1942) – Swiss. Slovak by birth he was a pioneer in thermodynamics and its applications. His 1903 published book had an appendix on gas turbines. Brown Boveri asked him to supervise the acceptance testing the world's first industrial gas turbine in 1939 that was installed at Neuchâtel in 1940. [100]

9 Charles Gordon Curtis (1860-1953) – American. Born in Boston, Massachusetts he applied for the first US gas turbine patent in 1899. Among his achievements was the Curtis steam turbine of 1896. He sold the rights for the turbine to GE in 1901. He received the first annual award from the Gas Turbine Power Division of the American Society of Mechanical Engineers (ASME) in 1948.

10 Aegidius Elling (1861-1949) Norwegian. He is considered in his home country Norway, to be the father of the gas turbine. His first gas turbine patent was granted in 1884. In 1903 he designed, constructed and tested the first constant pressure gas turbine. He is recognised as having produced the first gas turbine with a positive net output. He further improved this gas turbine in the period up to 1932 and reached 75hp. [89]

11 Charles Brown (1863-1924) British/Swiss. He was co-founder of the Brown Boveri Company (BBC) in 1891 in Baden, Switzerland. Charles Brown was born in Winterthur and his father was a British engineer who founded the SLM Swiss Locomotive and Machine Works. [121]

12 Auguste Camille Rateau (1863-1930) French. Associated with the work of Lemale and Armengaud and designed the compressor for their gas turbine. Rateau founded Rateau Industries and he manufactured the first turbocharger. His work was largely on compressors. [95]

13 Walter Boveri (1865-1924) German/Swiss. Was co-founder of the Brown Boveri Company (BBC) in 1891 in Baden, Switzerland. He was born in Bamberg, Bavaria and died in Baden, Switzerland. [121]

14 Sanford Alexander Moss (1872-1946) American. After graduation Moss joined GE where he carried out research into compressor design. Due to the low overall efficiencies achieved at the time GE ended his work on gas turbines in 1907. He went on to produce turbochargers.

15 Hans Theodor Holzwarth (1877-1953). In 1905 Dr Holzwarth proposed an explosion (constant volume) turbine. A prototype was built and experiments were carried out between 1909 and 1913 without a compressor. Several of these turbines were built but not put into commercial use. [5]

16 Adolf Meyer (1880-1965). During the 1930/40s Adolf Meyer played an important role in BBC Baden leading the engineering development of high pressure steam turbines as well the gas turbine for power generation. He was Chief Engineer after Brown and became Head of Thermal Engineering. [5]

17 John Lamb (1890-1958) British. He was a pioneer marine engineer who was Chief Engineer of the Anglo Saxon Petroleum Company. In 1951 he arranged for one of the diesel-electric engines on the tanker Auris to be replaced by a gas turbine, the BTH 1,200hp gas turbine generating set for electrical propulsion. He then carried out sea going trials with this ship and presented the results to the Institute of Marine Engineers in October 1953. [94]

18 Alan Arnold Griffith (1893-1963) – British. He was best known for his work on stress and fracture in metals, now known as metal fatigue, and also for being one of the first to develop a strong theoretical basis for the jet engine. In 1926 he published his highly influential and landmark paper "An Aerodynamic Theory of Turbine Design". [2][3]

19 Jakob Ackeret (1898-1981) Swiss. Worked at Escher Wyss AG in Zurich as Chief Engineer of Hydraulics and was considered as an expert on gas turbines; known for his research on axial flow compressors, airfoil theory, aerodynamics and high-speed propulsion problems. Along with Dr Curt Keller in 1935 Ackeret granted a patent for the closed-cycle gas turbine. He is recognised as a pioneer of modern aerodynamics. [113]

20 Georgy Jendrassik (1898-1954) – Hungarian. Jendrassik was educated at Budapest's József Technical University. From 1927 he worked at Ganz Rt, where he helped to develop diesel engines. He designed the world famous Jendrassik reciprocating engine. Jendrassik had a strong influence on the first design principles for the Siemens gas turbine. He also worked with Power Jets on pressure wave rotor research.

21 Dr Claude Seippel (1900-1986). A Swiss engineer who had broad impact on many engineering fields at BBC, but by far his greatest influence was in turbomachinery as a brilliant scientist, engineer and inventor. He became head of the newly formed Brown Boveri gas turbine department in 1938. In 1939 he was the person in charge of conceptual design for the Neuchatel gas turbine plant. Some sources refer to Professor Stodola as the Neuchatel designer, however the evidence suggests that Dr Sieppel should have the credit. Brown Boveri honoured him by naming their research centre at Daetwill, Baden after him. [6][121]

22 David Macleish Smith (1900-1986) British. D M Smith studied at Glasgow University where he obtained a BSc in mechanical engineering. In 1937 he became Chief Engineer of the Metrovick gas turbine department working under Karl Baumann the Metrovick Chief Engineer. He carried out pioneering work in the development of the first British axial flow jet engine for aircraft and is particularly associated with the Metrovick Beryl aircraft jet engine, being the first British successful axial flow compressor which became the forerunner of all aircraft engine axial compressors. [9]

23 Leslie Jack Cheshire (1900-1976) British. Cheshire studied at Manchester University. He started as a Design Engineer in the steam turbine department at BTH Rugby. In 1939 he was transferred to Power Jets working directly under Frank Whittle and in 1943 he joined Power Jets as Chief Experimental Engineer. In 1946 he joined English Electric as Chief Engineer of the newly formed English Electric gas turbine department.

24 Sir Harold Roxbee Cox (1902-1997) British. Was a British aeronautical engineer who became Chief Scientific Officer for the British Government. In 1944 he became both Chairman and Managing Director of the then nationalised Power Jets. Power Jets was restyled again in 1946 as the National Gas Turbine Establishment with Roxbee Cox as its Director. He had a key role in establishing Cranfield College later Cranfield University. [8]

25 Robert James Welsh (1902-1984) British. In 1938 he joined English Electric Diesels before eventually joining the gas turbine department. He is widely known for the landmark DEUA[4] 1948 technical paper presentation on the design and application of gas turbines and also his book entitled "The Gas Turbine Manual" published in 1951. He became a very prominent figure in the industrial gas turbine field and was a very active participant of technical discussions in the 1940s and 1950s. [10]

26 Alan Howard (1905–1966) American. He worked for the GE Company in Schenectady, NY on steam turbine activities of the company. He went on to design the GE version of the Whittle engine and is considered as the key figure in GE efforts to develop the gas turbine. He was appointed to a wartime committee to develop gas turbines for aircraft propulsion. He was also responsible for the engineering of the GE Belle Island machine. [58]

27 Basil Wood (1905–1992) British. Worked with the consulting firm of Merz and McLellan where he became Head of Research and was highly respected as an engineer. He was regarded by many as an expert in all matters relating to gas turbines. For many years he edited the gas turbine section of Kemps Yearbook. In 1970 he became President of the Diesel Engine Users Association (IDGTE). [40][61]

28 Air Commodore Sir Frank Whittle (1907-1996) British. Known as the inventor of the jet engine, he was a British Royal Air Force (RAF) engineer officer who shared credit with Dr Hans von Ohain for independently inventing the jet engine. In 1930, Frank Whittle applied for his patent for the jet engine and he went on to develop the Whittle engine. In 1932, Whittle published his first paper for the Royal Aeronautical Society. The Whittle engine ran for the first time in 1937. Whittle is hailed as the father of jet propulsion and the contribution he made to the development of the industrial gas turbine was significant. In 1936 he formed the company Power Jets. [4][21][25][70][101]

29 Professor Dr Rudolf Friedrich (1909-1998) German. He was employed by Siemens from 1948-1964 and was Chief Technical Officer for gas turbines at Siemens-Schuckert Works in Mülheim/Ruhr. From 1964-1976 he was full professor for turbine technology at Karlsruhe Technical University. He has been given the nickname "Mr Siemens-Gas Turbine" by his colleagues. [73]

