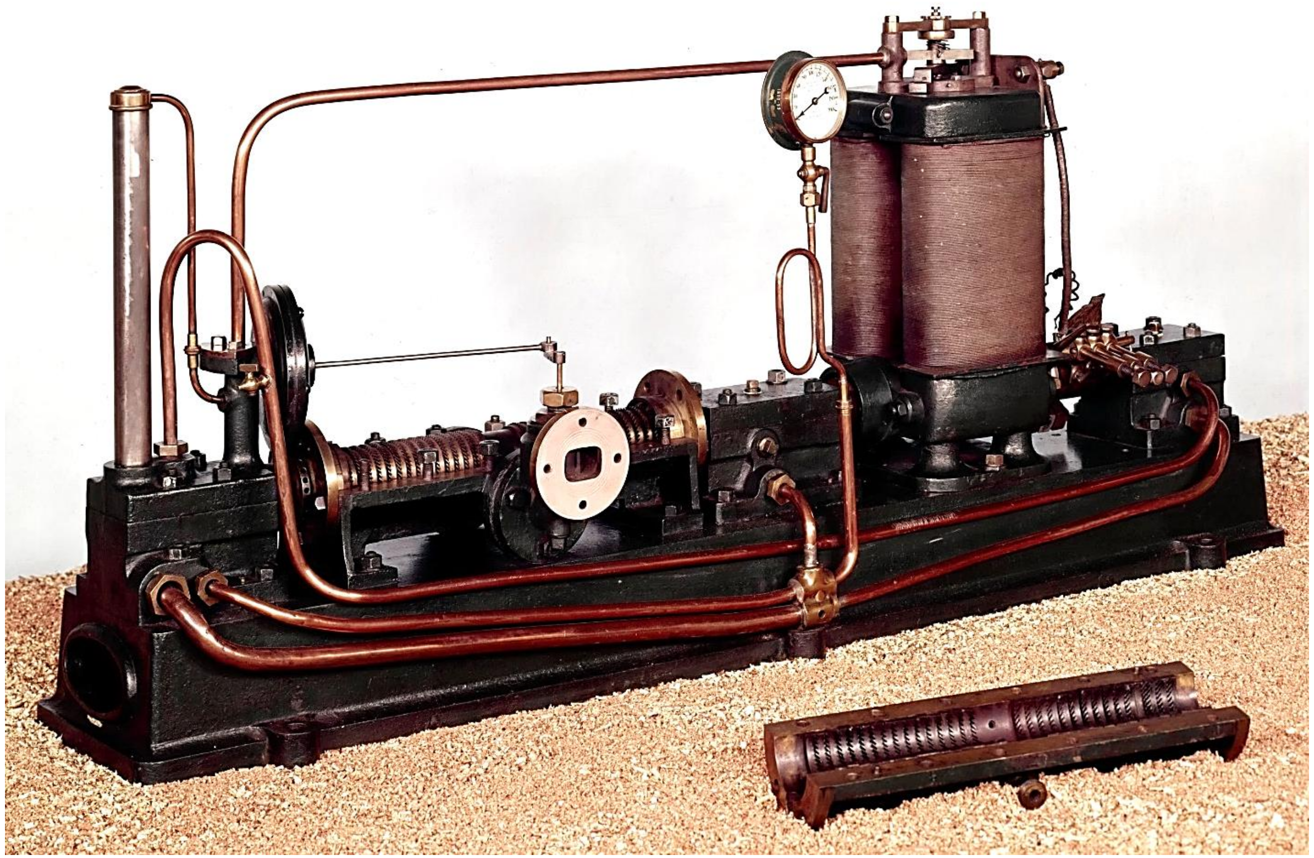


Evolution of the Parsons land steam turbine

Geoff Horseman

Birr Engineering Festival, 18th - 20th October 2024

The young Charles Parsons had ambitious aims

At the age of 27, Charles Parsons tried to invent a new type of engine which used pure rotary motion.

Between 1881 and 1883:

- He produced an ‘epicycloidal’ steam engine with four pistons in a cruciform arrangement where both the crankshaft and cylinder rotated.
- He designed torpedoes powered by a gas turbine using rocket propellant to create the gas flow.

These had some commercial success but they weren’t what he wanted.

In 1884, at the age of 29, he achieved his goal. He developed a type of steam turbine which in time would supersede the reciprocating steam engine both for electricity generation and for powering large, fast ships. At the same time, he developed a generator which could withstand the speed of the turbine.

Parsons wanted to achieve the efficiency of water turbines using steam

Water turbines were well established in the 1800s.
They were very efficient (70 – 80%).

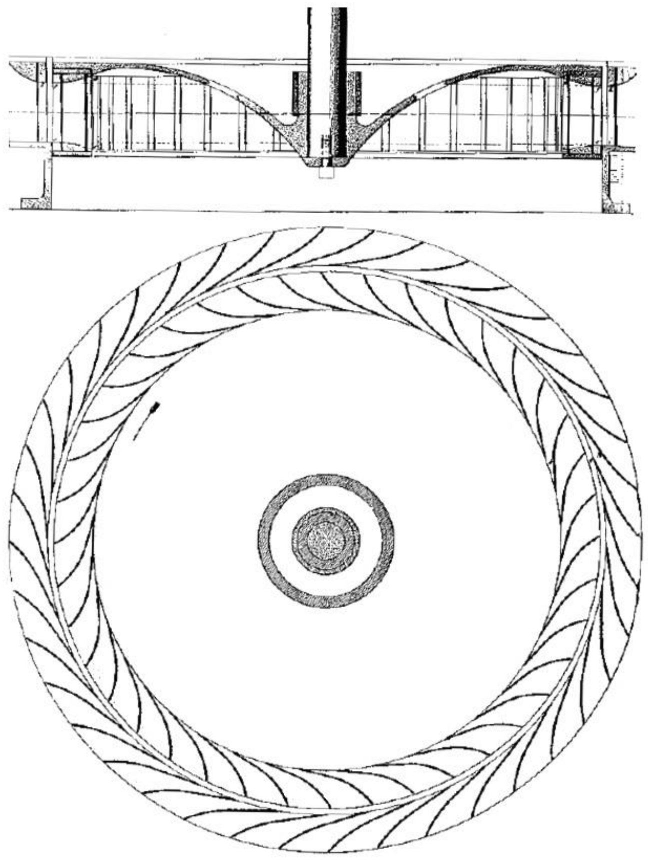
In 1833, Benoît Fourneyron determined how these worked mathematically.

The findings were applied successfully to water turbines by James Francis and others.

Charles Parsons learned of Francis' work, which had been published in 1855, and may have met him when he travelled to the USA in 1883.

Water turbines were limited by the available water supply, which was variable.

With steam, any amount of power could be produced anywhere.

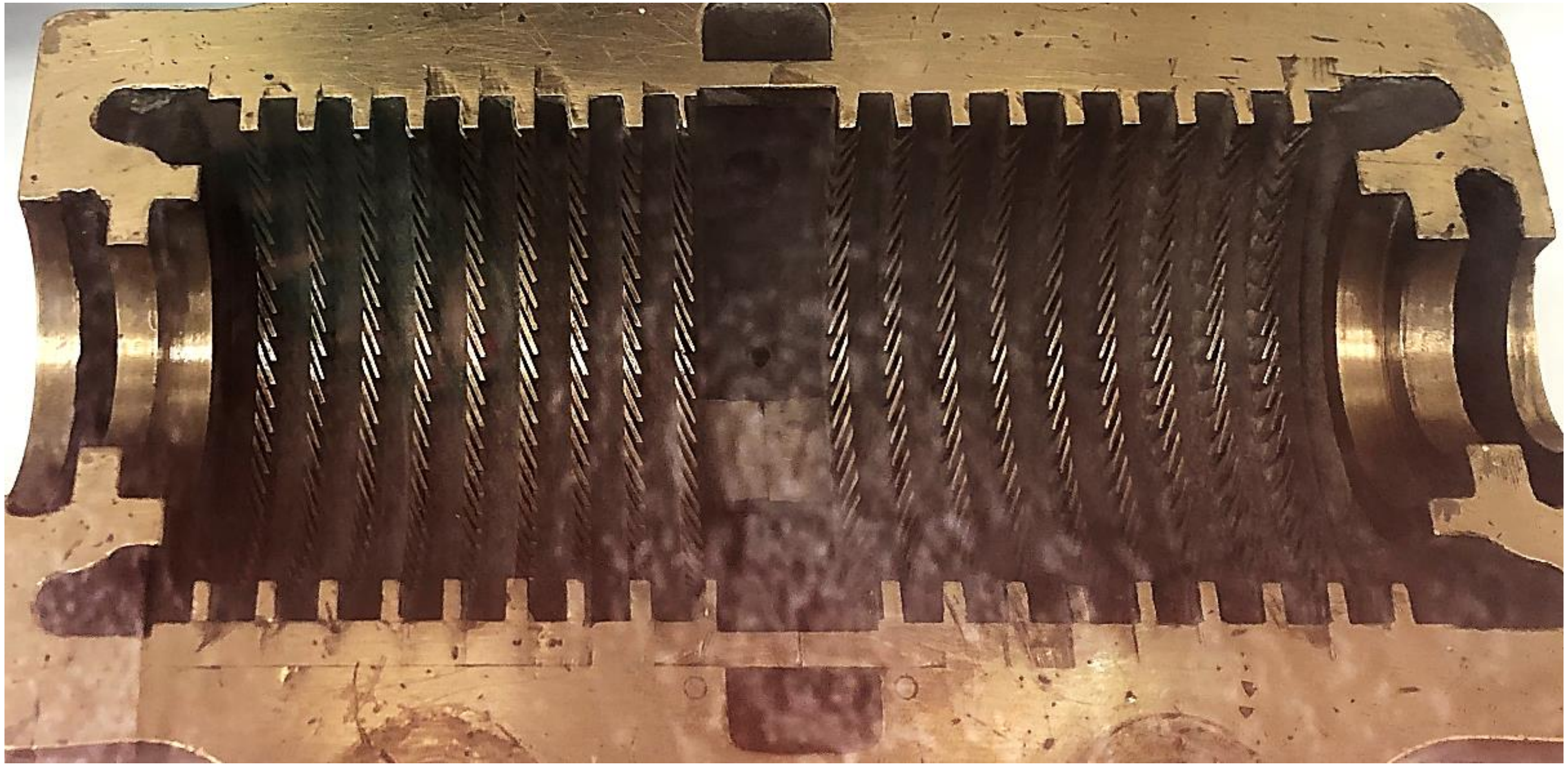


James Francis' first water turbine of 1855.
Water entered radially and exited axially.

By using many stages of blading to emulate incompressible flow, the principles of water turbines could be applied

Parsons early turbines used angled slots in brass discs to create the fixed and moving blades.

He used many stages so that the expansion of steam was small in each stage and so was analogous to many water wheels in series.



The cylinder of one of Parsons' earliest turbines

Between 1884 & 1889, 241 turbine-generators were manufactured

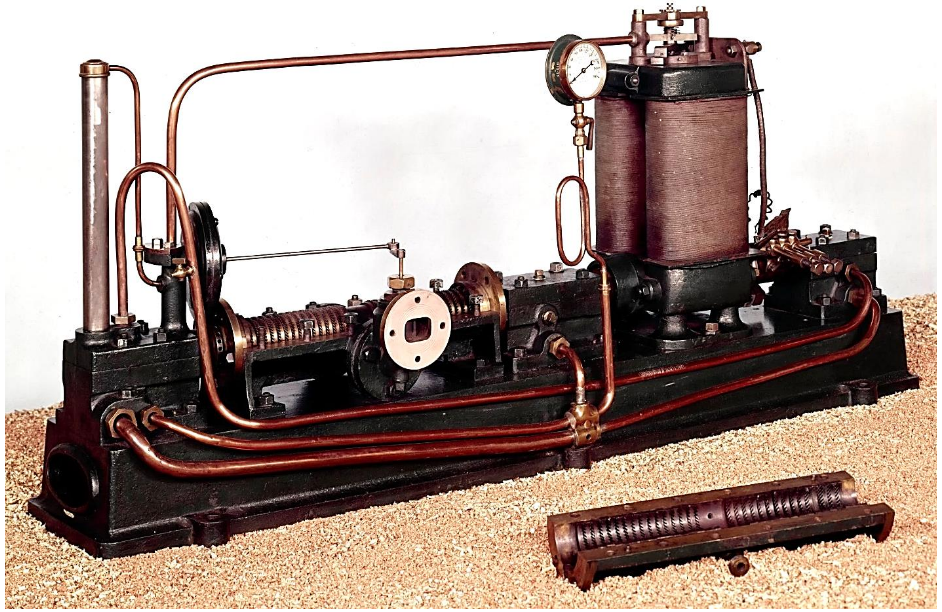
Charles Parsons was initially a junior partner in the firm
Clarke, Chapman, Parsons & Co in Gateshead.
They made equipment for ships.

The first machine produced 7.5 kW at 18,000 revs/min.
The largest machine generated 75 kW at 4,800 revs/min.
Curved blades were introduced in 1888.

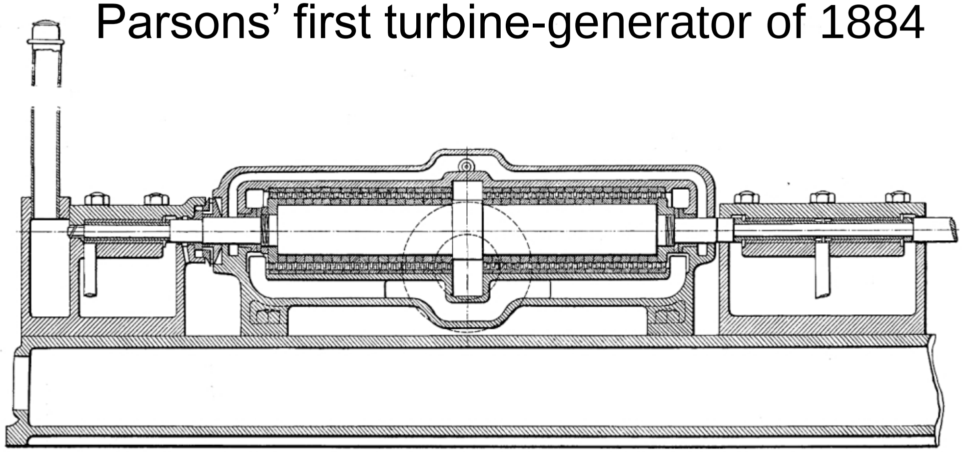
The later machines used 21 kg of steam per kWh
ie 17% more than a good reciprocating steam engine.

The major advantage was reliability.
Reciprocating engines broke down frequently.
Steam turbines were more reliable.

In 1888, Parsons formed a separate company to build and
operate the World's first steam turbine driven power station.
Clarke & Chapman didn't agree with this and so Parsons left.



Parsons' first turbine-generator of 1884



Cross-section through the turbine

From 1889 to 1894, Parsons built radial flow turbines

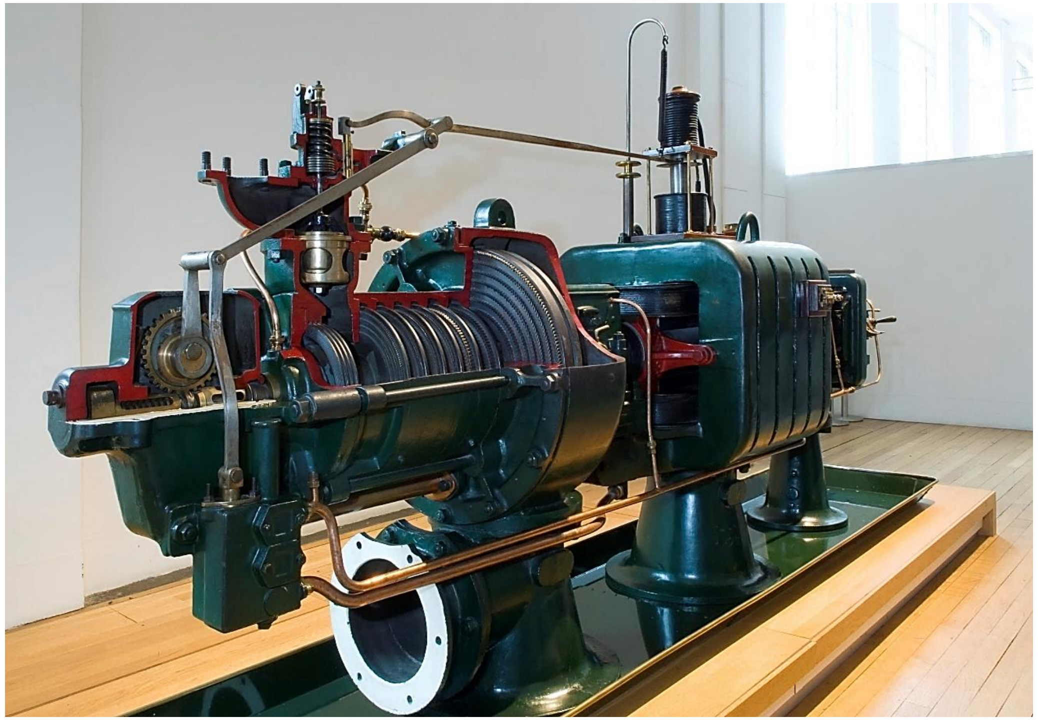
Parsons, Clarke & Chapman couldn't agree a value for the original turbine patents, so Parsons had to leave without them.

