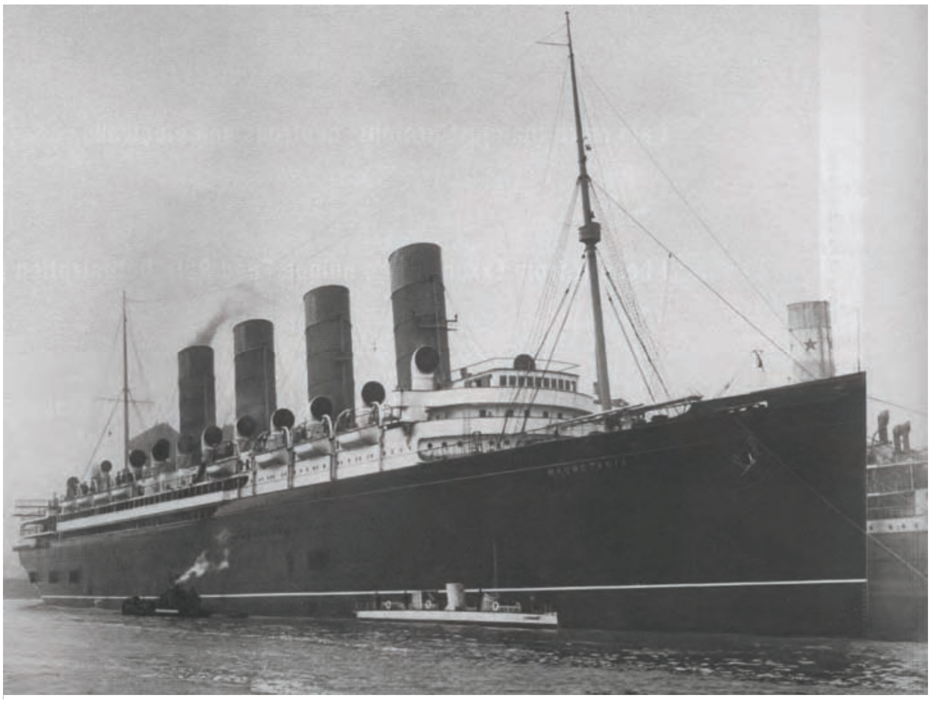
From *Turbinia* to LNG carriers via *Mauretania*

A potted history of the marine steam turbine, by Don Nicholas, formerly deputy general manager of the Medium Turbo-Machines Group at GEC-Alsthom UK



Rapid escalation: Turbinia and Mauretania, in about 1907

An impressive debut was made by the marine steam turbine in 1897 powering a 30m-long launch at a world record speed of 34.5 knots. Turbinia was built by the British turbine pioneer Sir Charles Parsons to demonstrate that a new form of propulsion was now available to challenge the monopoly of triple-expansion steam engines.

Notable in this early history is the rapid escalation in the power output of Parsons' designs. He had produced the first practical steam turbine only 13 years earlier and by the time Turbinia appeared had successfully created a market for turbo-generators with outputs up to around 300kW. But the machinery installed in the launch was five times this rating, at 1,500kW. and the success of her demonstration runs quickly led to an order from the Admiralty to engine two destroyers- *Viper* and *Cobra* - with turbines producing 10,000 shp on four shafts.

As the Admiralty was very much a guinea-pig in using high-powered propulsion turbines, Parsons had to accept a penalty clause of £100,000 if the ships did not exceed 30 knots. His money was safe, however, as they achieved another new record speed of 37 knots on trials.

Sir Charles was able to confidently produce turbines of progressively greater output because, from the start, he had evolved a low speed/low stress approach for his designs which was maintained throughout the roughly 50-year existence of the Parsons Marine Turbine Co, set up in 1894.

In Turbinia, for example, he employed 71 'reaction' stages. Each stage consisted of a circle of stationary blades attached to the inner surface of the casing, directing steam at a corresponding circle of blades attached to the rotor, in expanding the steam from 157 lb/in² to a vacuum of 1 lb/in² (a).