30 Hans von Ohain (1911–1998) German. Hans von Ohain was a German physicist and designer of the first German operational jet engine. According to his memoirs his first jet engine design ran in September 1937 after the Whittle engine. There is general agreement that Ohain started to develop his turbojet engine independently. However, Frank Whittle had already been working on his design in the late 1920s and had openly patented the design in 1930, a full 7 years before Ohain's design ran. It is known that Ohain was already in possession of the Whittle 1930 patents at this time. Ohain's first jet engine, ran successfully in 1937, just a few months after Whittle's first engine. [101]

31 Geoffrey Bertram Robert Feilden (1917-2004) British. Bob Feilden worked with Power Jets and after that he moved to Ruston & Hornsby in Lincoln where he led the team to produce the first Ruston type TA gas turbine. In 1963 he became Chairman of the Feilden Committee and the author of a widely acclaimed work on engineering design for which he is highly regarded. [17]

32 Arthur W Pope (1919-2012) British. He started his career in the aircraft branch of Rolls-Royce in Cheltenham then when Frank Whittle established Power Jets he was recruited to join the Power Jets team. From 1947 to 1966 he worked in W H Allen in Bedford leading the Allen gas turbine design team. His paper presented to IMechE in 1958 reveals the contribution he made to the design of industrial gas turbines. [26]

33 Dr Waheeb Rizk (1921-2009). Born and educated in Cairo he studied at Cambridge University. After graduating he carried out research and then joined the English Electric Company in 1954. He became a founder member of the mechanical engineering laboratory at Whetstone, Leicester and in 1957 was made Chief Engineer of the

[4] DEUA was, from 1913, the Diesel Engine Users Association which then became IDGTE in 1983

Gas Turbine Division. He became chairman of GEC English Electric Gas Turbines in 1983.

34 Andrew T Bowden (1968) British. After graduating at Herriot-Watt, Edinburgh he became Associate Professor of Mechanical Engineering in Western Australia. In 1939 he returned to the UK and became Assistant Director of Tank Design at the Ministry of Supply and after the war he joined C A Parsons as Chief Research Engineer. He set up the Gas Turbine Department and recruited a team of engineers. In 1955 he became Research Director. [11][23]

The list of deserving pioneers keeps growing and it is intended to add to the above list the names of C Hayne and A R Howell.

3 Technology developments

3.1 Landmark technical papers

The development of the industrial gas turbine came about as a result of the development of a large number of technologies and research into materials enabling the improvement in operating conditions. Over the years these have been described in various landmark technical papers, a few being mentioned below and others in the references. The six ages of development for the industrial gas turbine are shown by Figure 3. These six ages illustrate the stages of development and the significant events, which have all shaped the industrial gas turbine to the point we are at today.

In February 1939 Dr Adolf Meyer from Brown Boveri presented his outstanding paper on The Combustion Gas Turbine: Its History, Developments and Prospects to the Institution of Mechanical Engineers in London. This presentation coincided with the introduction of the first practical industrial gas turbine by that company in 1939. [5]

At a meeting of the Institution of Mechanical Engineers in London in June 1948, A T Bowden and J L Jefferson of C A Parsons presented their paper on the Design and Operation of the Parsons Experimental Gas Turbine [11]. The Parsons paper presents a detailed, no holds barred account of the gas turbine experimental work carried out at the Heaton Works of C A Parson in Newcastle upon Tyne.

Over the years the Diesel Engine Users Association (DEUA), now known as the Institution of Diesel and Gas Turbine Engineers (IDGTE), has presented many milestone papers on the design, development and application of the gas turbine. The first of these was given by R J Welsh of the English Electric Company, and presented in London in November 1948. Then in 1954 E A Kerez of Brown Boveri presented his paper on the Beznau Power Station. [10]

In 1951, at the time of The Festival of Britain, a document was published by Power Jets (Research and Development) called the "The Story of the British Gas Turbine". [15]

An account was presented by the British National Committee at the World Power Conference in Rio de Janeiro in 1954.

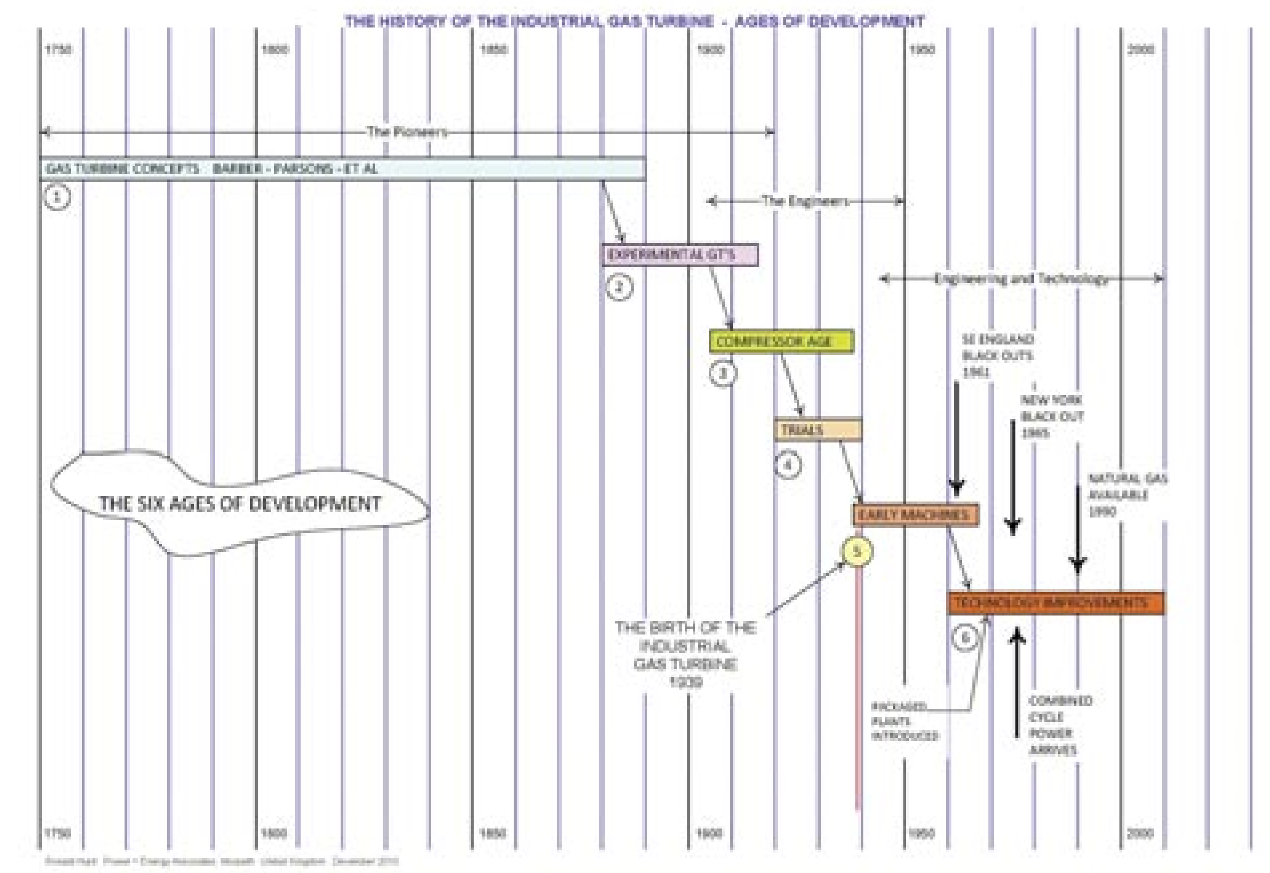

Figure 3 The six ages of development

This started with the work of John Barber and Charles Parsons and describes British gas turbine developments in power generation, traction, automotive engines and aircraft engines.

Around 1965, as mentioned in the paper of Dr Seippel [32], there appeared to have been a serious debate ongoing as to whether the industrial gas turbine was economically viable. At the same time it was recognised that the climb in gas turbine outputs had been spectacular. Dr Seippel introduced the concept of "combined gas-steam cycles" however this was immediately met by doubts as to the viability of such schemes.

3.2 Cycles and configurations

From the early stages of the development of the gas turbine researchers have considered whether to adopt either the open cycle or closed cycle with the primary proponents of the closed cycle being the Swiss. The advantages seen for the closed cycle included not having to have compressor intake filtration and reduced gas path dimensions due to the higher working pressures. The capability of the closed cycle to burn otherwise unsuitable fuels was another big incentive. The disadvantages turned out to be the cost of building these complex plants, limitations on the gas circuit materials, lower turbine inlet temperatures and lower efficiencies. The two cycles were the closed cycle air cycle and the closed cycle helium cycle.