Unable to use axial flow, Parsons developed the World's first radial flow steam turbine.
120 radial flow land turbines were built up to 200 kW in size.
The largest radial flow turbine was Turbinia's engine 1.23 MW.

In 1891, a condenser was employed on a 120 kW turbine.
This machine achieved a steam economy comparable with a good reciprocating steam engine of similar size.

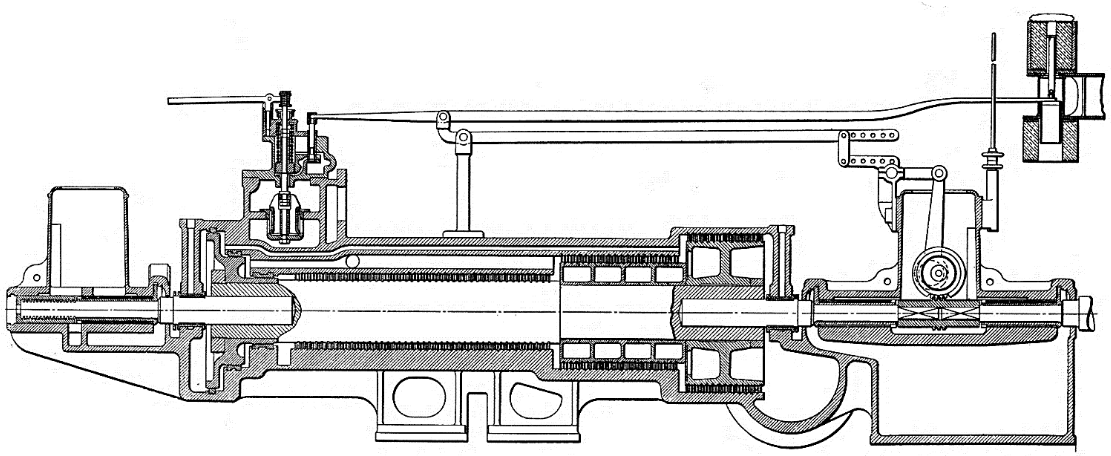
In other words, a steam turbine which did not operate at optimum velocity ratios, which had crude blading, poor blade seals and was limited by primitive construction achieved a performance level comparable with well-developed steam engines.

This was the turning point in the competition between steam turbines and reciprocating steam engines.

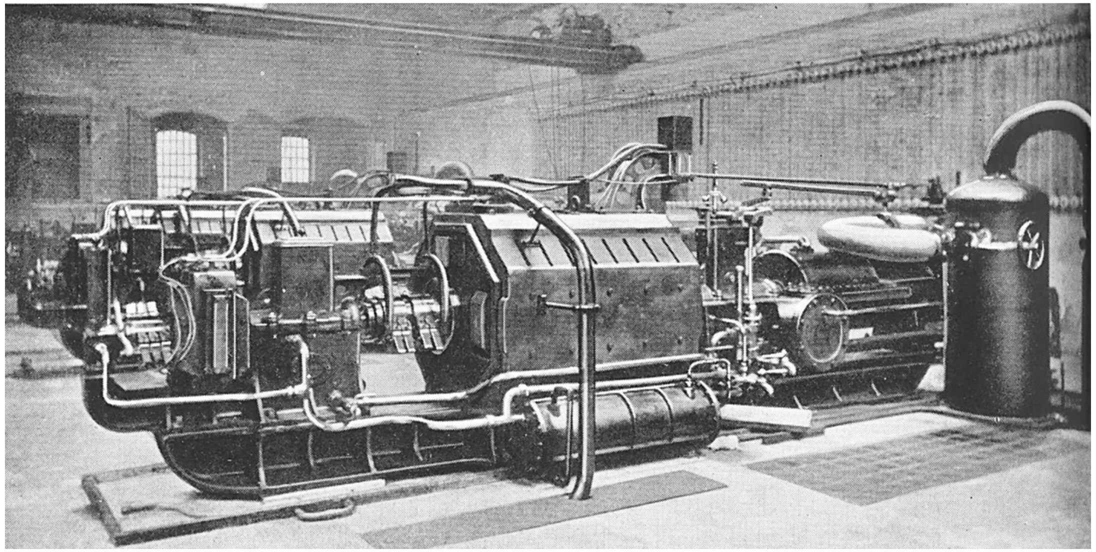


World's first condensing steam turbine-generator
120 kW at 4,800 revs/min for Cambridge.

An event in 1895 triggered growth in demand for turbines in the UK



350 kW turbine at 3,000 revs/min



Sister units at Sardinia Street station

In 1894, Parsons regained his original patents and returned to developing axial flow machines.

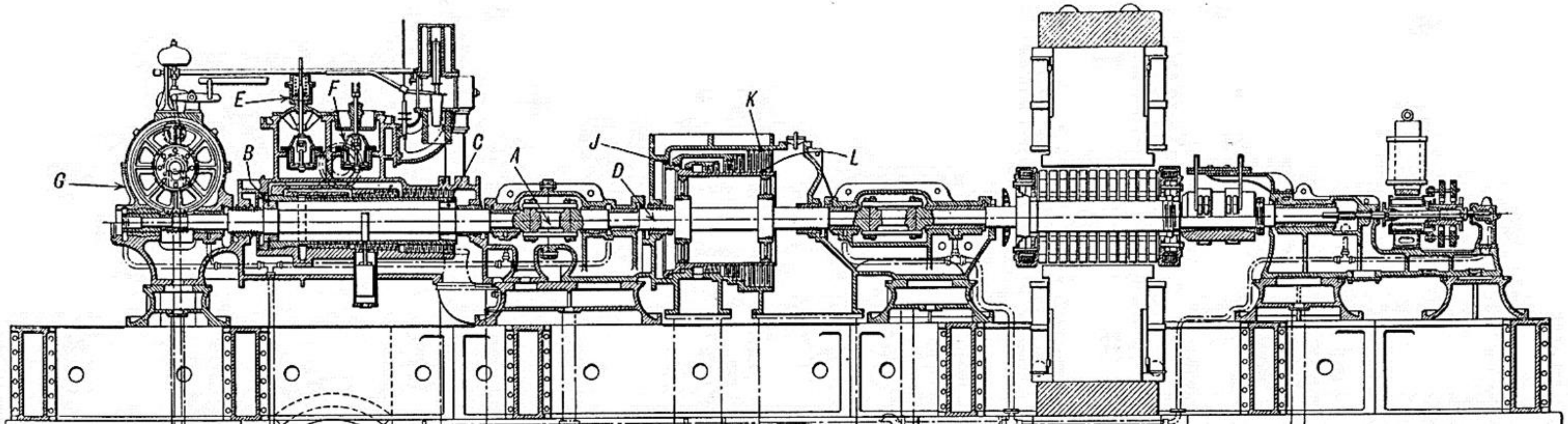
In London, Manchester Square power station employed 10 Willans reciprocating steam engines. The noise and vibration were so bad a Court ordered the owners to modify or close the plant. Modifications were unsuccessful.

They installed a Parsons 350 kW unit. In comparison, the turbine was practically silent and vibration-free. This saved the station. The units were also more efficient, more reliable, required less upkeep etc.

There were around 70 generating companies in London. Parsons success drew a lot of attention and triggered growth in demand for steam turbine-generators.

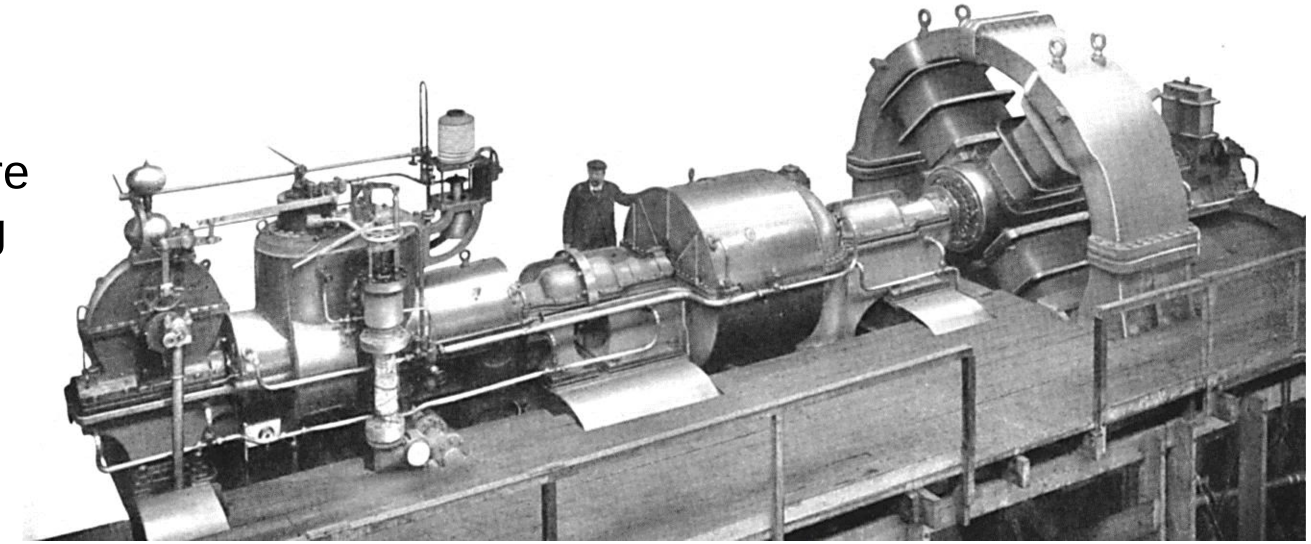
Many people sought a license to manufacture Parsons machines including George Westinghouse in 1896.

The first steam turbine-generators > 1 MW were built in 1900



Two 1.25 MW units were supplied to Elberfeld PS in Germany in 1900. They were studied in depth by leading European engineers.

The units were far more efficient than reciprocating steam engines.



This led to a rapid increase in demand for machines outside the UK and many more licensees, most notably Brown Boveri.

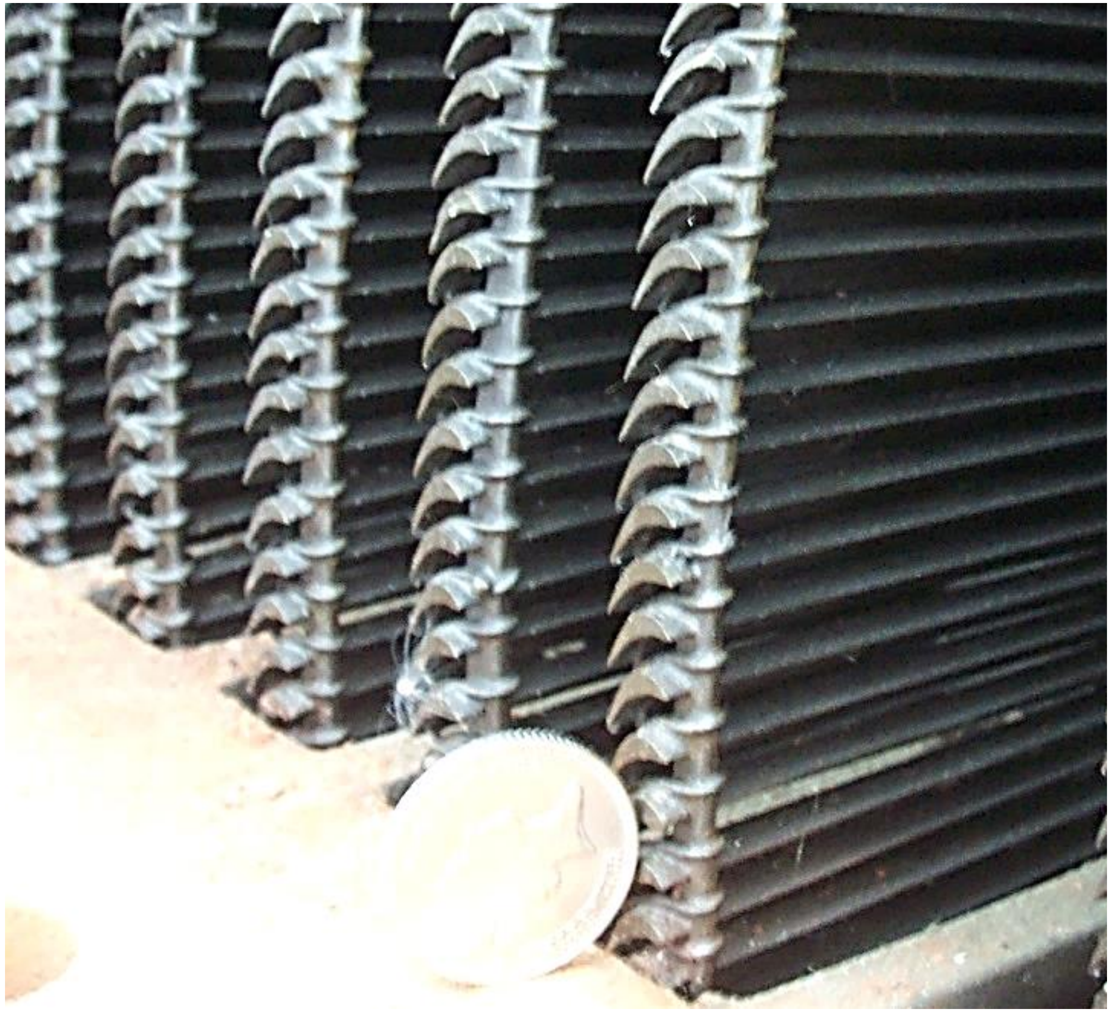
By 1900, standardised blades with true aerofoils were used

This photo shows the 400 series blade which was used widely in land and marine turbines. It achieved an aerofoil efficiency of 90%.

A 10p coin (24 mm diameter) provides scale.

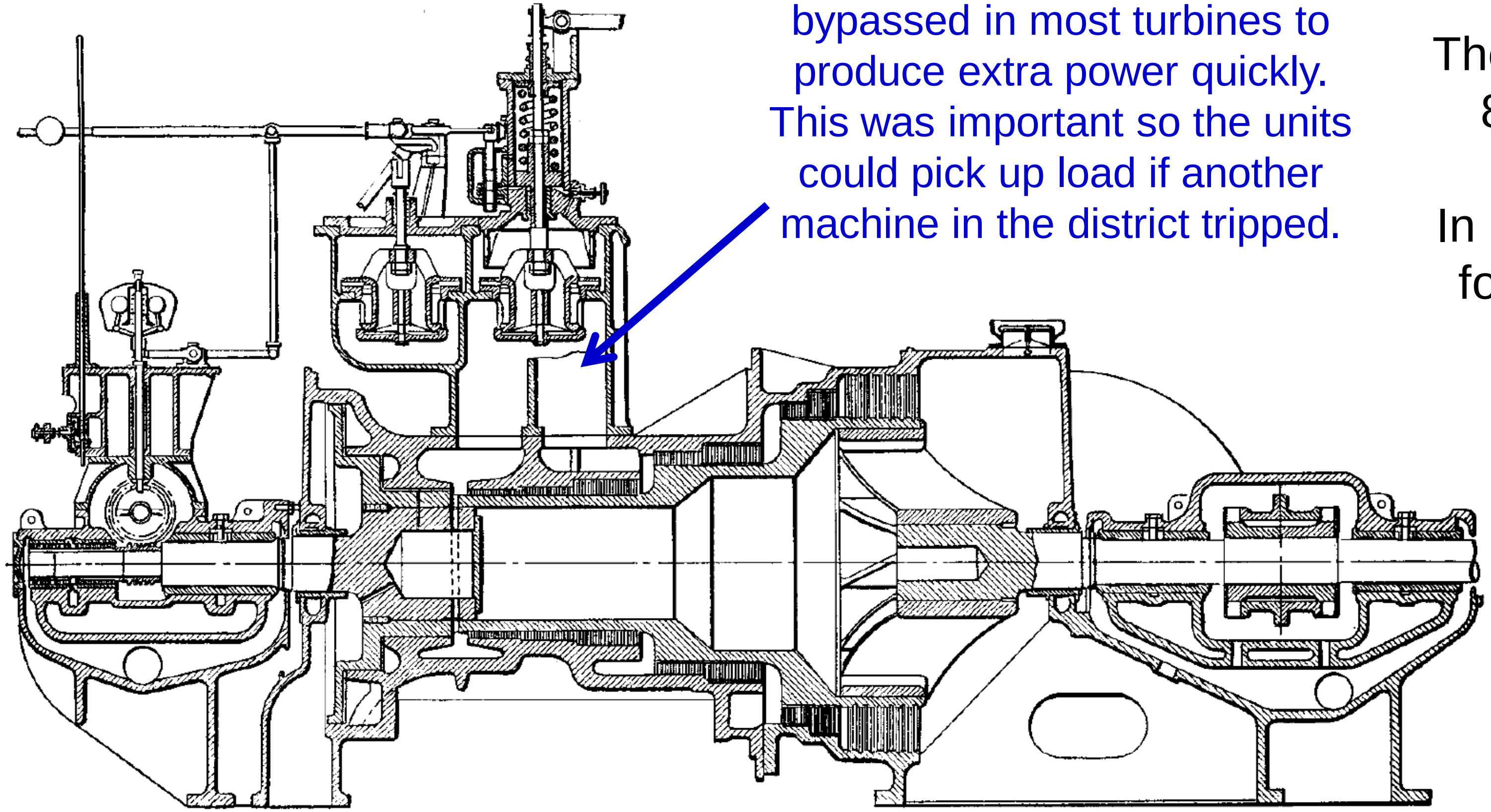
The blades were open-tipped with a radial clearance and they were laced.

Within a few years, the blades employed thin-tipping to minimise damage in case of rubbing.



Between 1900 and 1904, turbine efficiency improved further

The first blade group could be bypassed in most turbines to produce extra power quickly. This was important so the units could pick up load if another machine in the district tripped.



Cross-section through a Carville A turbine.
With a nameplate rating of 3.5 MW at 1,200 revs/min, the units were capable of producing 6 MW.

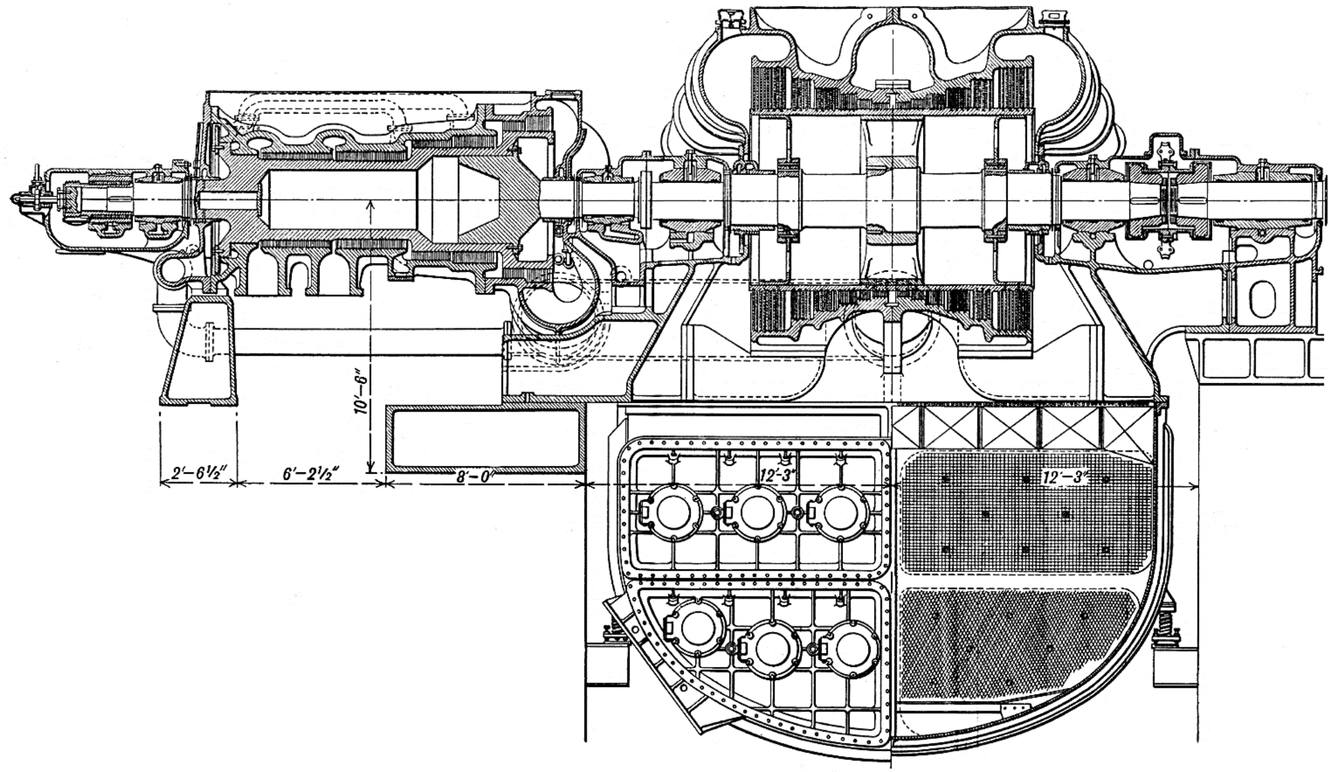
The steam economy of the Elberfeld units was 8.63 kg/kWh which was remarkably good.

In 1903, units at Carville A achieved 7 kg/kWh followed by machines with additional stages which achieved 6 kg/kWh.

By 1904, the reciprocating steam engine was considered obsolete for electricity generation. No further reciprocating steam engines were ordered for central power stations in the UK after this.

The steam turbine was now dominant in terms of power output, efficiency, reliability, cost, upkeep and size.

In 1912, a 25 MW unit was supplied to Fisk Street PS in Chicago



The turbine ran at 750 revs/min to produce 25 Hz electricity.

Samuel Insull was President of the Commonwealth Edison Company in Chicago. He understood the gains which could be made from economy of scale. He installed 5 MW GE turbines at Fisk Street in 1903 followed by 12 MW sets by 1911.

In 1912, he decided to install a Parsons 25 MW unit to gain the efficiency benefits of reaction blades as well. This was the largest and most efficient TG set in the World at that time. The steam consumption was 4.74 kg/kWh and the cycle efficiency 25.7%.

The machine behaved much better than the GE Curtis turbines and became known as 'Old Reliability'.

Engineers preferred large radial clearances because they couldn't predict casing distortion

In 1912, Parsons introduced 'end tightened' blading.

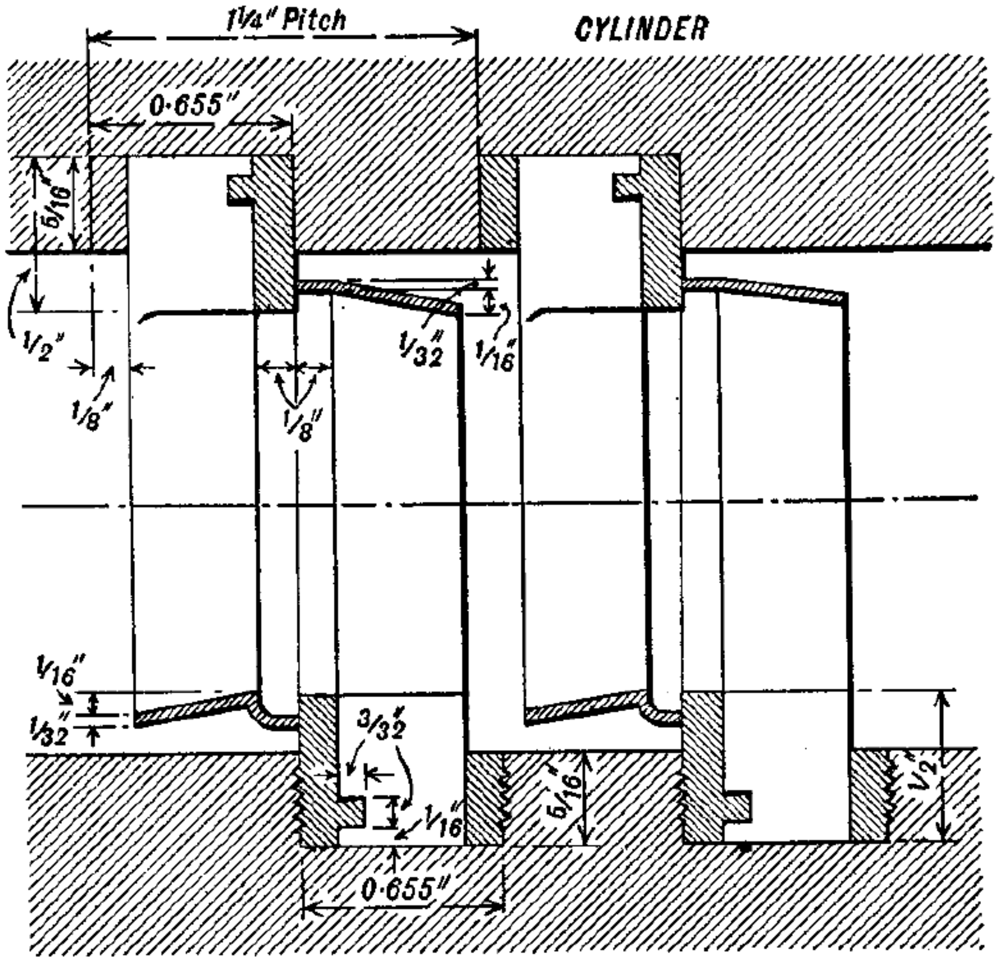
These were reaction stages with only axial sealing fins so that any casing ovality or distortion couldn't affect performance. They were used in the HP turbine.

Each turbine shaft had its own thrust bearing. On the HP shaft, the bearing could be moved in service to open the clearances for start up and large load changes, then tightened again once thermal transients were passed.

This was VERY effective as tight clearances could reduce tip leakage rates considerably.

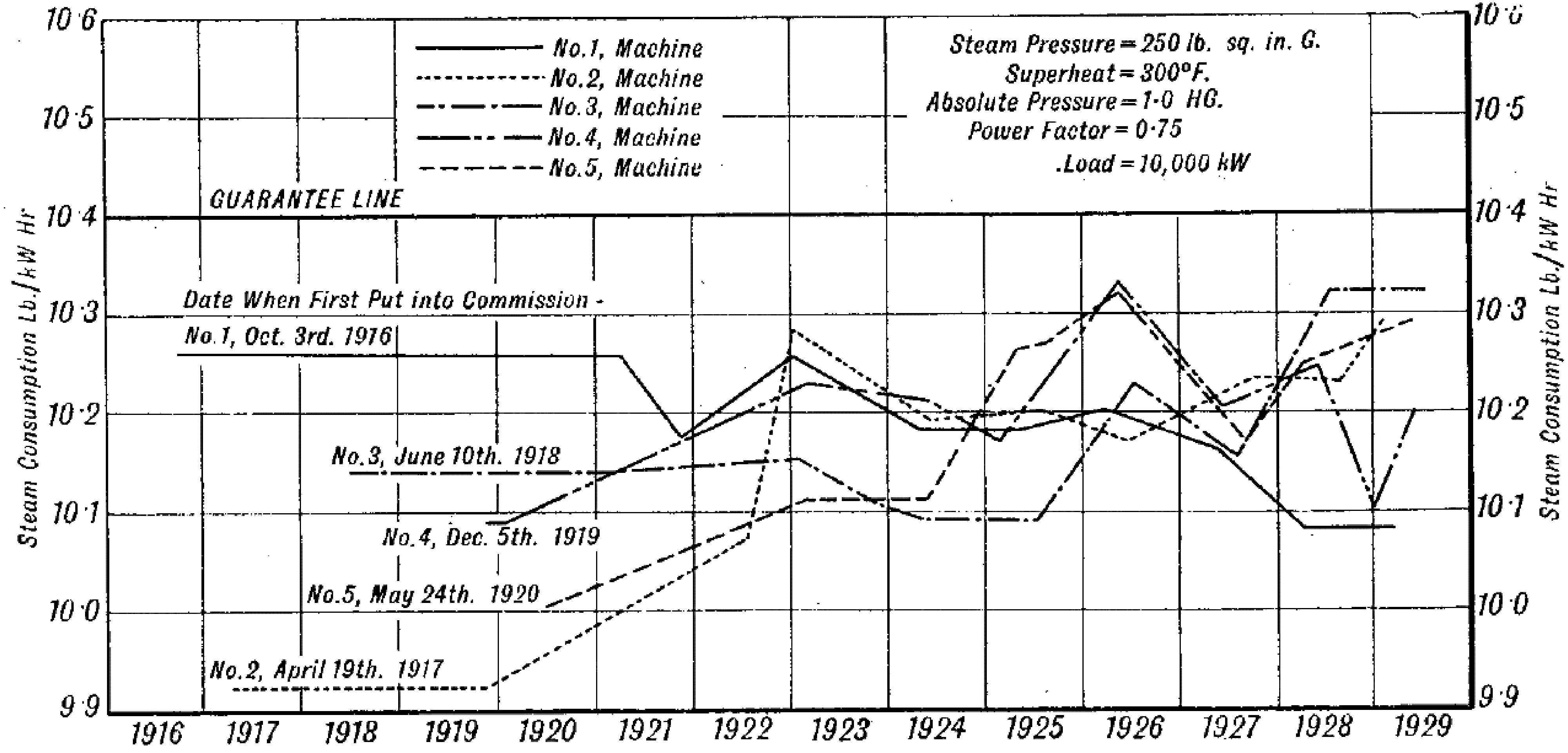
Also, the clearances could be retightened over the life of the plant to restore losses due to wear.

This feature made Parsons turbines very efficient and was used until the 1970s.

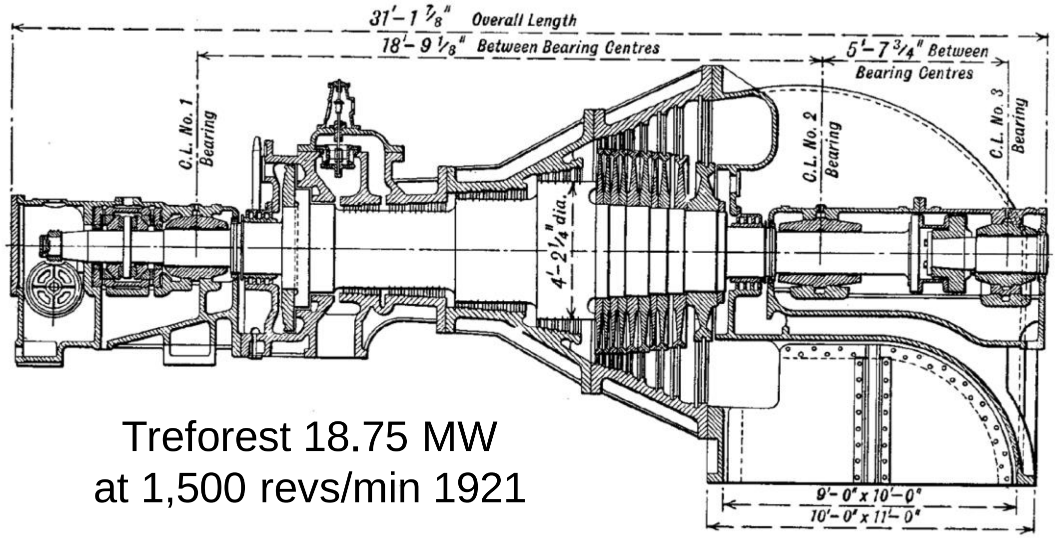


The earliest form of end tightened blading

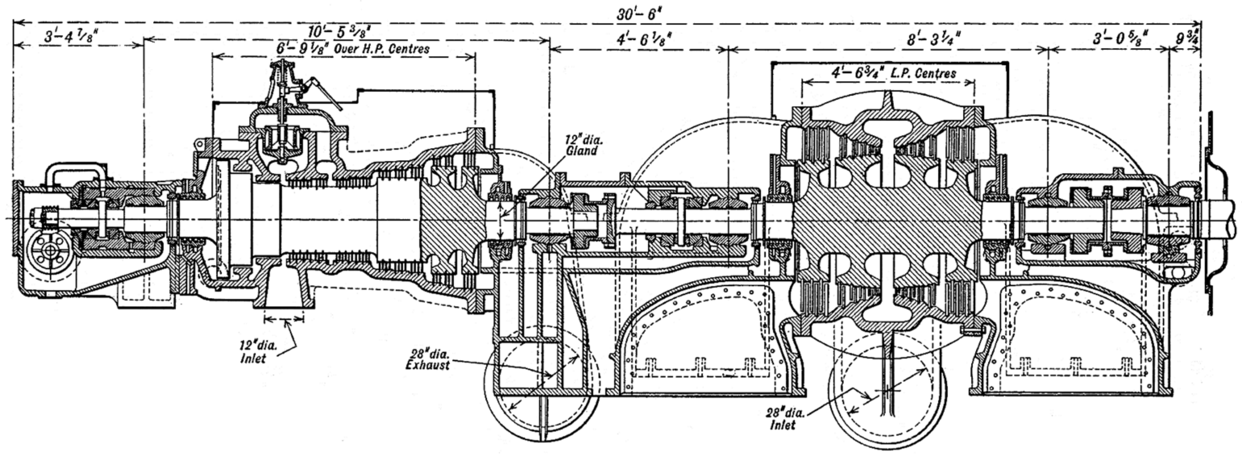
The test results from Carville B showed no loss of performance over the life of the plant due to the benefits of end tightening