Early developers of industrial gas turbines were seen to have used every possible means to improve efficiency and to make the gas turbine economically viable. They built machines incorporating inter-cooling, reheat, exhaust heat recovery and recuperation. Many configurations were considered including open cycle single shaft with/without exhaust heat recuperation, open cycle two shafts with/without exhaust heat recuperation, open cycle single shaft with exhaust heat recuperation and inter-cooling, open cycle two shaft with exhaust heat recuperation and inter-cooling, open cycle three shaft with exhaust heat recuperation and inter-cooling, closed cycle air CLAGT, closed cycle helium CLHGT and eventually combined cycle steam and gas turbines CCGT.

The efforts of those keen to promote closed cycle plants against open cycle lasted only until about 1975 and then finally it was the merging of Escher Wyss with Brown Boveri that sealed the fate of the closed cycle. By that time CCGT was already getting well established and higher operating conditions for the open cycle meant that the goal of beating the conventional cycle would follow the CCGT route.

After 10-15 years from the first introduction of the practical industrial gas turbine the general industry trend for industrial gas turbine configurations was to move to simple single shaft options without inter-cooling or recuperation. On the other hand, in the aero engine world, the trend was towards inter-cooled and multiple shaft arrangements with separate power turbines.

3.3 Unit outputs

Starting from only 4,000kW in 1939 the output of the industrial gas turbine has grown in size phenomenally to around 250,000kW by the late 1990s and to over 375,000kW in 2010 and by end 2017 to over 500,000kW (see Figure 4).

There are two groups of companies in the industrial turbine world, one being the group targeting the small

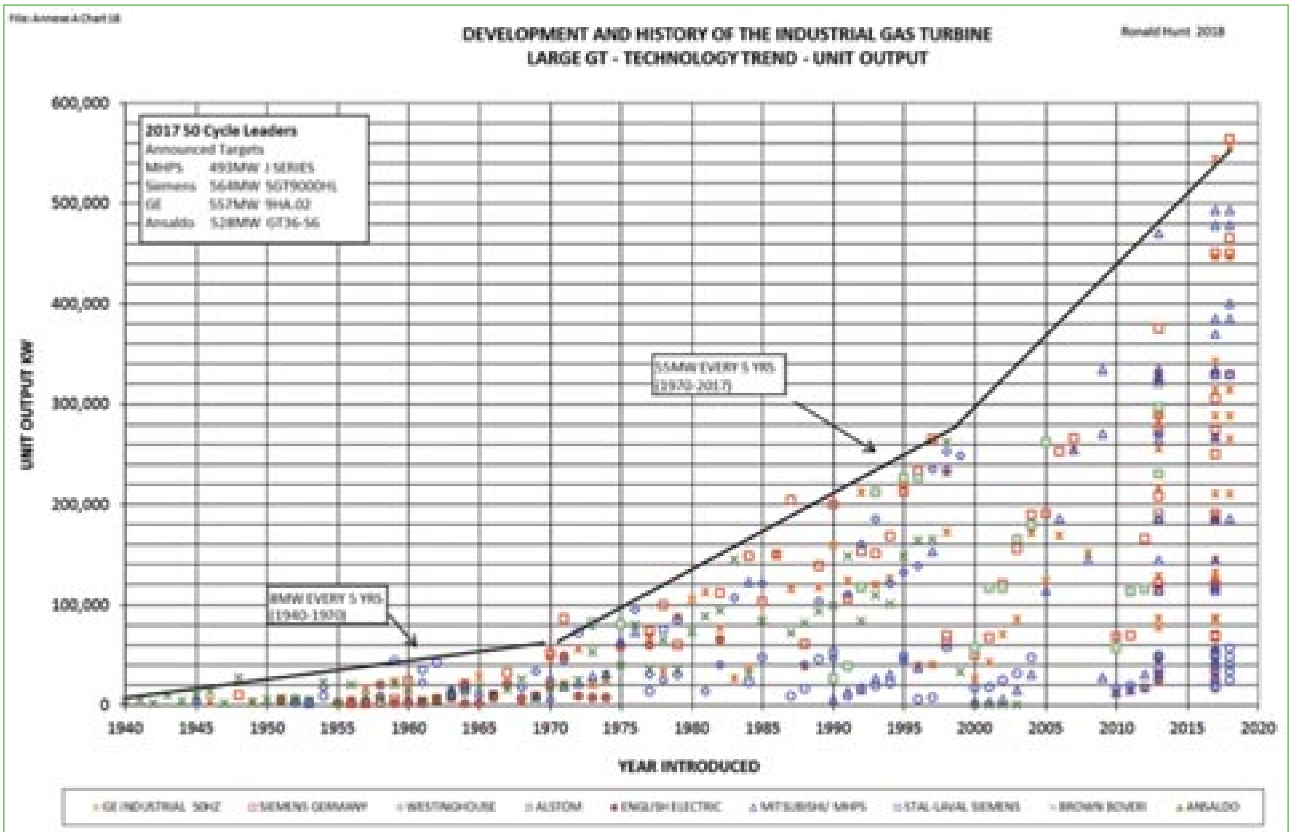

Figure 4 Growth in unit ratings

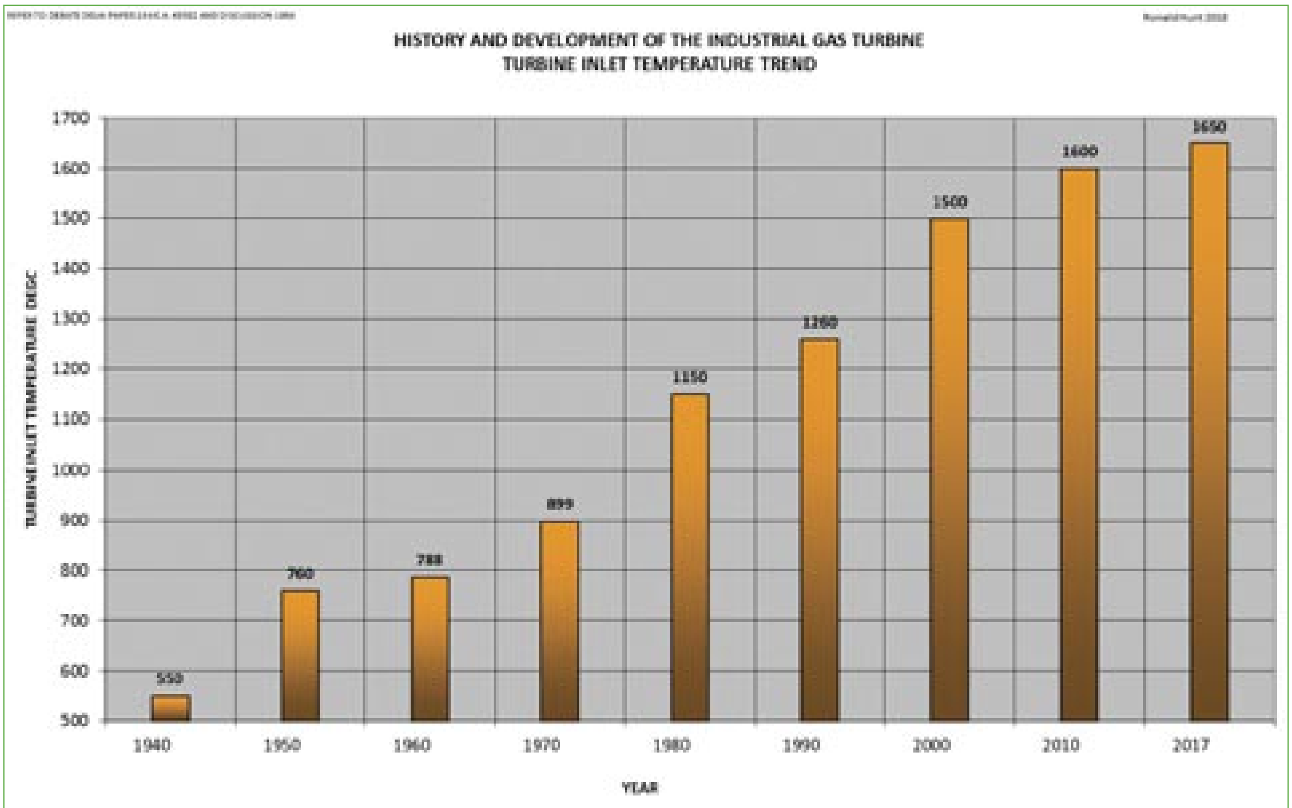

Figure 5 Technology trends - inlet temperature

industrial market, and the other group being the large machines group who continue to seek to dominate the market for thermal power generation and take over from conventional cycles as Riall Sankey had predicted in 1917.