Most turbines from 1912 to 1930 were single or twin cylinder designs



Treforest 18.75 MW
at 1,500 revs/min 1921



Mersey Power 12.5 MW at 3,000 revs/min 1919

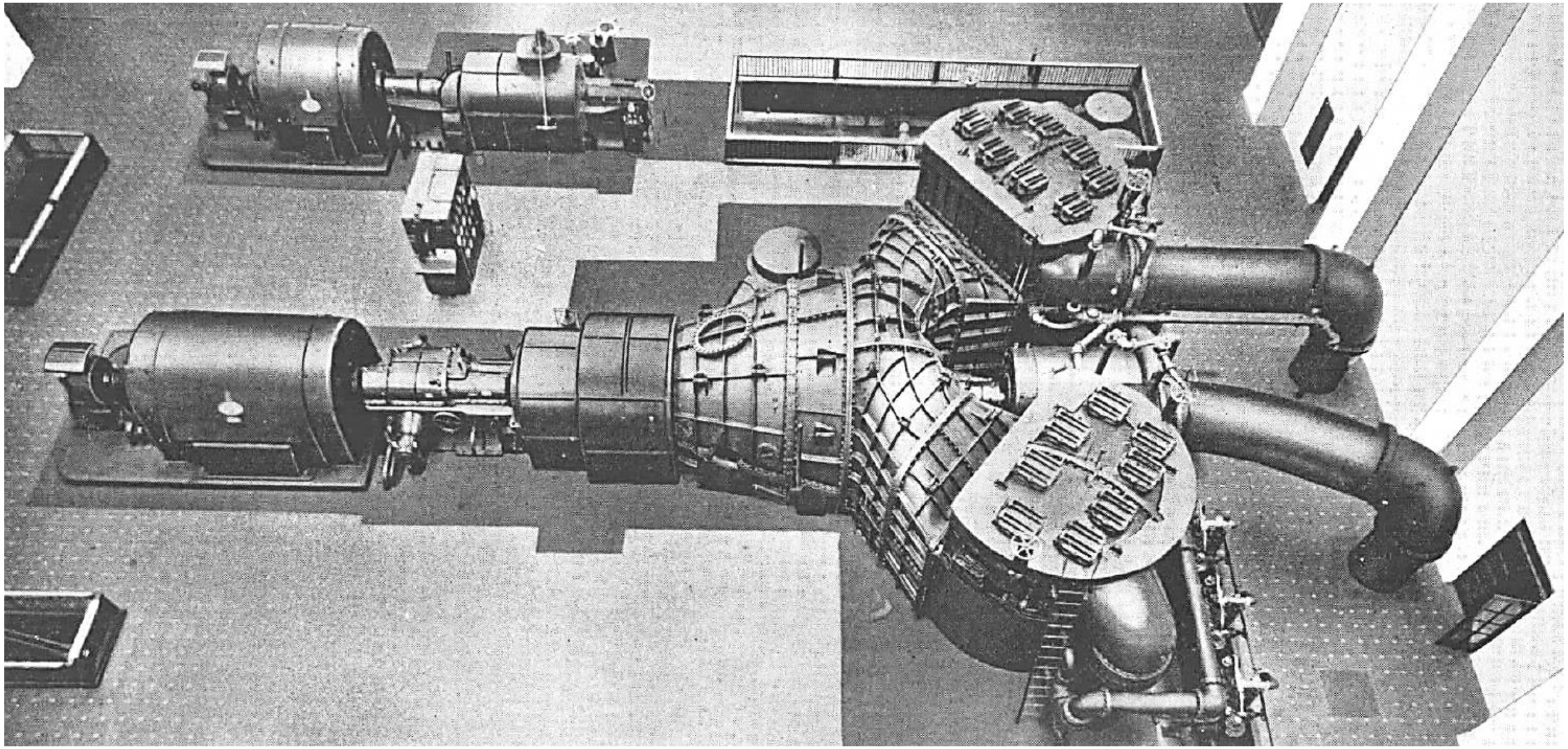
Most turbines in this period were single line, tandem compound units.
High speed (2,400 or 3,000 revs/min) turbines used solid or hollow monobloc shafts.
Half speed (1,200 or 1,500 revs/min) units used disc construction LP rotors to achieve the desired diameters.

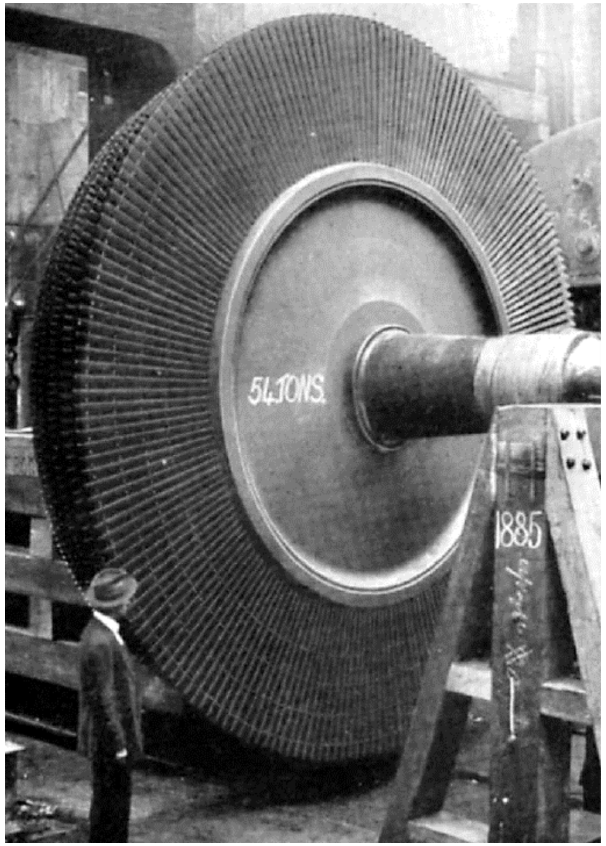
The first ever continuous* use of reheat at a power station was at Carville B designed in 1914.
The first ever use of feedwater heaters on a steam TG set was at Blaydon Burn in 1916.
Blade materials were changed from copper and brass to Monel metal (NiCu) in 1918 then mild steel in 1919.
Parsons first 3,000 revs/min tandem compound turbines were supplied to the Mersey Power Co in 1919.
The first tapered and twisted Parsons blades were used in 1919.

*First temporary use of reheat on a steam turbine was on an Elberfeld unit before shipping from the UK

Parsons first 50 MW unit was ordered in 1922

Samuel Insull and Commonwealth Edison Co ordered a 50 MW 60 Hz TG set for Crawford Avenue PS in Chicago. Steam conditions were 550 lbs/in^2 750^{o}F with reheat to 700^{o}F. It achieved a heat rate of 10,590 kJ/kWh corresponding with a cycle efficiency of 34.0%. The last stage blades were 40” long with a tip diameter of 200”.

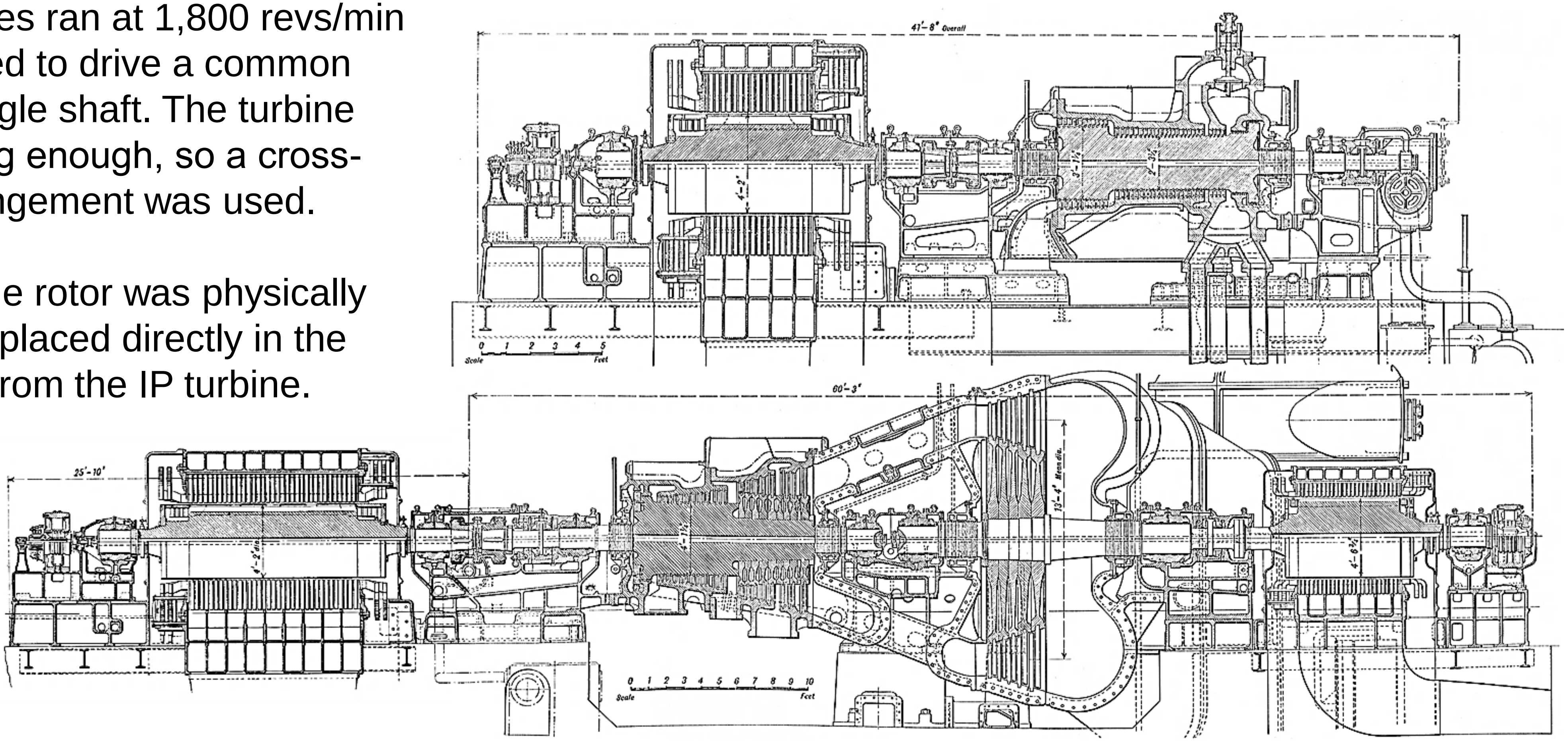




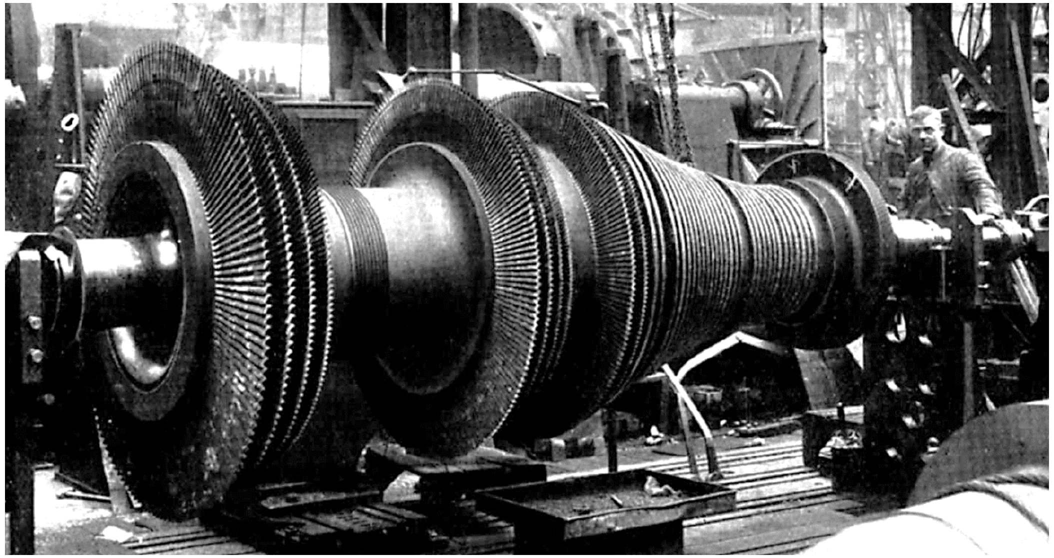
The last 5 stages were on a separate rotor and ran at 720 revs/min

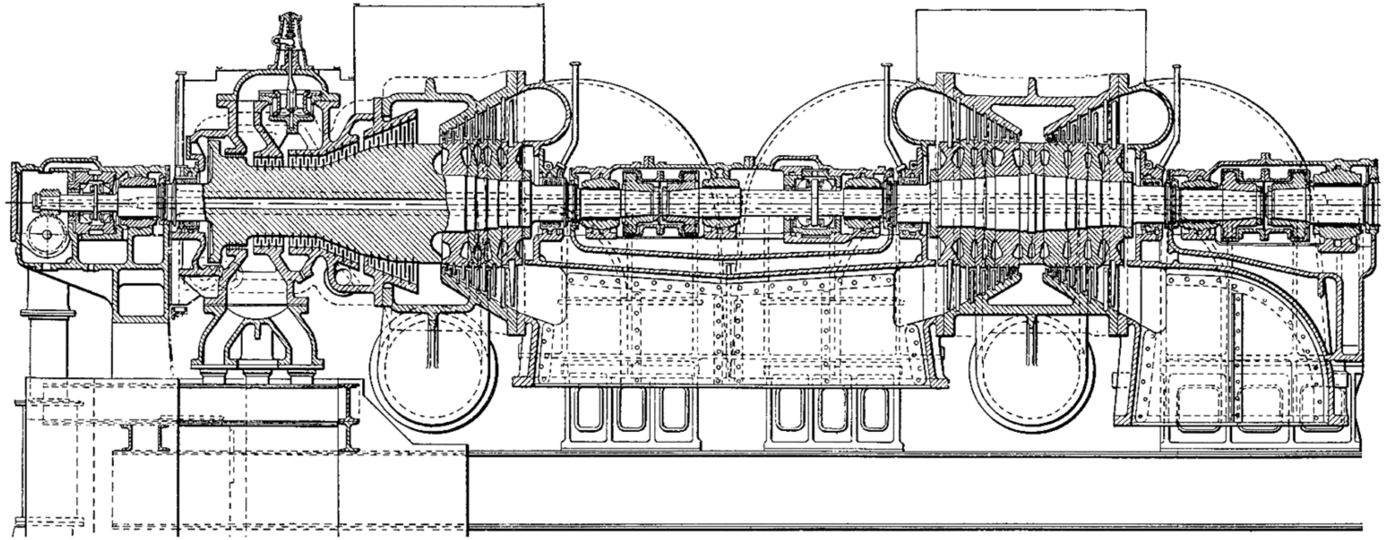
The HP and IP turbines ran at 1,800 revs/min and were supposed to drive a common generator on a single shaft. The turbine building wasn't long enough, so a cross-compound arrangement was used.

The short LP turbine rotor was physically separate but was placed directly in the discharge flow from the IP turbine.