3.4 Operational conditions

It was known from the earliest experiments and theory that higher efficiency was linked to the achievable turbine inlet temperatures. There is evidence of considerable discussion

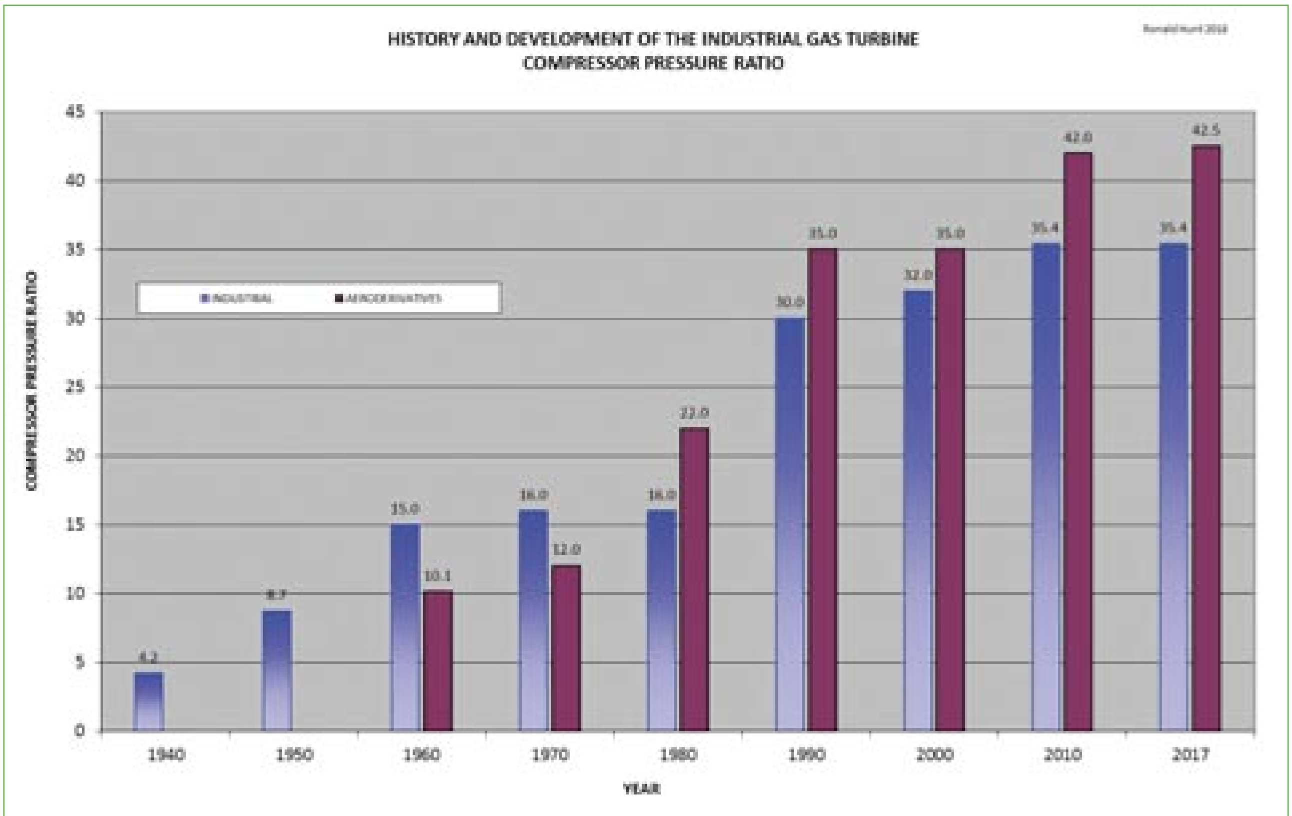

Figure 6 Technology trends - compressor pressure ratio

amongst the early pioneers about the safely achievable inlet temperatures with the available heat resisting steels at the time. This led to many ingenious and complicated schemes for cooling of the hot gas path components initially with water passages. It was always going to be a combination of materials, cooling technologies and (eventually) thermal barrier coatings that would push the industrial gas turbine forward and enable higher and higher inlet temperatures to be achieved (see Figure 5).

A review of the achieved turbine inlet temperatures based on this historical research shows that, whilst industrial gas turbine inlet temperatures have been consistently below those of aero engines, convergence is now taking place. When the Neuchatel gas turbine power plant was put into service in 1940 the operational conditions for the gas turbine cycle included a turbine inlet temperature of 550°C and pressure ratio of 4.2:1. In his 1939 paper Dr Meyer was comparing inlet conditions of 538°C (1,000°F), 649°C (1,200°F) and 816°C (1,500°F). He stated that 1,000°F (538°C) was absolutely safe for uncooled blades made of the available heat resisting steel. Then he went on to say that he could foresee the prospect of the gas turbine inlet temperature being increased to 816°C (1,500°F).

It was not until the late 1950s that turbine inlet temperatures for industrial gas turbines exceeded the 816°C (1,500°F) level. It was however Siemens who broke away from the trend with a short lived achievement in 1957. The whole field continued to steadily increase inlet temperatures by roughly about 125°C for every 10 years. By the late 1990s turbine inlet temperatures of approximately 1,300°C were achieved and in 2017 it was 1,600°C+.

3.5 Pressure ratios

Pressure ratios of the gas turbine compressor have increased by about 3 units each decade from 1940. Since about 1985 there appears to be a convergence taking place as a majority of machines large and small began to fall into the same band.

Industrial gas turbines and the modern turbo-fan aero engines operate with pressure ratios as high as 44:1. As a consequence aero-derivative gas turbines modified for land based power generation applications also operate with similarly high pressure ratios (see Figure 6).

3.6 Thermal efficiencies

According to the reports of Brown Boveri, the Neuchatel power plant achieved a noteworthy compressor efficiency of 88%, turbine efficiency of 89% and a thermal efficiency of 17.38 %. Associated with increase in turbine inlet temperatures the corresponding overall cycle efficiency was foreseen in 1939 to rise from 18% to 26%. The achievement of 26% overall efficiency actually took about 20 years.

At the time of the emergence of the practical industrial gas turbine in 1939 the thermal efficiency was 17-18 % and this was being compared with steam cycle efficiencies of 25-26 % of that day. As we now know, over the following years the steam cycle thermal efficiency continued to improve always keeping ahead of the simple cycle gas turbine until the late 1990s when advanced class gas turbines became operational.

This race between the open cycle gas turbine and the conventional steam cycle for highest efficiency was effectively halted in the 1960s when the combined gas turbine steam turbine cycle (CCGT) emerged and started pushing plant thermal efficiencies over 40% and beyond. In 2016 the open cycle efficiency has reached 40% and CCGT efficiency 62.2%. By the end of 2017 these have reached 42% and 63% for large units.