In 1926, additional LP flows were added to rotors

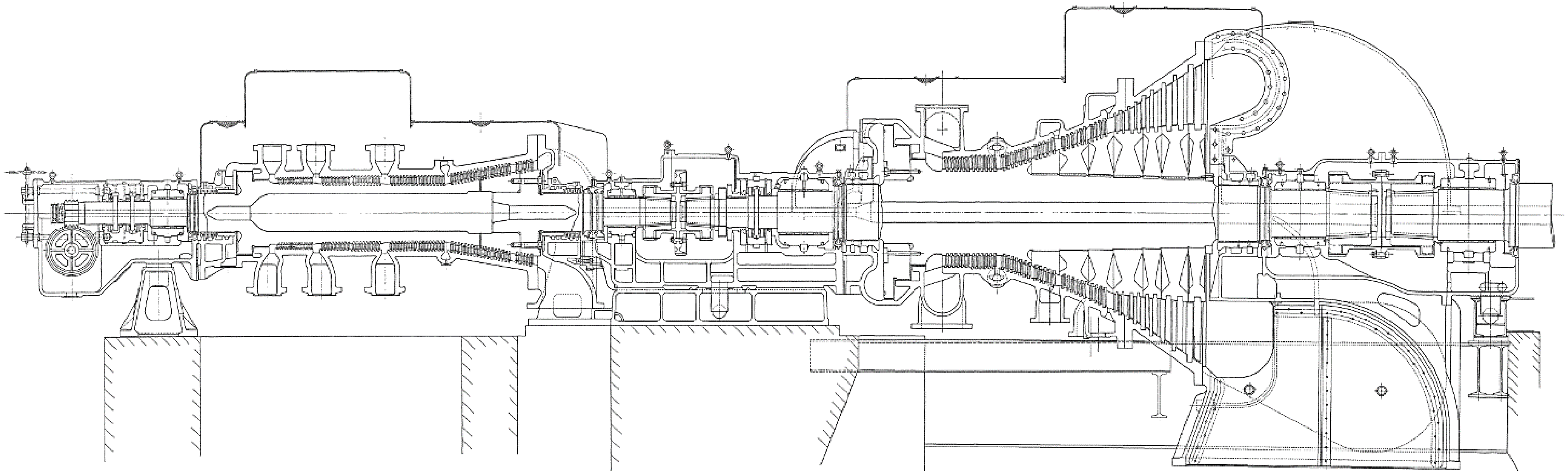

Parsons first duplex turbine 12 MW Congella PS


Parsons first three exhaust turbine 25 MW Brimsdown PS

Single cylinder turbines were much cheaper to make than twin cylinder designs, so two LP flows were installed on one shaft to increase the unit size which could be built. The first unit was rated at only 12 MW but this arrangement was used many times up to 30 MW at both 3,000 and 3,600 revs/min with the last units manufactured in 1951. The design had limited potential because higher conditions required more stages and it couldn't incorporate reheat.

Similarly, two cylinders were cheaper to build than three, so Parsons provided a third exhaust flow in some machines starting with a 25 MW unit for Brimsdown in 1926. At high pressures (above 1500 lbs/in^2) in the 1950s, an HP turbine was added to make an effective reheat machine. Units up to 150 MW at 3,600 revs/min were built up to 1973.

The last turbines to be supervised by Sir Charles Parsons were the 50 MW 1,500 revs/min reheat turbines for Dunston B in 1930



In 1930, Parsons built 3,000 revs/min turbines up to 30 MW and 1,500 revs/min units up to 50 MW. Steam conditions were 600 lbs/in^2 800^{o}F with reheat to 800^{o}F. The Dunston B design included three alternative inlets for good part load performance. The units had four stages of feedheating. The heat rate was 9790.4 kJ/kWh with a cycle efficiency of 36.8%. Units of this type were built until 1944; high speed 50 MW units were introduced in 1937. The LP turbine rotor was a useful concept which was used until the 1970s for single cylinder turbines since it allowed high temperature and low temperature steels to be used in combination.

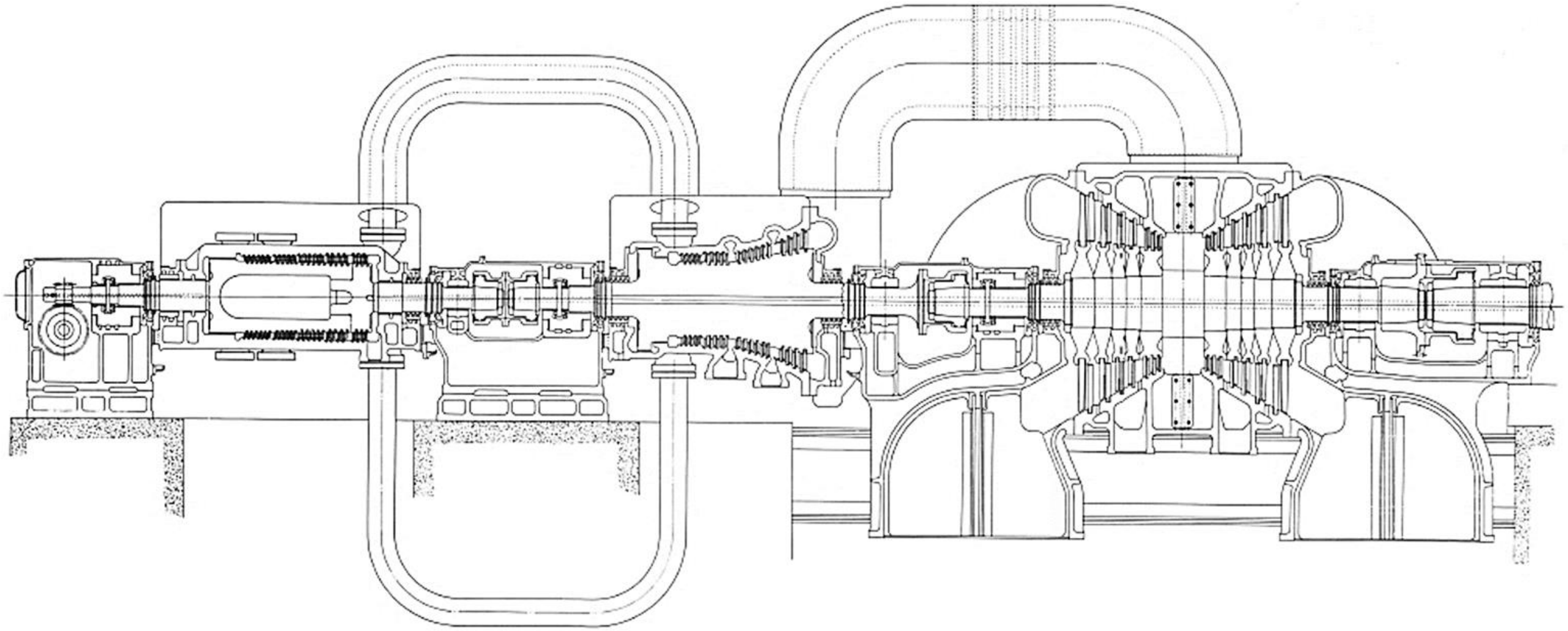
Sir Charles passed away in 1931.

Hollow last stage blades were introduced on Dunston B and were used for all new last stage designs until 1951

The blades were made by placing a layer of mild steel between two plates of stainless iron. The composite structure was hot rolled to fuse the outer plates and form the aerofoil profile. The mild steel core was then dissolved using boiling 50% nitric acid.

The next fundamental change in design came in 1946 with 60 MW sets

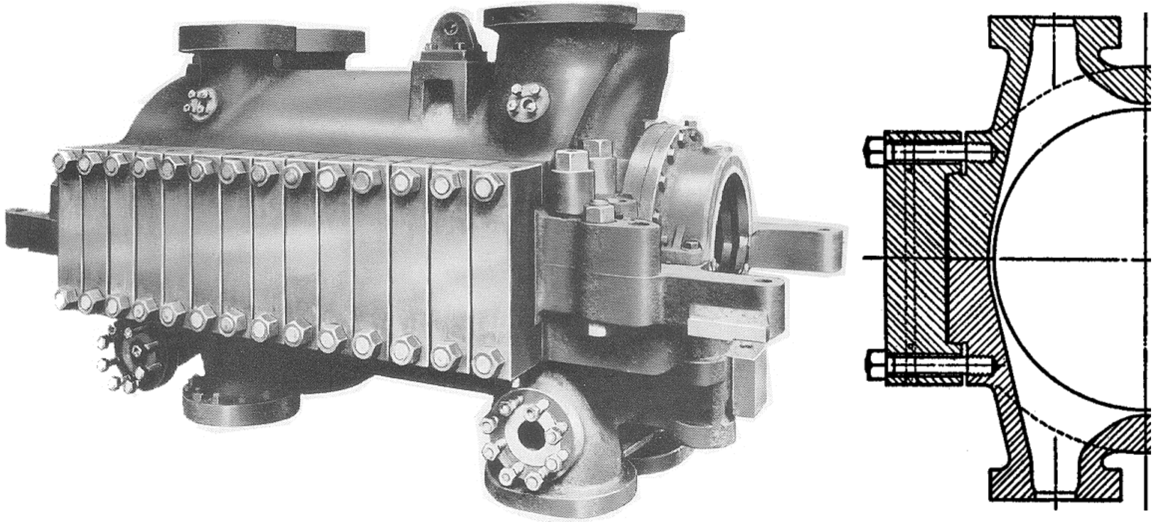
Parsons first 60 MW units were ordered in 1946 for North Tees C.
Steam conditions increased to 900 lbs/in^2 900^{o}F.



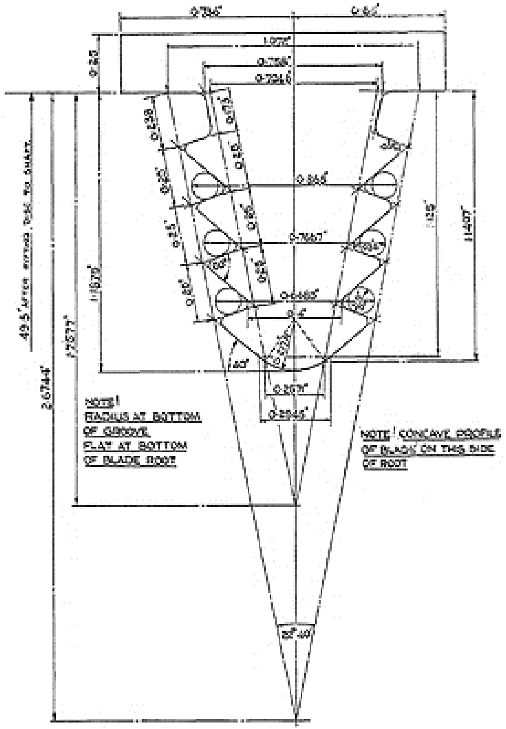
High temperature rotor & casing materials changed from carbon steel to ½ Mo steel, blades used 12 CrMo.
Three cylinders allowed an increased stage count to be used together with end tightening and a new casing type.
The 60 MW fleet were the first 'high temperature' machines and demonstrated the features which would be needed for reliable fast starting and two shifting.

Several new technologies were introduced

High temperature blades were made from forged bar with integral roots and shrouds, brazed into segments

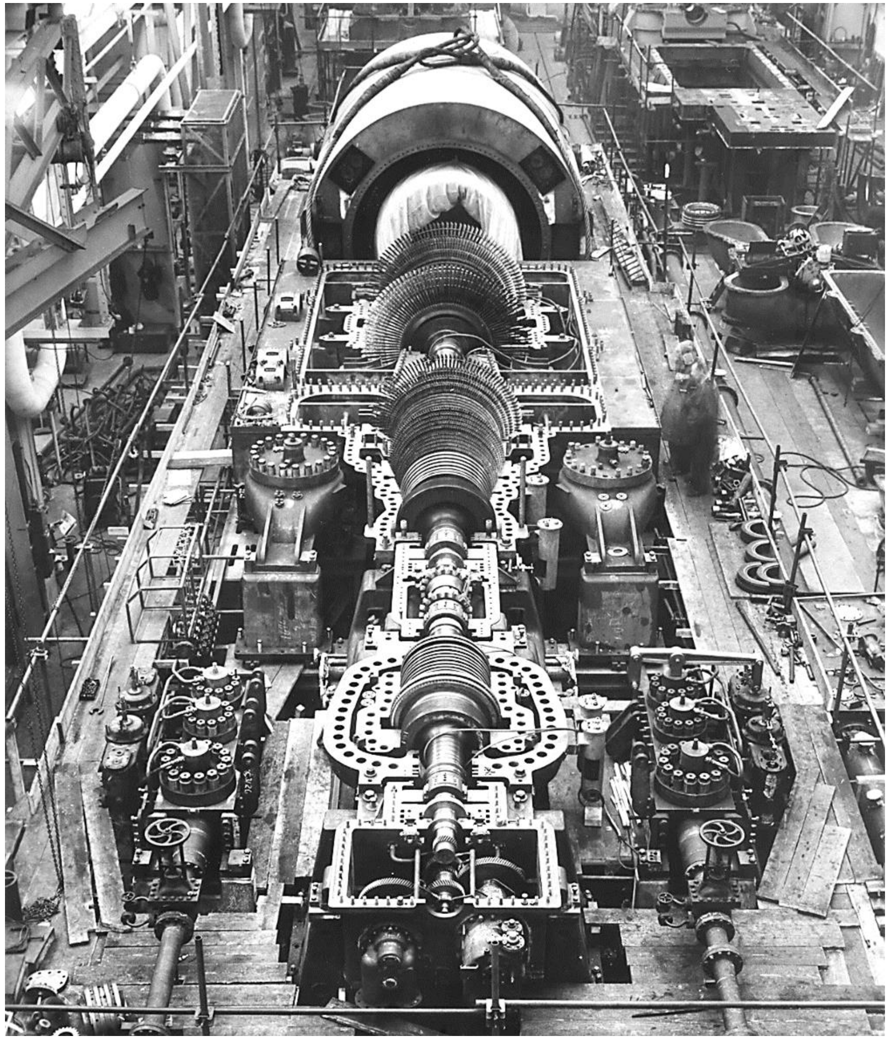


HP turbine casings used clamps which were capable of carrying 50% higher pressure than conventional flanged joints using bolts only one third the normal size.

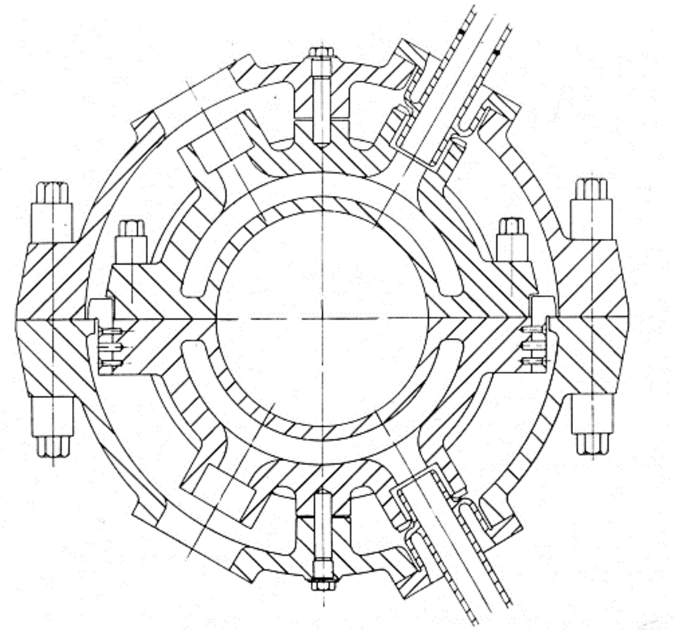


After 1951, all new last stage LP blades were solid and used axial fir tree roots which came from joint working on gas turbines with Sir Frank Whittle’s company Power Jets.