3.7 Materials and cooling

Owing to the complexity of the metallurgy and materials sciences it is only possible to touch briefly in this historical

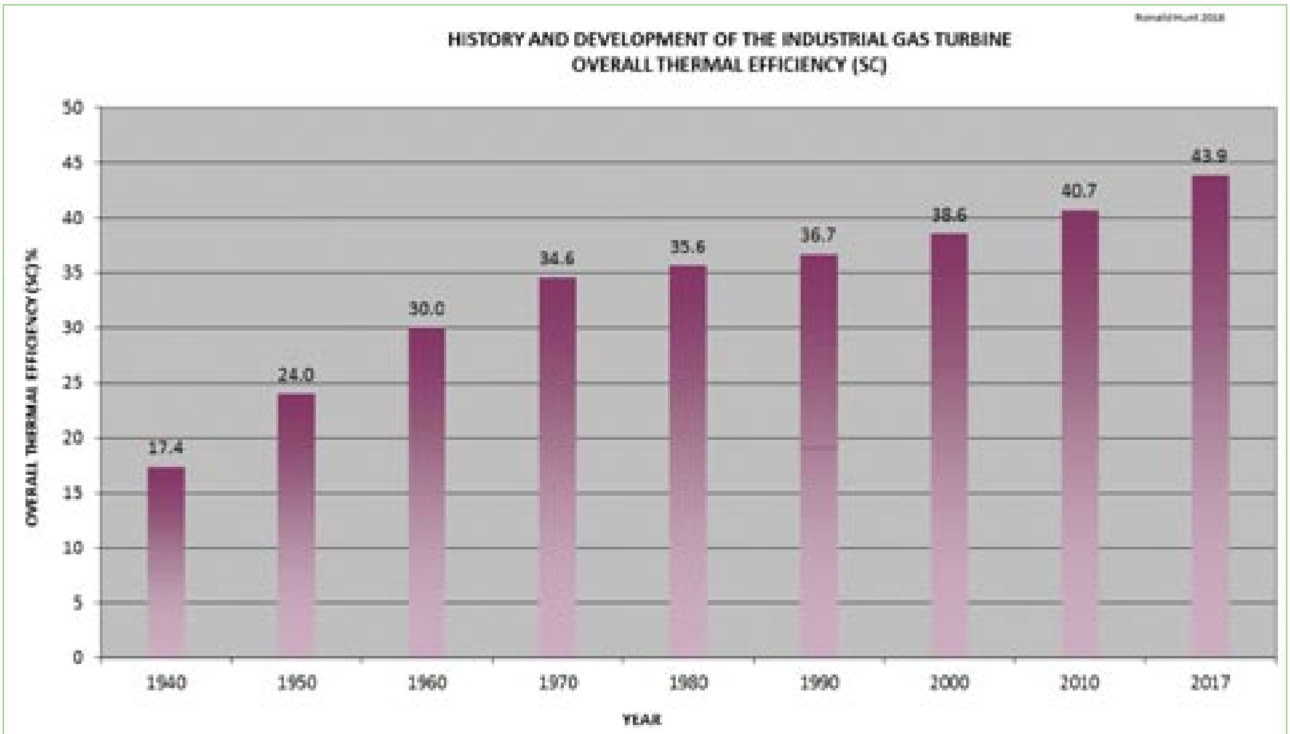

Figure 7 Technology Trends - overall thermal efficiency

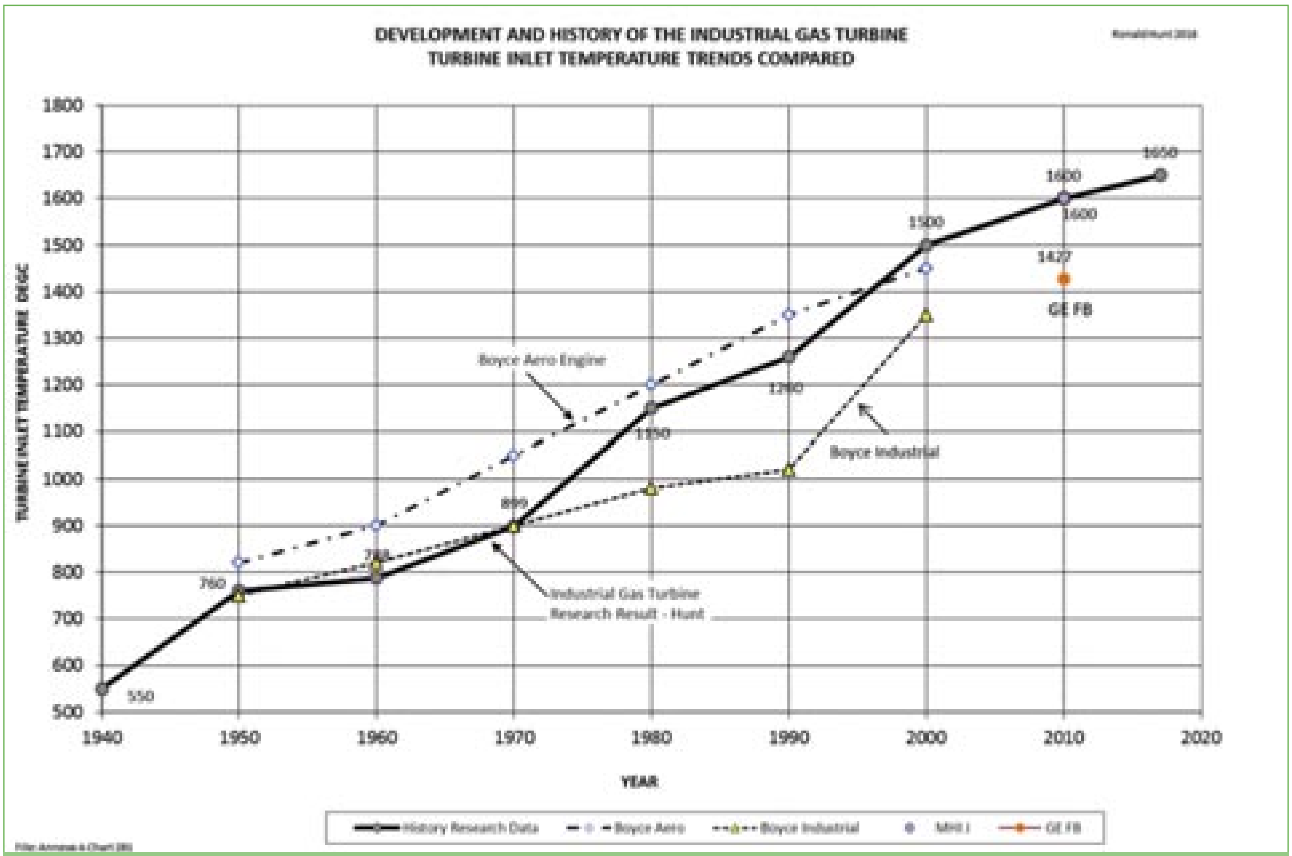

Figure 8 Material temperature limits

Figure 9 Exhaust emissions trend (NOx)

review on the impact that these have had on gas turbine technology and in particular on higher firing temperatures. As with the steam turbine, the gas turbine stage 1 blade (bucket) has to withstand the highest temperatures, stresses in the turbine, and is therefore considered to be the limiting component (see Figure 8).

In the early 1940s high grade heat-resisting steels were not available therefore steel temperatures were limited to around 1,050°F (566°C) for continuous running. Advances in materials accounted for the majority of the firing temperature increase until air cooling was widely exploited in the 1970s. These advances all enabled increased firing temperatures, increased output and improved thermal efficiency.

3D printing has now become a reality for gas turbine blade manufacturing and in 2017 – becoming a world first – with the production of a successfully tested 3D printed gas turbine blade.

It is worth noting that during the early 1950s the National Gas Turbine Establishment (NGTE) was carrying out experiments into the air cooling of gas turbine blades [20]. We can see therefore that the present day methods of air cooling were already being developed in 1953. In addition to the limit on the material capability metal temperatures above 870°C have resulted in the need to apply thermal barrier coatings due to hot corrosion effects.

3.8 Emissions

Over the years gas turbine emissions have gradually become more and more important and in particular those for NOx. Until the early 1990s, the United Kingdom and the EU had no statutory requirements for gas turbine emissions. It was then seen that Tokyo and California were leading the drive for lower and lower permissible limits. In 1970 a value of 75ppmv NOx was considered acceptable, by 1980 this had been reduced to 50ppmv and then by 1994 15ppmv. Today 15ppmv (30mg/NM3) NOx is typical and the trend to 3ppmv (see Figure 9).

The present day trends show that "single digit" NOx is now becoming the norm.

4. Gas turbine applications and fuels

Although the prime area of interest in the gas turbine in the early years was land based power generation and aircraft engines, almost immediately the industrial gas turbine had become a reality the applications being exploited seemed limitless. In addition to power generation the applications for the industrial gas turbine in 1940 immediately included locomotive engines, blast furnace blowers, marine propulsion, road vehicle engines and mechanical drives. Economics drove engineers to look at a wide range of fuels and many different applications and alternative fuels were being trialled.

4.1 Marine propulsion

In 1947 a Metrovick F2 axial-flow jet engine, known as the Beryl engine, was installed in the MGB2009 to become the world's first ever gas turbine propelled sea going vessel.

- 1951 The first ever merchant vessel to be fitted with a gas turbine propulsion system was the Anglo Saxon Petroleum Company Tanker "Auris" 12,000 tons dw with a BTH 1,200hp gas turbine
- 1953 Rolls-Royce designed the RM60 gas turbine rated at 4,000kW; which was installed in the British naval vessel HMS Grey Goose. The world's first ever solely gas turbine propelled ship
- 1956 A GE FS3 gas turbine of 6,000hp (4,500kW) was installed in the US Maritime Administration vessel, the John Sargent, to become the first US vessel to be gas turbine powered
- 1958 Three Bristol Proteus engines were employed in a fast patrol boat. HMS Brave Borderer starts sea trials fitted with the Rolls-Royce Proteus GT
- 1967 The British Royal Navy decided to use gas turbine propulsion for all future warships
- 1969 The first GE LM2500 aero derivative enters service with US Navy GTS Adm William Callaghan
- 1968 A Bristol Siddeley Olympus was installed in the RN vessel HMS Exmouth
- 1980 All propulsion power for the HMS Invincible, HMS Illustrious and HMS Ark Royal aircraft carriers provided by four Olympus engines on each ship, providing 72,000kW total shaft power (see Figure 10).

Figure 10 HMS Ark Royal - aircraft carrier 1980

The 1967 decision of the British Royal Navy to only use gas turbines for propulsion was quite a milestone in itself for the gas turbine. Today all gas turbine manufacturers have marine variants of their gas turbines and aero derivatives have now found a real place in marine propulsion.

In the UK the Queen Elizabeth class aircraft carrier has been commissioned in 2017, the primary power plant being two Rolls-Royce MT30 gas turbines delivering 40,000kW each.

4.2 Road vehicle engines

The application of gas turbines to road vehicles was a real quest in the late 1940s and 1950s.

First off the mark was Centrax who designed and manufactured a 160hp engine in 1948 and tested for use as a truck engine in 1951. The Rover Company became famous for producing JET1 the Rover gas turbine car, a world first. The Rover gas turbine car with 100bhp was first demonstrated to the public in March 1950 achieving a speed of 85mph. The updated version with an engine of 230bhp went on to achieve a speed of 152mph. This certainly gained public attention.

Figure 11 JET1 Rover Car 1950 © British Motor Industry Heritage Trust

Figure 12 Austin Sheerline Car 1952 © British Motor Industry Heritage Trust

Work was started by the Austin Motor Company on their gas turbine in 1952 and their first unit ran in 1954 using a Rolls-Royce Merlin supercharger as a compressor. Leyland, the successor of Austin, developed a gas turbine powered truck. In 1954 a specially designed Parsons 1,000hp (746kW) gas turbine was installed in the Conqueror tank.

In 1956 Donald Campbell's "Bluebird" was powered by a Bristol Siddeley "Proteus" engine rated at 3,320kW, the first to use a gas turbine engine. The initial test in the USA did not succeed but during a later attempt in 1964 the car reached 429mph during tests at Lake Eyre, Australia.

Other gas turbine cars competing were the Fiat Turbina (1954), General Motors Firebird (1953), Renault Étoile Filante (1954), and the Toyota GTV (1987). Since 2010 there has been some renewed interest in a gas turbine driven cars with developments using micro turbines together with electric motors.

4.3 Locomotive engines

At a very early stage work was under way applying the gas turbine to railway locomotive use. There was considerable progress made and some notable achievements up to around 1970. Eventually, however, the ultimate fate of gas turbine powered locomotives was to be sealed when the price of fuel oil became too high. Some rail system operational considerations eventually went against the gas turbine locomotive. The exception has been heavy freight locomotives in Russia still running.

In 1939 Brown Boveri was already well advanced with the design of gas turbine powered locomotives and their first gas turbine powered locomotive at 1,620kW was actually delivered in 1941. In the UK the first was the BR18000 1,800kW unit from Brown Boveri for the Great Western Railway, delivered in 1949, (see Figure 13). In 1951 Metrovick built the BR18100 2,200kW engine based on an aircraft engine. Then in 1961 English Electric built the GT3 locomotive with an EM27 engine. The last to be built in the UK was the British Rail APT-E prototype using a British Leyland gas turbine.

Both Westinghouse and GE developed gas turbine locomotives. In 1951 the Union Pacific Railroad had a GE FS3 gas turbine powered locomotive rated at 8,500hp (6,300kW). USA succeeded in introducing a large fleet of gas turbine locomotives; being operated by Union Pacific, these ran successfully for nearly 20 years from 1950 to 1969. In July 1952 C A Parsons received an order from the UK Ministry of Fuel & Power to design and construct a prototype coal burning gas turbine locomotive for the North British Railway company. The testing of the gas turbine unit mounted on the loco frame was carried out at Parsons' Heaton Works, Newcastle. After trials the project closed down in March 1959.

The first version of the TGV in France was TGV001 gas turbine electric (GTEL) built by Alsthom and first commissioned in 1969. The TGV rail trials were carried out from 1972-1978 and the gas turbine powered unit achieved a record 318km/h (200mph) on 8 December 1972. Only one gas turbine set was built.

APT-E (Advanced Passenger Train Experimental) was British and the world's prototype advanced passenger tilting train, powered by multiple gas turbines. This was the only multiple gas turbine powered train built by British Rail. On 10 August 1975 this train achieved a new British railway speed record of 152.3mph.

Gas turbine powered locomotives were under test in Russia from 1959 to 1970. Then in 2006, Russia introduced a 1,000kW LNG fired GTEL and in 2007 an 8,300kW GTEL.

Figure 13 BR18000 Gas Turbine Locomotive 1949 ref 245546
Photo courtesy of Historisches Archiv ABB Schweiz

4.4 Power station standby and peak lopping

A new application for gas turbines was found in 1959 when the South West Electricity Board decided to install a Proteus engine as a remotely operated peak lopping station. Then in 1960 CEGB decided to install fast start gas turbines using aero engines as gas generators with free power turbines. In the early 1960s severe grid disturbances led to electricity black-outs over the south east of England. This, together with the predicted load growth at the time, made it necessary for the Central Electricity Generating Board (CEGB) to install quick starting gas turbines suitable for peaking duties.

Orders were placed by CEGB in 1962 and installation started the following year as described R G Henbest paper delivered to DEUA (IDGTE) in 1970 [40]. The gas generators used were mainly Bristol Siddeley Olympus and Rolls-Royce Avon engines. A few were built with Pratt & Whitney FT8 engines. There were the three main contractors at the time, these being AEI, Bristol Siddeley and English Electric/GEC all supplying either Olympus or Avon based sets. It was not all plain sailing for these peak load sets as initially the aero engines were installed as designed, then it was found that the new operational conditions faced by operating these engines in a land based power station environment showed up unforeseen problems (refer ASME 69-GT-110).

4.5 Mechanical drive

Whilst a major part of industrial gas turbine development activity has been directed to power generation and marine applications, from the earliest days gas turbines have been used for mechanical drive applications.

In 1946 Solar Turbines produced a 35kW portable gas turbine driven pump for the US Navy, this was used for firefighting duties. The 1949 air bleed unit of C A Parsons 2,170bhp (2,022kW) was a gas turbine driven compressor. Rover gas turbines manufactured engines for a variety of stationary applications. The Austin engine was put on the market in 1961 as an independent prime mover and pump drive. Today about 30% of the gas turbine market by number of units is for mechanical drive applications.

In the UK there are currently over 70 compressor drives on the national grid gas network alone. The gas generators include GE aeroderivatives, Rolls-Royce Avons, Rolls-Royce RB211s, Solar and Siemens SGT400 units.