Further major steps occurred on the 100 / 120 / 200 MW fleet



Ferrybridge B 100 MW turbine

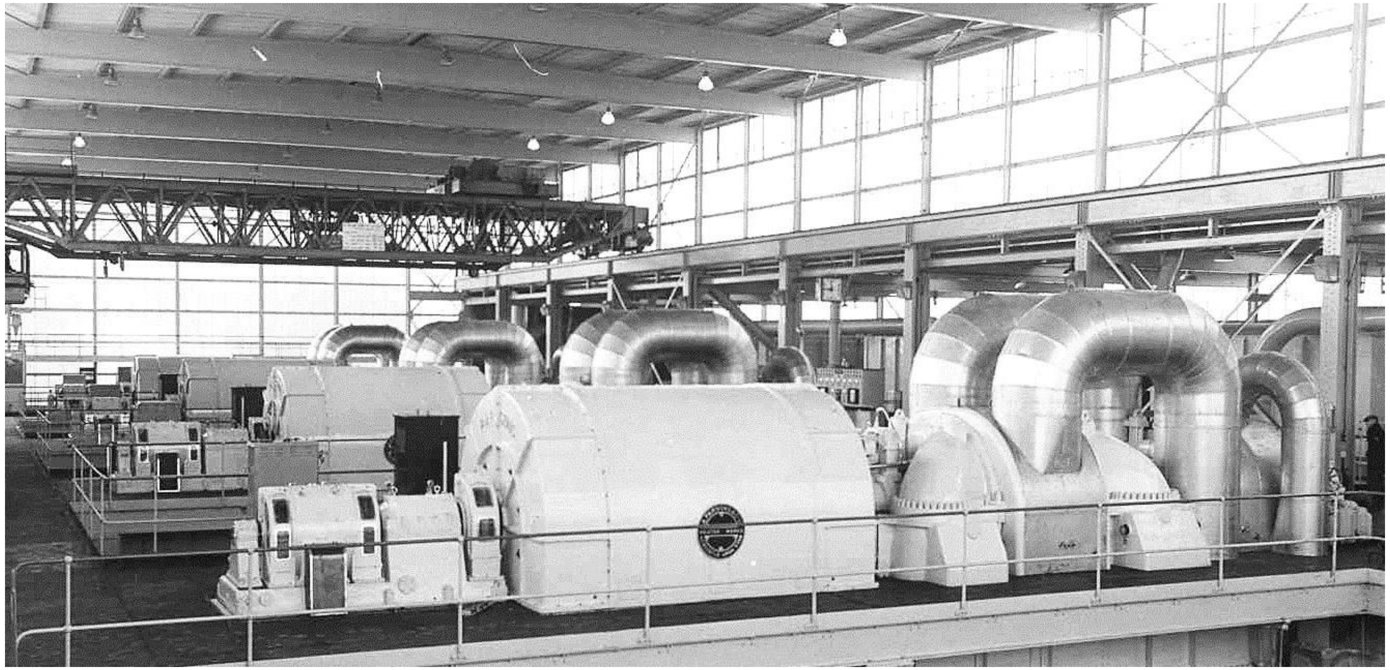


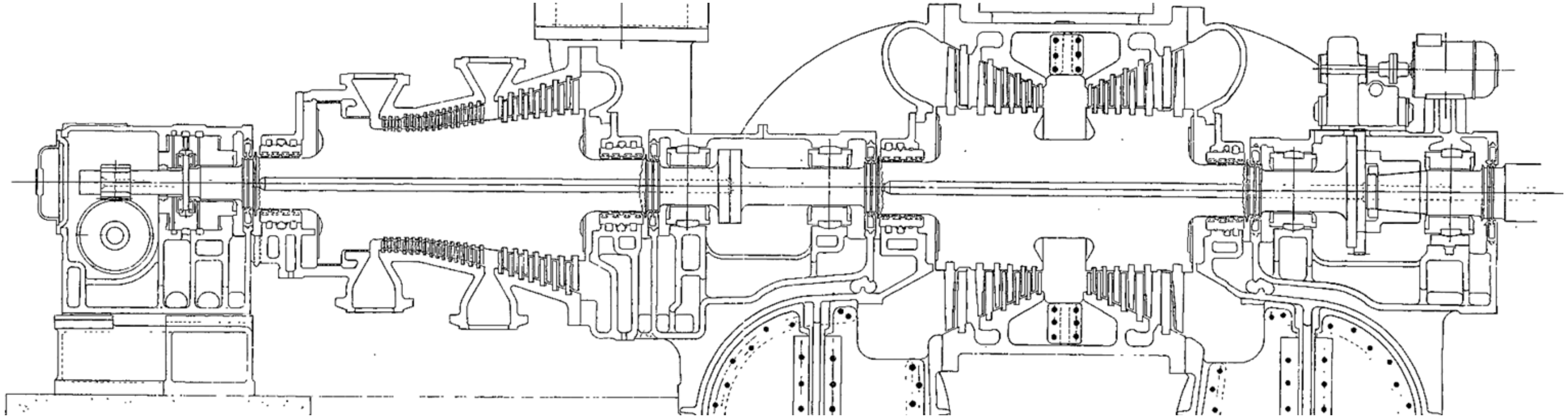
Cross-section through 100 MW HP inlets

HP turbine Curtis stage

Steam pressures increased to 1500 lbs/in^2 by 1951 and 2350 lbs/in^2 by 1956 with temperatures up to 1050ºF. Twin shell HP turbine casings were introduced to handle this and provide the best arrangement for fast starting. Curtis stages were used to drop the pressure so that casing joints could be designed with confidence and to reduce the temperature acting on the new 1 CrMoV steels. Separate nozzle chests and IP rotor cooling were employed on the 200 MW units.

The World's first nuclear power station Calder Hall used Parsons plant





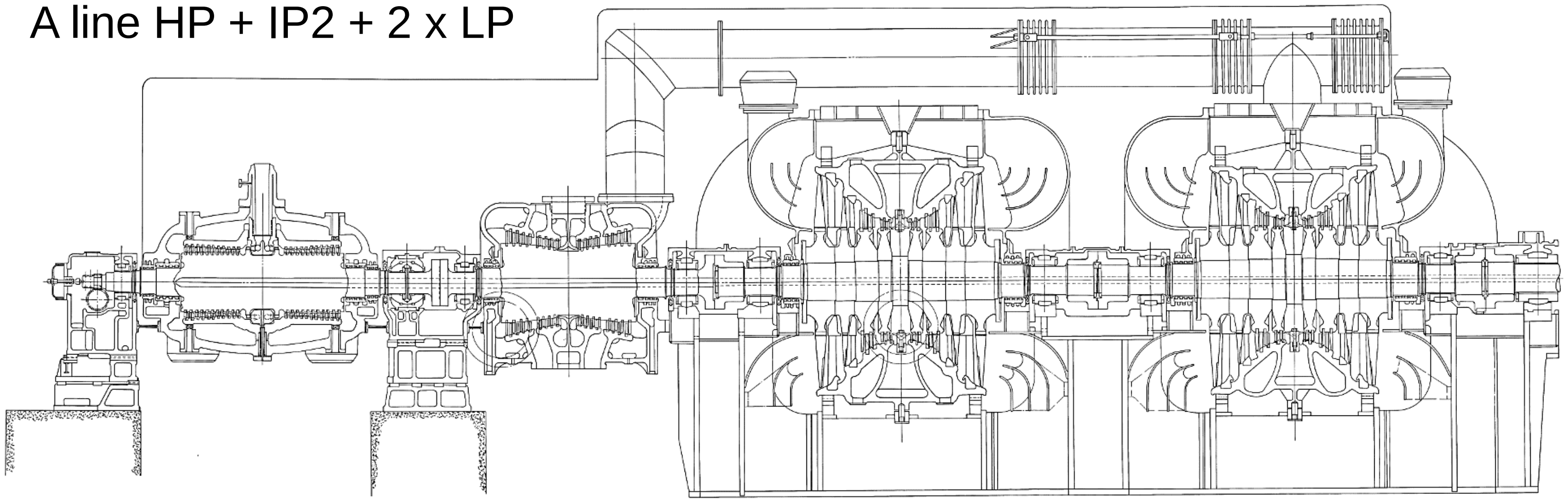
In 1946, Parsons starting working with the UK Atomic Energy Research Establishment. This led to orders for 8 x 23 MW TG sets and other plant for Calder Hall PS, which became operational in 1956.

Subsequently, orders were won for further units of 23, 52, 70 and 142.5 MW for other Magnox power stations.

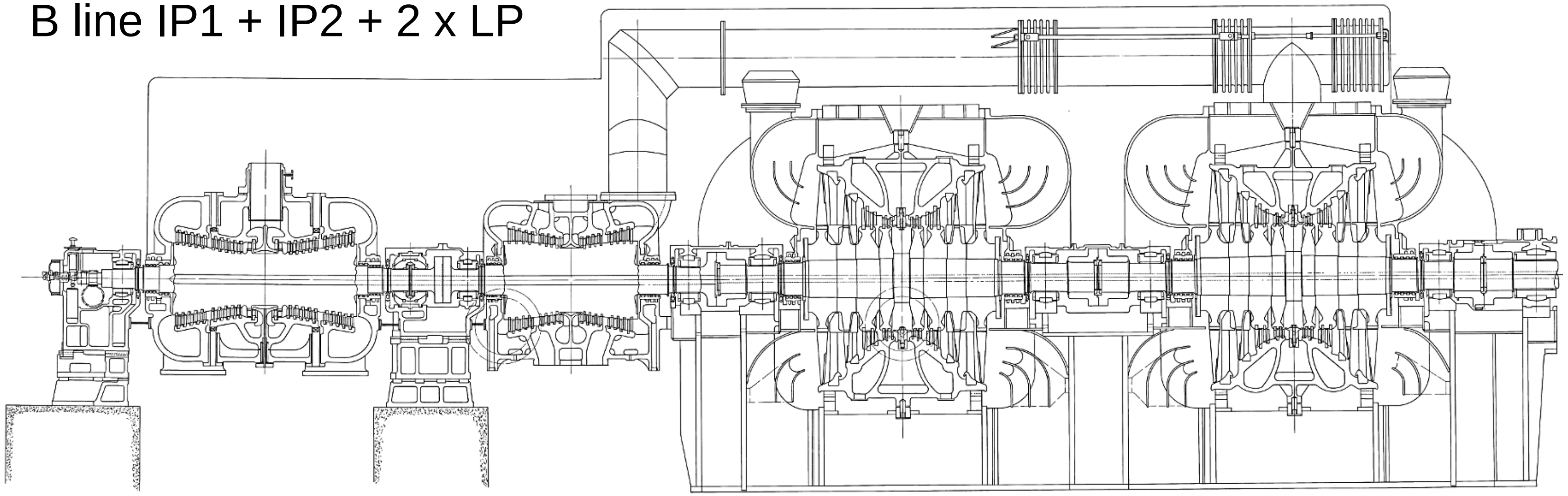
Steam conditions were moderate 200 lbs/in^2 590^{o}F at first rising to 535 lbs/in^2 736^{o}F by 1960.

Between 1956 & 1958, cross-compounding was used to raise power output to 550 MW

A line HP + IP2 + 2 x LP



B line IP1 + IP2 + 2 x LP



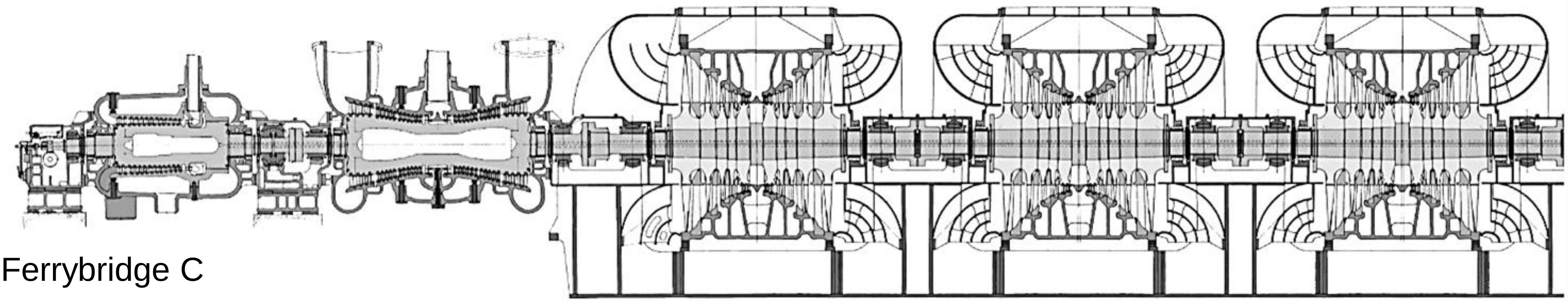
The industry was prepared to order units of 200 & 300 MW before the first reheat 100 MW sets were running. Then there was a giant leap to 550 MW.

In 1958, generators were limited to 275 MW so two shafts were needed. Last stage LP blades were 30" long but eight exhaust flows were needed for good economy.

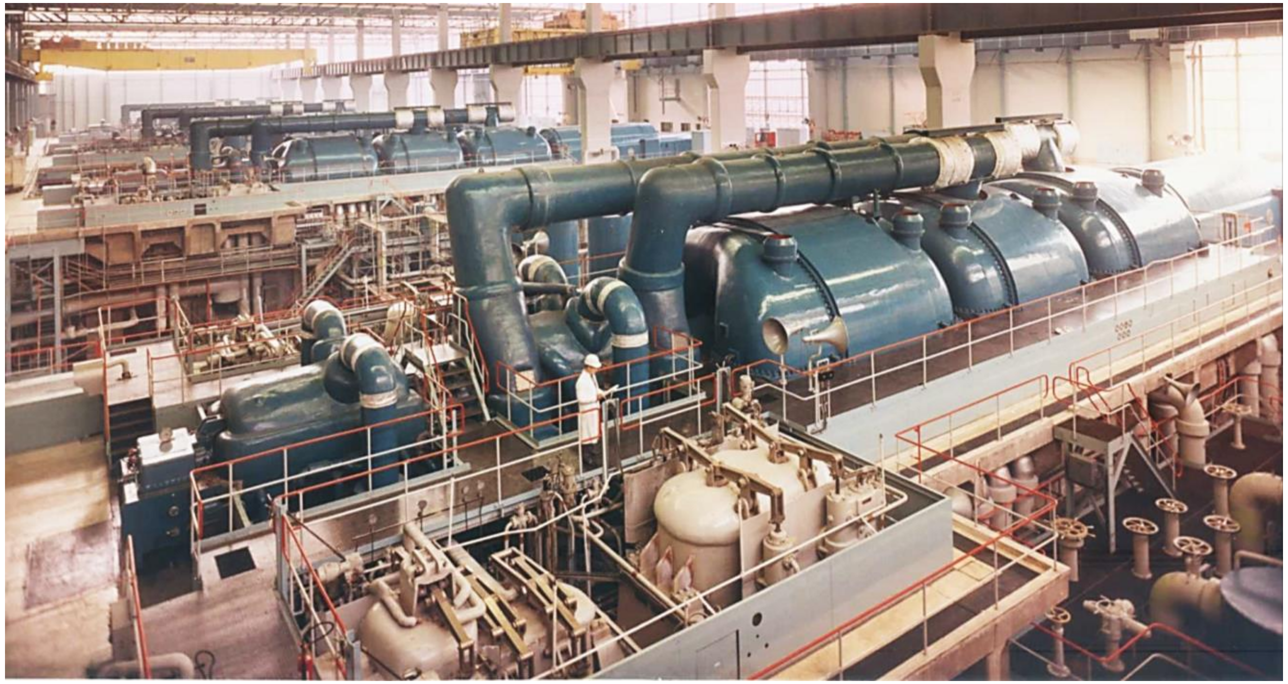
Limitations on rotor diameter required eight cylinders to accommodate the stage count.

Thorpe Marsh Unit 1 was the most complex turbine Parsons ever built but it was also by far the largest TG set in the World at that time.

In 1961, single line 500 MW units were designed for Ferrybridge C



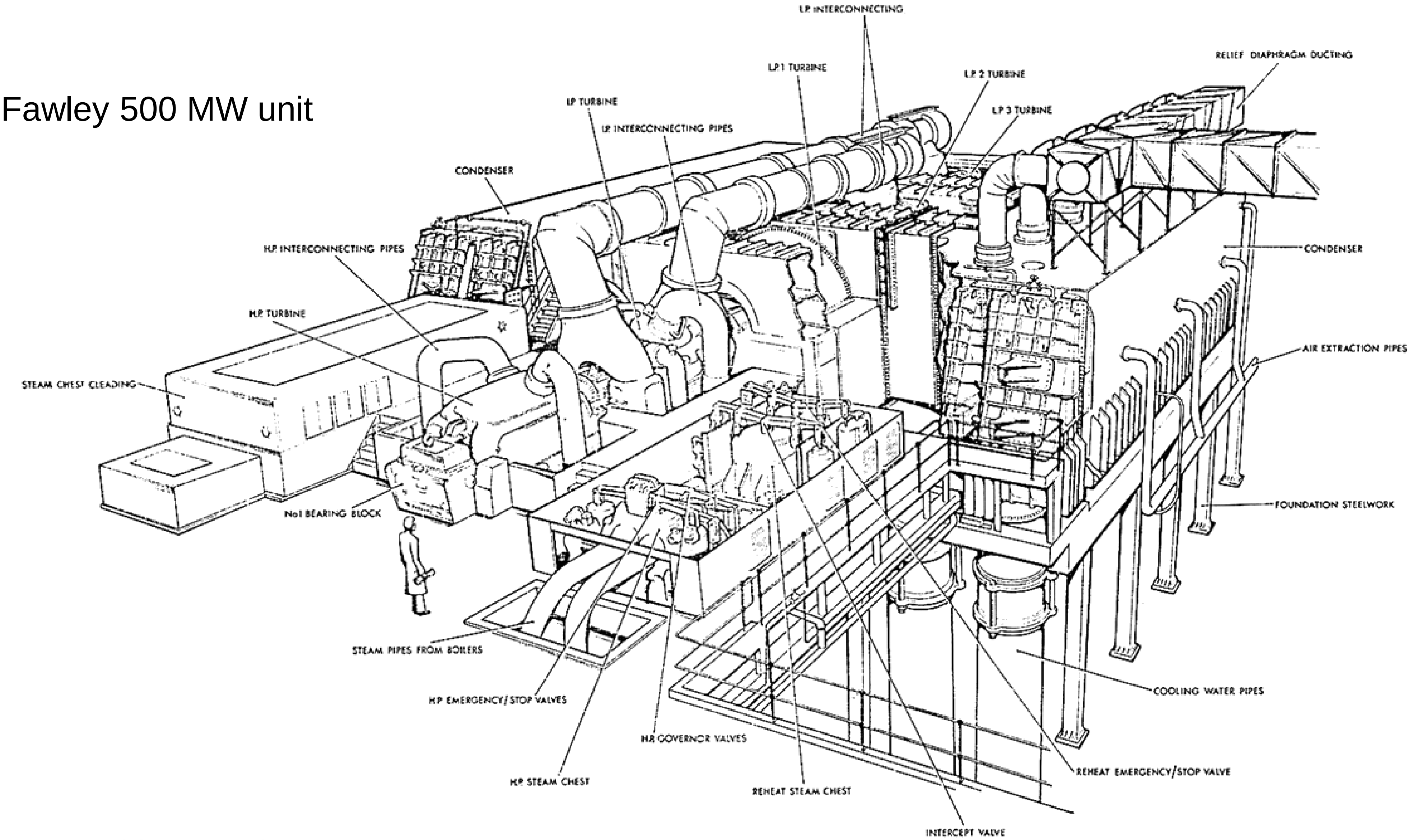
Ferrybridge C



By this time, there was confidence to build 500 MW single line turbines. Four exhaust flows could have been used, but six flows were chosen to achieve low leaving losses. HP & IP rotors and casings were made from 1 CrMoV with 12 CrMoV high temperature blades. Inefficient Curtis stages were no longer needed. End tightening had been discontinued on machines of 120 MW and above since claw couplings could not be used. Thick section rotors required a change from steam quenching to oil quenching which stretched forgemasters capabilities. Parsons 500 MW units routinely held the highest efficiency ratings of any CEGB machine.