4.6 Combined heat and power – cogeneration

In the 1960s the term "total energy" became a popular concept. Today this is better known as combined heat and power (CHP) and in some parts of the world as cogeneration. These schemes involve the combined production of electricity and heat for process or other uses. Today cogeneration has been extended to mean the combined production of electricity and heat or cooling; and occasionally "trigeneration".

4.7 Combined cycle

A combined cycle power plant (CCGT) is a power plant that produces electricity from a combination of gas and steam turbines and the most highly successful of all applications. The gas turbine drives a generator and the exhaust gas energy from the gas turbine is used to generate steam in a heat recovery steam generator (HRSG) which then produces electricity from a steam turbine. Today many of the CCGT plants are "single shaft" units sharing a common generator. The advent of the combined gas and steam cycle enabled the gas turbine to leap to prominence as a primary power generator.

The possibility of the combined cycle was foreseen by Dr Meyer in his 1939 paper. At the same time lots of applications were found to recover gas turbine exhaust heat. It was not however until around 1965 that CCGT became a serious contender. The beginnings of combined cycle are described in the 1970 paper of Basil Wood.

1960	BBC Korneuburg, Austria 75MW (2+1)
1963	Horsehoe Lake, Oklahoma
1965	Siemens – Hohe Wand Austria 12.8MW
1968	GE Wolverine Cooperative 21MW (1+1)
1979	Siemens Bang Pakong 250MW (2+1)

Table 1 Some early combined cycle plants

From 1968 onwards the CCGT cycle has made rapid progress and together the gas turbine has overtaken the conventional cycle reaching unbelievably high cycle thermal efficiencies. In the UK the first CCGT was the Roosecote Station in Cumbria commissioned in 1991 producing 224,000kW with efficiency 49%. In 2016 the achieved thermal efficiency for combined cycle steam and gas turbine plant reached 62%. A new record of over 63% has already been claimed and future targets of 65% set.

4.8 The educational units

A large number of small gas turbines were produced and sold for educational purposes. Significant numbers of these went to colleges and universities around the world. Between 1955 and 1965 the Rover Company made more than 250 of these small gas turbines (60hp) for educational establishments. In addition to UK colleges and universities they also went to 40 countries worldwide from Australia to Uruguay. Others of this type were made by Austin and Budworth. Interestingly MTT Netherlands, a new entry to the field, in 2017 has introduced a microturbine being offered as an educational unit.

4.9 Small and micro gas turbines

The term micro gas turbine, or micro turbine, is a fairly recent description. It has to be recalled that the early practical machines started with turbines of about 500kW and after that came 100kW or so turbines for motor vehicles. It is the physical size of the small and micro turbines today that is most impressive. There have been more than 30 companies worldwide producing micro turbines however many appeared on the market and then did not succeed.

Suggested definitions:	
Large gas turbines	> 15,000kW
Small gas turbines	> 500 - < 15,000kW
Micro gas turbine	> 1 – < 499kW
Miniature gas turbine	< 1kW

Table 2 Definition of small and micro gas turbines

Today there are around 10 active microturbine companies: USA (4), France (2), UK (1), Italy (1), Netherlands (1) and Japan (1) [92].

4.10 Gas turbine fuel options

Light oil and distillate fuel oil grades started out as the preferred gas turbine fuels, however from very early in the life of the gas turbine economics were pushing the need to burn a wide range of fuels. The fuels that have been tried with varying success include: light oil, heavy oil, crude, coal, peat, BFG, wood, natural gas and syngas. What has changed since many of these were tried of course has been the availability of natural gas for power generation. Up to 2,000 all gas turbine power plants were built with duel fuel capability, but since that time this is no longer the case as gas supplies became abundant. The future looks to be hydrogen and progress is being made.

4.10.1 Light oils

In trials of the 1940s gas oil was used as well as heavier grades of fuel oil, some of the latter resulting in serious ash deposition problems. Operators preferred to use a cheaper fuel so kerosene was replaced by gas oil. Oil filtration was then introduced to maintain the fuel specifications.

4.10.2 Heavy oil/crude

Since then various other liquid fuels including heavy oil, crude and naphtha have been used extensively in gas turbines incurring penalties on maintenance intervals and costs. Only a few models of gas turbines are suitable for burning heavy oils and crude.

The oil producing states of the Middle East pushed the use of crude oil for direct burning in gas turbines and from the 1970s this became quite normal and continues to the present time, however the cost of maintaining such turbines is high due to corrosion and deposition. Degradation of output performance could be up to 15%. Fuel treatment was found to be an effective means of handling these fuels.

4.10.3 Coal

By 1939 work was already under way testing gas turbines with pulverised coal. One paper stated that an experimental gas turbine set had been run on pulverised fuel for many months at the Brown Boveri testing plant. In the UK during the 1950s a great deal of effort was employed on gas turbine coal burning trials; these being reported by C A Parsons, Ruston, Metrovick and others. In Canada the government awarded a contract to McGill University in 1950 to construct an experimental coal burning locomotive. In 1961 Union Pacific in the USA made trials with UP80 an experimental coal burning gas turbine (GTEL) locomotive. These were not successful.

The Escher Wyss closed cycle was much more successful in burning coal in conjunction with the gas turbine. These closed cycle plants burning coal were built in Germany, Russia and the UK between 1950 and 1963. Some closed cycle plants ran for over 100,000 hours. In 1999 the US DOE (Office of Industrial Technologies Energy Efficiency) promoted a coal-fired air turbine (CAT) cycle plant to deliver more than 40% efficiency, currently at the feasibility study stage. This work is no longer being pursued however IGCC remains as the contender.

4.10.4 Peat

In the days before awareness of the impacts of depletion of peat resources, it was foreseen that peat could exploited for power generation. For a time this was promoted by the UK Government and the North of Scotland Hydro Electric Board. The process required the peat to be milled and then passed to the combustors. The first open cycle gas turbine to run on Peat was built in 1949 by Ruston & Hornsby [17]. A test facility was constructed in Lincoln and tests carried out during 1952 and 1953. The systems were developed to the extent that a full scale trial in Scotland was envisaged.

At the same time John Brown, developed a gas turbine using Escher Wyss closed cycle technology and carried out trials in their works in 1950. They went on to install two peat burning plants in Scotland, one at Altnabreac and the other Dundee. Work was stopped on the peat plants around 1960 due to the problems experienced and the cost of producing electricity from peat being significantly higher than conventional methods.

4.10.5 Blast furnace gas

Gas turbines have been successfully modified to burn blast furnace gas (BFG). This was known to be possible during the 1930s. Blast furnace gas, however, has major drawbacks for gas turbines as it is of low calorific value resulting in huge gas volumes and also contains significant amounts of dust. In 1951 Brown Boveri ran a blast furnace gas fired machine at Dudelange, Luxemburg. In 1955 a Westinghouse W201 machine was modified as a blast furnace gas blower fired on blast furnace gas. There were 30 BFG fired gas turbines reported to be installed in Europe from 1950 to 1965. There is an environmental benefit of these plants as BFG firing makes more efficient use of the by-product gases emitted by steel plants and reduces environmental pollution.

In 1958 MHI supplied their first BFG fired gas turbine, this was an 850kW machine for Nippon Steel. Up to 2013 MHI had supplied 59 BFG fired gas turbines worldwide and the unit size has now increased to 180MW [87].

4.10.6 Natural gas

Natural gas is widely considered as the clean fuel, easy to burn and good for gas turbines. Until the early 1980s natural gas was not available for power generation. The exception to this was the Middle East where oil producing states had huge quantities of residual gas to burn. Until the gas turbine came along this gas was just disposed of by burning by flare to atmosphere. A memorable sight of the Arabian Gulf in the late 1970s, especially seen by air at night, was the large number of flares burning across the Middle East. At that time the gas turbine power plants of the Middle East were either distillate or crude fired. The 1973 oil crisis became the driver for the petroleum industry to develop new oil fields and the result of this was natural gas becoming available in sufficient quantities to burn in gas turbines.

Since the early 21st century and amidst much controversy in many countries, shale gas has become available. In the USA there are huge quantities with an expectancy of 50% of the gas demand coming from this source. The extraction of shale oil and gas from major reserves has revolutionised the energy market.

5 Recent developments – advanced class gas turbines

A further step in the gas turbine story was described in the 2002 paper presented by Siemens Westinghouse in The Netherlands June 2002 [81]. Starting in 1992 the US Advanced Turbine Systems Program, called ATS, and co-funded by the US Department of Energy, Office of Fossil Energy was launched.

The programme was described as "an ambitious ten-year effort to develop the necessary technologies which will result in a significant increase in natural gas-fired power generation plant efficiencies, decrease in cost of electricity, and a reduction in emissions, while maintaining the current state-of-art reliability, availability, and maintainability levels". This technology development and associated demonstration program was completed in 2001. The objective of the ATS program was to develop "ultrahigh efficiency, environmentally superior and cost competitive systems for base load application" covering utility, independent power producer and industrial markets.

GE introduced their H advanced class gas turbine with the steam cooled Frame 9, the first such unit went into service in 2003 at Baglan Bay in the UK. In 2014 it was announced by GE that the steam cooling had been replaced in the HA by full air cooling. [126]

In 2004 the Japanese Government funded gas turbine project called the "National Project" with the main target being the development of a 1,700°C (3,092°F) class gas turbine in order to achieve 62-65% (LHV) combined cycle efficiency. The developments are ongoing and being incorporated into the advanced class of turbine include EGR combustion recirculation, higher cooling efficiencies, advanced thermal barrier coatings, improved turbine aerodynamics and advanced turbine materials.

The combined impact of all these programmes is that reported CCGT and GT efficiencies for large gas turbine systems by various OEMs have all significantly improved since 1992. At that time the GT efficiency of the larger machines was around 37% and the CCGT efficiency between 50 and 53%. There was a gradual improvement in these efficiencies up to 2004 and then after 2004 the advanced GT developments began to take effect and around 2011-12 the GT efficiency reached 40% and CCGT efficiency has now passed the 60% mark. In 2017 GT efficiency reached 42%+ and CCGT efficiency 63%.

6 Manufacturing companies

Starting from only two countries and six competing manufacturing companies in 1940, by 1965 the number of industrial gas turbine manufacturers had grown to 61 from 15 countries. In 2018 the number of industrial gas turbine manufacturers worldwide is found to be around 38 from 14 countries.

This GT history research has identified that since 1940 to 2017 there have been in total more than 94 manufacturers of industrial gas turbines. This number will be higher since there are some countries where historical information is not easily accessible.

In the United Kingdom 24 gas turbine manufacturers have been identified. In Europe (excluding the UK) there have been 26, in North America there have been 23, and in Japan there have been 13 identified. Other regions include China, India, Iran, Russia, and Ukraine with 9 OEMs identified.

7 The future

Whilst there has been a significant reduction in demand for gas turbines in the last three years, the signs are now good and the future prospects of the industrial gas turbine are still being predicted to be excellent including:

- The continued development of all industrial gas turbines in an even more highly competitive market adopting all technology improvements from the advanced class gas turbines
- In power generation the gas turbine module has already reached 500MW which is predicted to grow further and with higher efficiencies
- Possible further developments with IGCC gasification with CO^2 capture and removal to provide new opportunities and challenges
- Even with increased renewables the gas turbine will continue to play a major and essential role
- Higher efficiencies will come from further increases in operating conditions
- Major improvements in operational flexibility will continue including performance at low load
- Continued development of combustion technology including H2 fuels reducing emissions to "single digit" NOx as the norm
- The continued widespread application of micro gas turbines

8 Conclusion

It has not been possible in this paper to cover the entire research carried out for this history of the development and future of the industrial gas turbine. The complete version of the research is now being published in a book.

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Written contributions to the history are always welcomed. If you have a question, comment or wish to make a contribution to the history, please contact the author. ■

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Code	Name of Gas Turbine Manufacturer	Country	Code	Name of Gas Turbine Manufacturer	Country
A1	W H Allen Engineering	UK	K2	Kawasaki	Japan
A2	ACEC Ateliers	Belgium	K3	KHD Deutz	Germany
A3	AEG Kanis	Germany	K4	Kobe Steel	Japan
A4	Allison Gas Turbine Division	USA	K5	Komatsu	Japan
A5	Allis Chalmers	USA	L1	Joseph Lucas (Gas Turbine Equip.)	UK
A6	Alsthom / Alstom	France	L2	Leyland Gas Turbines	UK
A7	Ansaldo Energia	Italy	L3	Lycoming Engines (AVCO) / MTU	USA
A8	Associated Electrical Industries	UK	M1	Mapna	Iran
A9	Austin Motor Company	UK	M2	MAN Diesel and Turbo	Germany
A10	Aviadvigatel Perm	Russia	M3	Metropolitan Vickers (Metrovick)	UK
B1	Boeing Industrial Turbines (USA)	USA	M4	Mercier (Societe COMET)	France
B2	Bristol Siddeley	UK	M5	Mitsubishi Heavy industries (MHI)	Japan
B3	British Thomson Houston (BTH)	UK	M6	Mitsui Engineering & Shipbuilding	Japan
B4	Brown Boveri / ABB - Baden	Switzerland	M7	Motor Sich	Ukraine
B5	Brush Electrical	UK	M8	Micro Turbine France/ Safran	France
B6	BMW Munich	Germany	N1	Niigata Power Systems	Japan
B7	Budworth Turbines	UK	N2	Nuovo Pignone	Italy
B8	Bharat Heavy Electrical	India	N3	D. Napier & Son	UK
B9	Bladon Jets	UK	O1	Orenda Engines - Magellan	Canada
C1	Centrax Gas Turbines	UK	O2	OPRA Gas Turbines	Holland
C2	C A Parsons & Co	UK	P1	PAMETRADA	UK
C3	Capstone Turbine	USA	P2	Perkins Gas Turbines	UK
C4	Chrysler Corporation	USA	P3	Noel Penny	UK
C5	Cooper Bessemer – Cooper Rolls	USA	P4	Power Jets	UK
C6	Curtiss Wright	USA	R1	Rateau	France
C7	Creusot Loire Schneider	France	R2	Rolls-Royce	UK
D1	Dresser Industries	USA	R3	Rover Company	UK
D2	D2 Dongfang Turbine Company	China	R4	Ruston & Hornsby (R&H) - Ruston	UK
E1	Elliott Turbomachinery	USA	R5	Russian / Soviet States	Russia
E2	English Electric Company/ GEC – Heavy Ind	UK	S1	Siemens - Schuckert Werke	Germany
E3	English Electric Company/ GEC – Aero Deriv	UK	S2	Siemens Aeroderivatives	Canada
E4	Escher Wyss	Switzerland	S3	Skoda – First Brno	Czech
E5	Ebara Corporation	Japan	S4	Solar Turbines	USA
F1	Fiat Termomeccanica	Italy	S5	Stal-Laval/ ASEA	Sweden
F2	Ford	USA	S6	Sulzer / Brown Boveri Sulzer (BST)	Switzerland
F3	Fuji Electric	Japan	T1	Thomassen	Holland
G1	General Electric Heavy Industrial	USA	T2	Toshiba Corporation	Japan
G2	General Electric Aero Derivatives	USA	T3	Turbomeca	France
G3	Garrett Corporation/ Honeywell	USA	T4	THM Hispano Suiza Bois Colombes	France
H1	Hindustan Aeronautics	India	T5	Turbec AB (now Italy)	Sweden
H2	Hitachi	Japan	U1	United Technologies/ TP&M/ Pratt & Whitney	USA
H3	Hitachi Zozen	Japan	U2	United Technologies/ TP&M/ Pratt & Whitney	Canada
I1	IHI	Japan	U3	US Turbine	USA
I2	Ingersoll Rand	USA	V1	Volvo	Sweden
J1	John Brown Engineering	UK	W1	Westinghouse	USA
J2	Japan Gas Turbine – until 1999	Japan	W2	Waukesha Motor	USA
K1	Kongsberg/ Dresser-Rand	Norway	Z1	Zorya Mashproekt	Ukraine
94	Gas Turbine Manufacturers				
18	Countries worldwide				

Table 3 Gas turbine manufacturers since 1940

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