In 1963, the UK industry adopted pannier condensers to achieve lower exhaust losses. This trend continued until 1973.

Fawley 500 MW unit

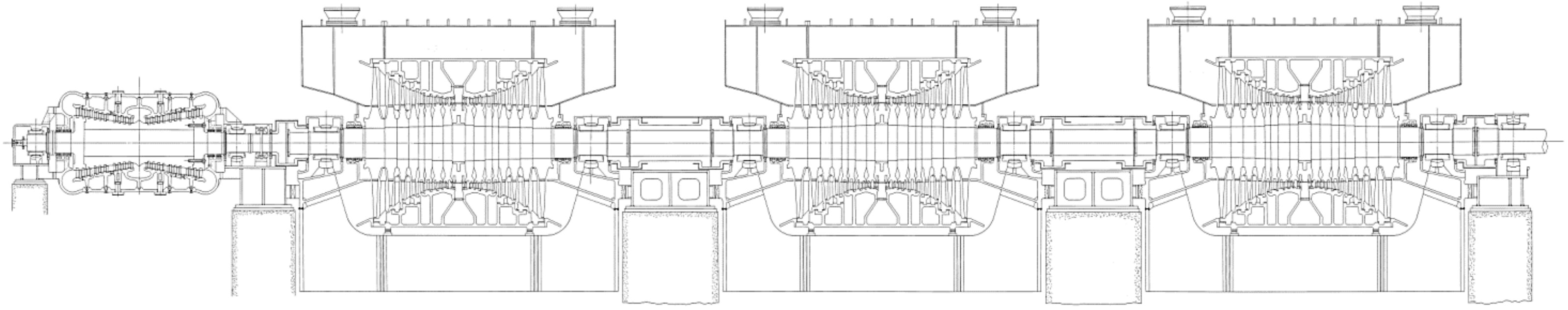


In 1965, Parsons designed turbines for CANDU nuclear operation

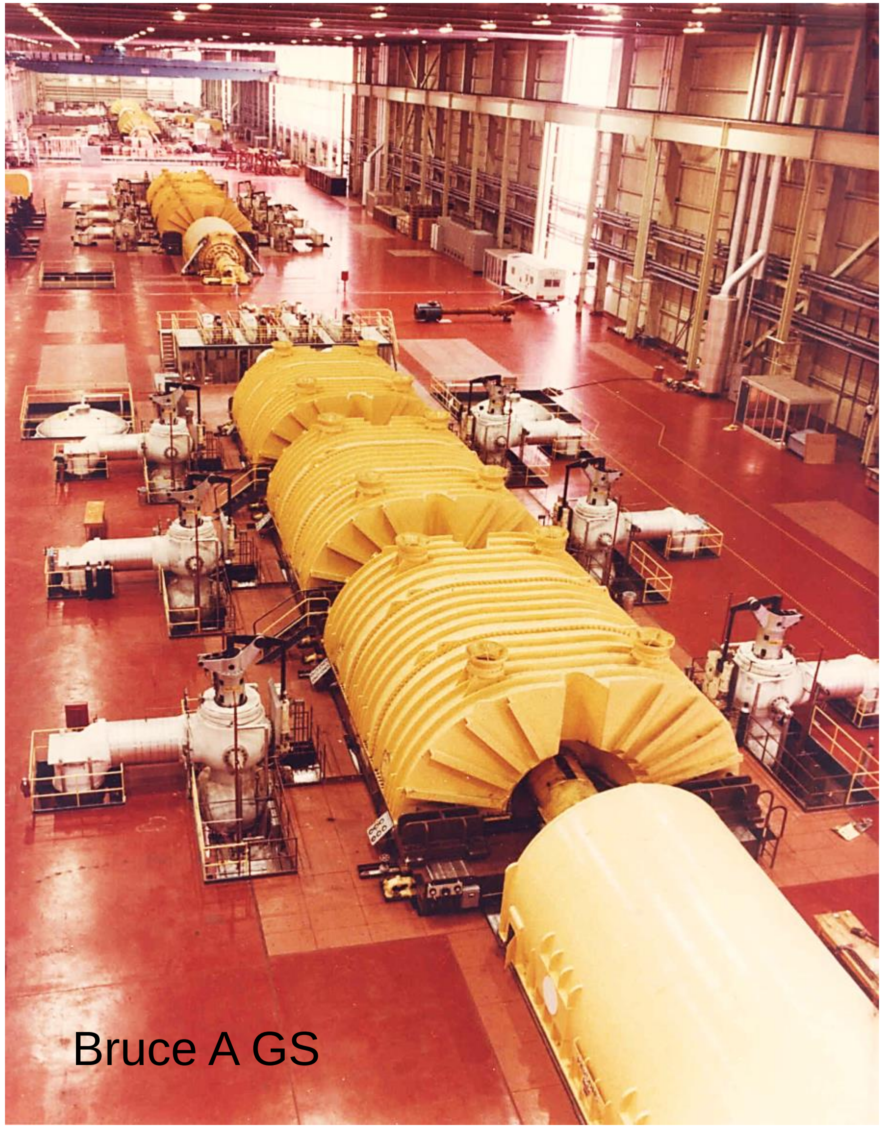
In 1965, Parsons won the order for 4 x 540 MW turbines for Pickering A nuclear power station in Ontario Canada, followed later by a further 4 units for Pickering B. In 1969, an order for 4 x 800 MW sets for Bruce A GS was received. The Bruce machines were the largest TGs Parsons would build. Further units of 680 MW were supplied for other CANDU power stations.

The steam was saturated at the HP turbine inlet and so high wetness levels existed in the bladepath. Special arrangements for water extraction were developed at Heaton Works as well as novel cyclone separators to take water out of the HP turbine exhaust steam. These were very effective.

The units are still in operation today and for many years held the record for highest availability of any nuclear steam turbine in the World.



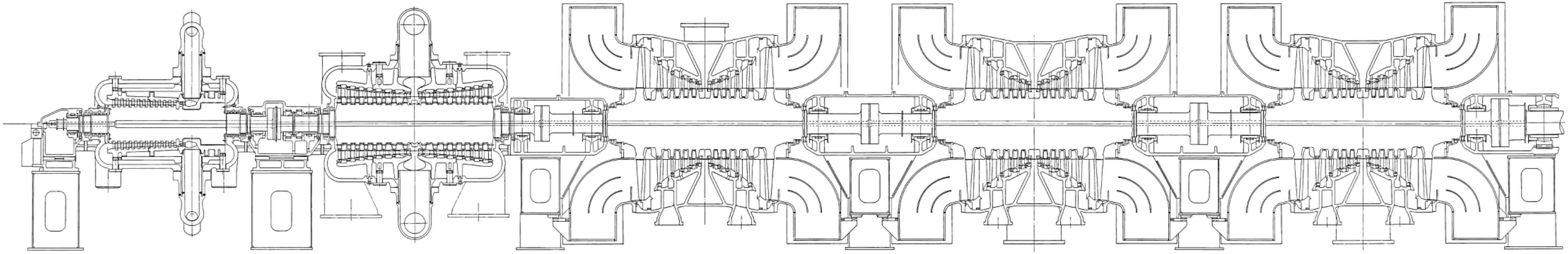
The turbines used reaction blading with open tips for water removal



Bruce A GS

In 1965, Parsons took over the TG business of GEC

Drax 660 MW unit

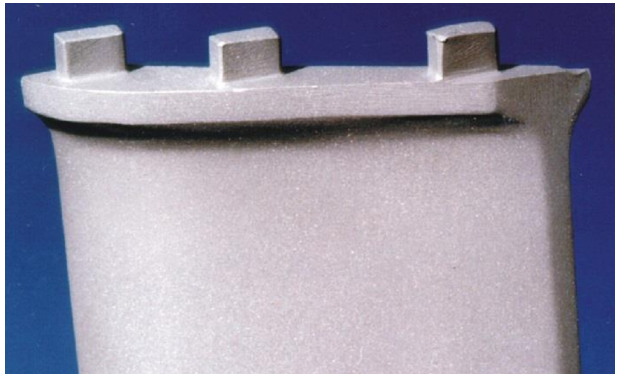


The CEGB encouraged the UK industry to reduce from six main manufacturers to two.
Parsons (a reaction turbine manufacturer) took over the turbine-generator business of GEC
(an impulse turbine builder). Subsequent machines were a hybrid of the two technologies starting in 1967.

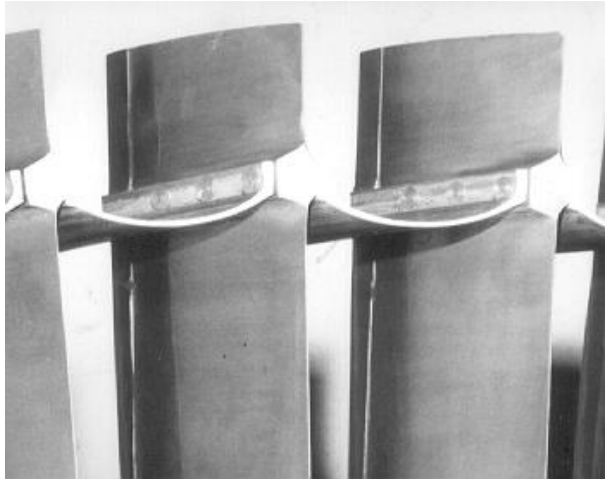
The first machines to be designed were Drax 660 MW coal-fired and Hunterston B 660 MW AGR nuclear units.
Based upon the available data, it was decided to use a reaction HP with impulse IP and LP turbines.

At one point, Drax might have been specified as a supercritical station but this did not go ahead. Parsons decided to proceed with a barrel construction HP turbine anyway so that they had a design for supercritical duty in service. Key design features which were effective were: monobloc rotors, fully double cased IP turbines, elimination of lacing wires in the bladepath and pinned fork root fixings for all IP and LP blades except the last stage.

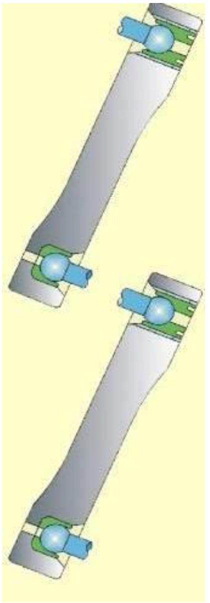
By this time, any operating issues were related to detail features rather than any aspect of fundamental construction



Three sharp edged tenons on the LP L-1 blades had to be changed to two obround tenons



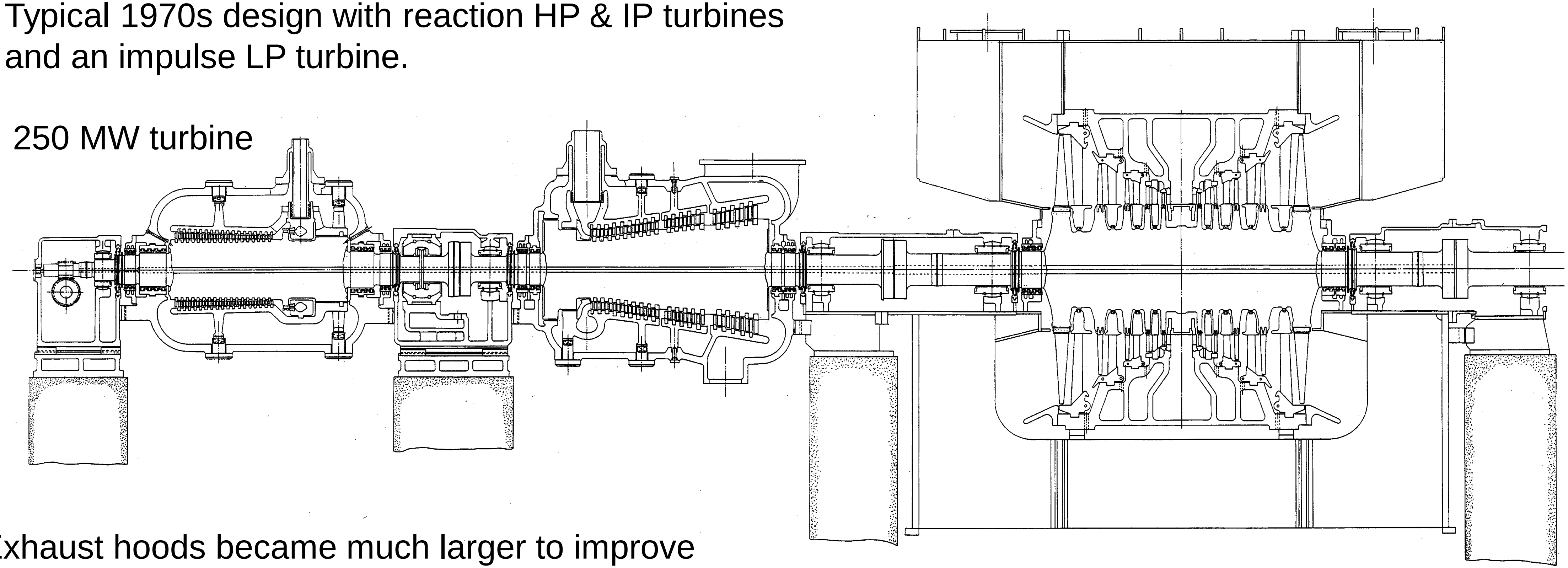
The inverted arch coverbands on the LP L-0 blades did not allow blades to untwist during the run to speed. Articulating tip struts were adopted in the 1980s. Brazed erosion shields were superseded by laser hardening in the 1990s.



Once large GEC-type turbines became operational, it was seen that reaction designs would perform better

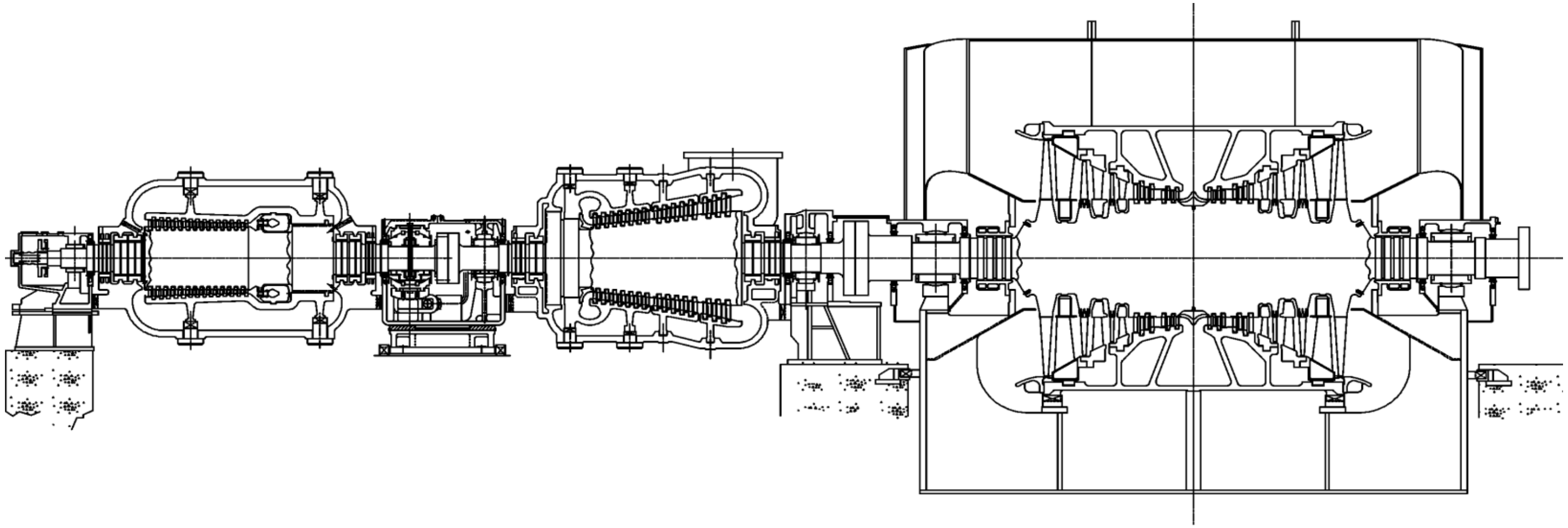
Typical 1970s design with reaction HP & IP turbines and an impulse LP turbine.

250 MW turbine



Exhaust hoods became much larger to improve performance. This led to chilling of the LP inner casing and so thermal shields were fitted.

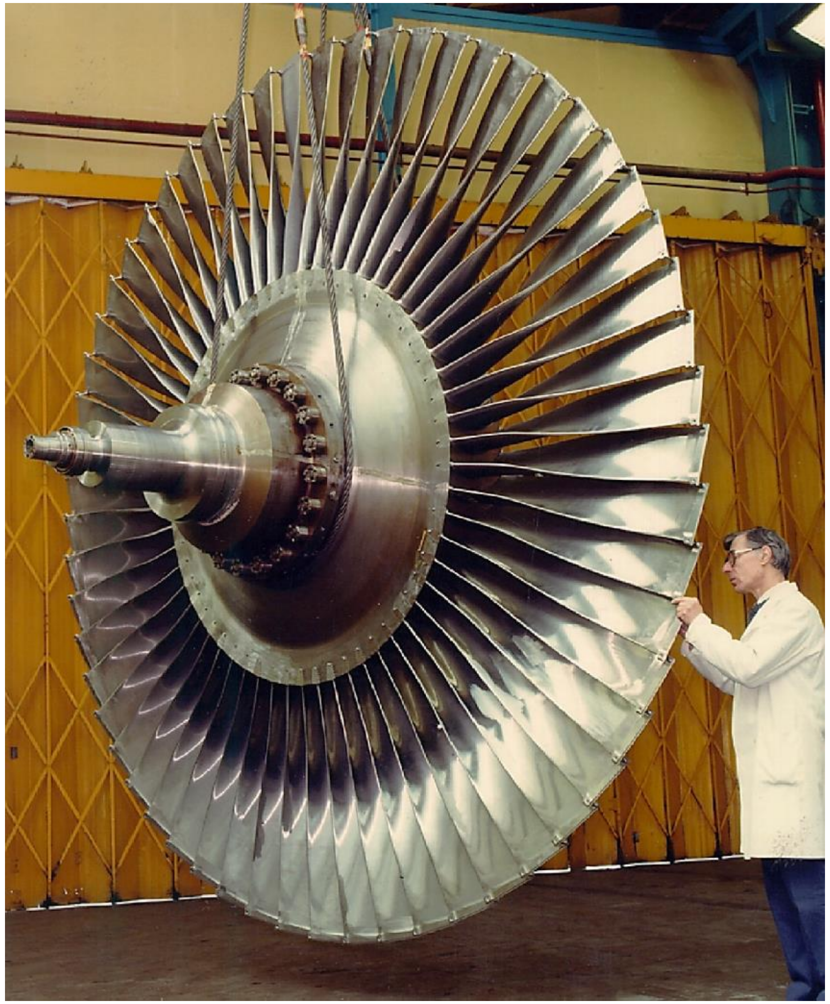
After 1980, all turbine cylinders used reaction blading



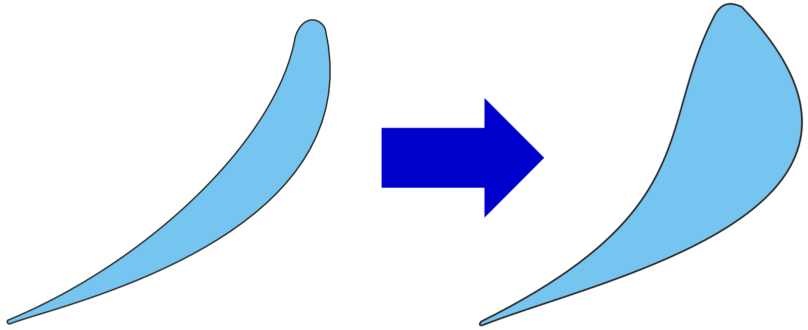
Pulau Seraya I power station in Singapore 3 x 250 MW units. The first Parsons turbines to be designed using CFD software.

Reaction LP turbines were used in the 1980s and 90s.
In addition, computational fluid dynamics (CFD) tools became available. The immediate effect was to reduce the flare of the LP bladepath from 45^{o}-50^{o} to 35^{o}, smooth the flow boundaries and change the taper, twist and lean of the blading to achieve more uniform flow distribution, lower peak velocities, better stage loading, lower leaving losses and improved degree of reaction. New generations of blading were also developed.

Completely new families of blades were developed in the 1980s



New LP turbine blades were developed using CFD. The blades had increased twist which was non-linear along the blade length. They became known as 'high twist' blades.



1960s '600 series' aerofoil

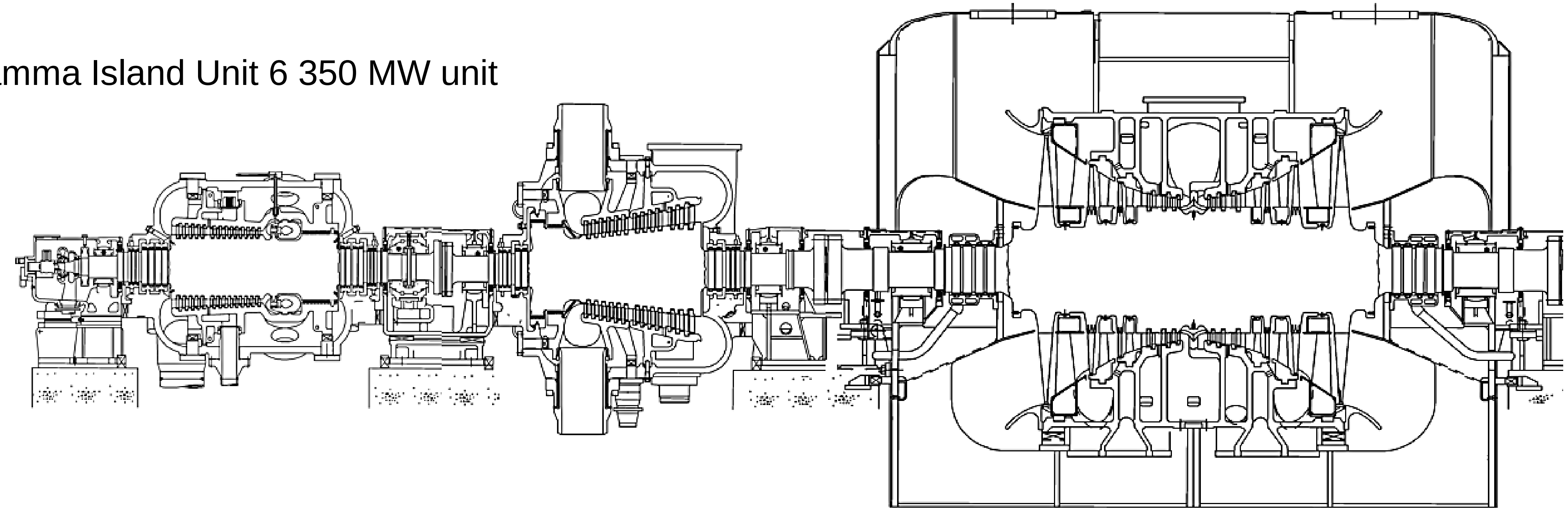
1980s 'R series' aerofoil

The R series blade was more efficient, withstood a very wide range of steam incidence, was stronger allowing better aspect ratios and required fewer blades per row.

In addition, 'RT series' twisted reaction aerofoils for IP turbines, 'HL series' blades for high stage loading and 'CN/CB series' profiles for control stages were designed under the leadership of Dr John Grant.

In the late 1980s, Lamma Island Unit 6 in Hong Kong became the first turbine to use the new CFD blades in all cylinders

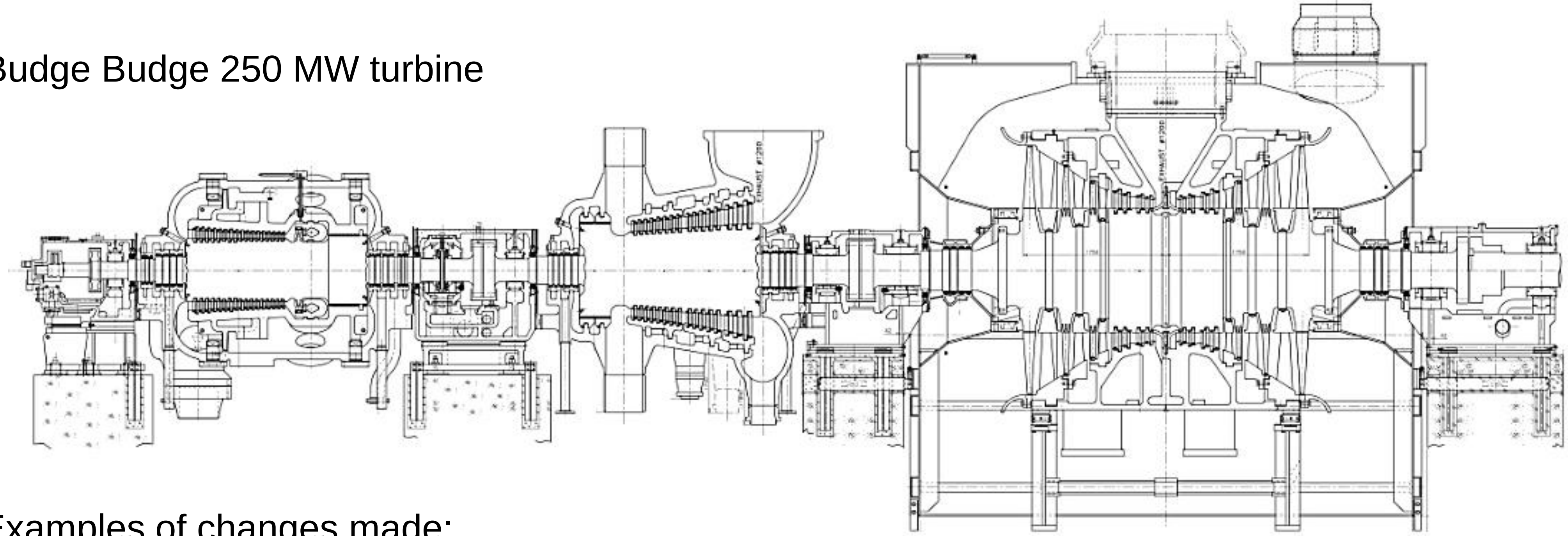
Lamma Island Unit 6 350 MW unit



The blading performed well. Producing the turbine layouts was difficult, however, because the bladepaths were much shorter than previous machines. R series blades were so strong, much smaller chord widths could be used which benefited efficiency and cost. The IP bladepath, for example, was 29” shorter than before and so it proved difficult to find enough space to incorporate all of the feedheat extraction belts.

In the 1990s, turbines evolved once again

Budge Budge 250 MW turbine



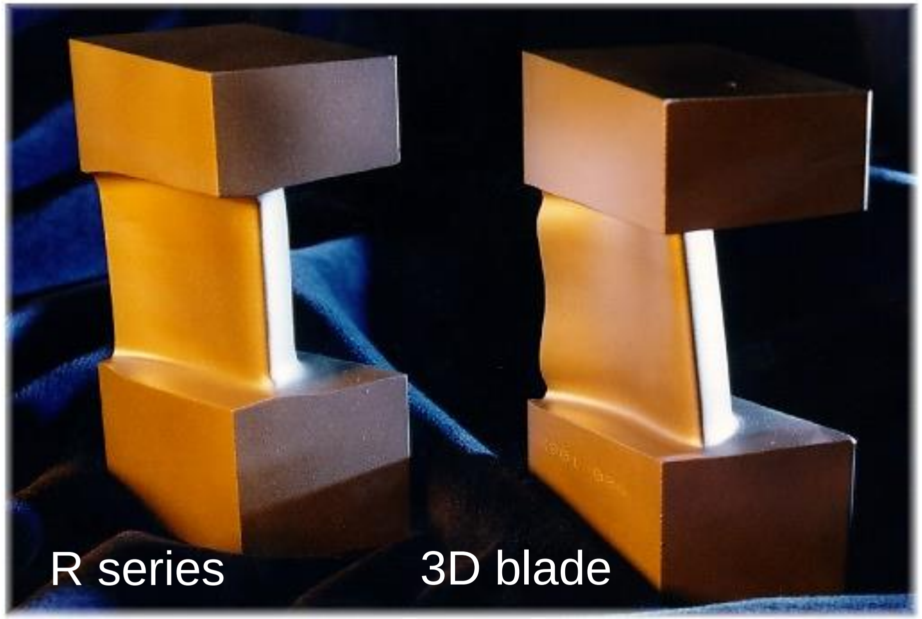
Examples of changes made:

Bladepath software:	1980s – automatically optimised on the basis of efficiency.
	1990s – optimised on the basis of cost & performance using heuristic algorithms. This favoured HP & IP turbines with more stages on smaller shaft diameters.
HP turbines:	New materials eg alloyed nodular cast iron.
IP turbines:	Steam forces were carried by the outer casing allowing the blade rings to be optimised to suit the needs of the blading alone.
LP turbines:	Improved casing and exhaust hood design.

From 1965 to 1997, Parsons merged or formed partnerships with other companies to be secure and provide new opportunities

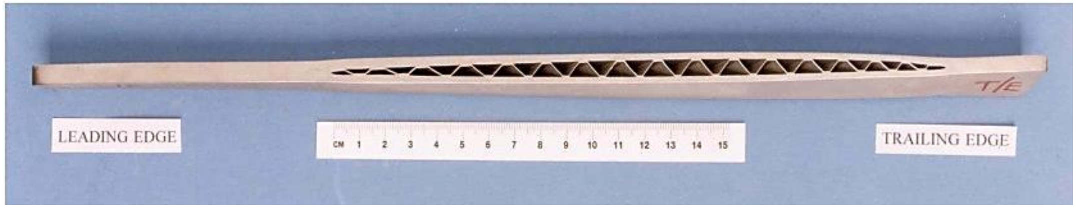
1965	Parsons took over the TG business of GEC.
1968	Reyrolle-Parsons company was formed.
1977	Reyrolle-Parsons merged with Clarke Chapman to form Northern Engineering Industries. During the 1980s, NEI grew until there were 15 constituent companies.
1987	A joint venture was formed with ABB to gain access to large gas turbines & other technology.
1989	NEI became part of Rolls-Royce. This provided access to aero-engine technology.
1992	Parsons and Westinghouse started exchanging steam and gas turbine technology. This gave access to extensive experience with combined HP/IP turbines.
1994	Parsons and Westinghouse commenced joint steam turbine development.
1997	Parsons became part of Siemens. Westinghouse also joined the family in 1998. In the 2000s, there were 12 turbine companies merged and shared technology in the Siemens family.

Rolls-Royce technologies which were available to Parsons



3-dimensional reaction blading with 'end bends' to reduce secondary losses were adopted in HP turbines.

Other technologies included abradable, honeycomb and brush tip seals.



Hollow titanium blades based on the Trent aero-engine fan blade construction allowed last stage LP blade design to be revolutionised.

Summary

The work of Sir Charles Parsons resulted in the World’s first practical, high performance turbine-generator.

The largest machines today - around 1,700 MW - are recognisably similar to the first 7.5 kW unit of 1884.

Due to Sir Charles, turbines quickly became the dominant engine for electricity generation and for propelling ships which required high power and/or high speed.

The ability to produce power at far higher levels than any other prime mover made it possible to provide electricity to the entire population of countries not just local groups of people.

Parsons turbines include machines which were the first of their kind, the most powerful in their day, the most efficient and those which achieved the highest availability.

Some of the largest power stations in the World have employed Parsons turbine-generators.

The Parsons factory in Newcastle-Upon-Tyne is still active today as part of the Siemens family.