This represents a pressure drop per stage of only slightly more than 2 lb/in2: a gentle puff of steam from the nozzles, which illustrates Parsons' low stress approach. The power output of subsequent turbines was raised by increasing the flow capacity by lengthening the blades; and, because both blade and steam speeds were low, the general stress levels were low and reliability was maintained despite the huge increases in output introduced.

Applying this philosophy enabled Parsons to supply high power naval machinery to meet Admiral Fisher's requirements for enlarging and modernising the Royal Navy, calling for installed powers up to 108,000 shp for the battleship *HMS Tiger* in 1909.

Some 1,000 tons in weight were reportedly saved by fitting steam turbines rather than reciprocating engines to the revolutionary battleship *HMS Dreadnought*, built in 1904 The overall benefits were considerable, and by the Battle of Jutland in World War 1 every participating warship, German and British, was propelled by turbines.

In commercial shipping the first turbine vessel was the 650-ton Clyde steamer *King Edward*, built in 1900. Transatlantic tonnage soon followed, however, led in 1905 by the Alien Line's Virginian and the Victorian, both of 11,000 shp, and Cunard's *Carpathia* of 21,000 shp.

A particularly important development in 1907 was the 36,000-ton liner *Mauretania* built by Cunard with financial help from the government on the basis that she would be fast enough to recover the coveted Blue Riband from three German ships powered by massive reciprocating engines which were making the fastest Atlantic crossings at **23 knots**.

In order to achieve this, Parsons produced turbines which gave 73,000 shp on four shafts, the sets being the most powerful in the world and enabling *Mauretania* to set and hold the transatlantic record for 22 years with a speed of **27 knots**.

The construction of these early reaction turbines took the form of a cast iron cylinder split along the horizontal centreline, with flanges and close-pitched bolts to hold two halves together after the rotor had been inserted. Circles of stationary blades, whose outer ends were located in grooves in the inner surface, were spaced axially to allow the rows of identical blades fitted to the rotor interpose between them.

Flow through the stationary blades created a rotating mass of steam, giving a shock-free entry to the curved passages formed between the rotor blades, the expansion and acceleration of the steam around these passages setting up a reactive force against the blades which gave the name to this type of turbine.

The rotor was made in the form of an elongated drum so that a small running clearance was provided between it and the inner tips of the stationary blades. A similar small clearance existed between the tips of the rotor blades and the inner surface of the cylinder, this being the method of limiting the leakage steam which could bypass the blade passages.

As the steam expanded through the turbine the length of the blades and the diameter of the rotor were increased in line with the increase in volume of the steam to provide the necessary flow area. Because a pressure drop existed across the rotor blades a considerable aggregate thrust was developed, which was balanced by a so-called 'dummy piston' at the inlet end of the rotor.

The ends of the rotor were sealed by labyrinth glands consisting of a series of restrictions that progressively throttled the leakage steam, so reducing the leakage to a negligible amount which was condensed to avoid the nuisance effect in the engine room.

The dummy piston is essentially a large diameter labyrinth gland in which the pressure difference between the inner and outer ends acts upon its effective area to partially balance the aggregate blade thrust. Multi-collar thrust bearings were also required to absorb the residual load and to accurately locate the rotor in the casing, but these were replaced by tilting-pad Michell type bearings when they became available.

Parsons conceived the idea of providing astern power by arranging a compact astern turbine in the exhaust end of the main ahead turbine. When the ship was going ahead the astern blades 'windmilled' but little loss in efficiency was incurred as they operated in a vacuum, and this method was adopted for all marine turbines.

Until this time turbines were directly coupled to the propeller shaft, dictating running at a compromised speed which was too low for the turbine and too fast for the propellers. In 1910, however, single reduction gearing became available which resulted in gains in the efficiency of both elements.

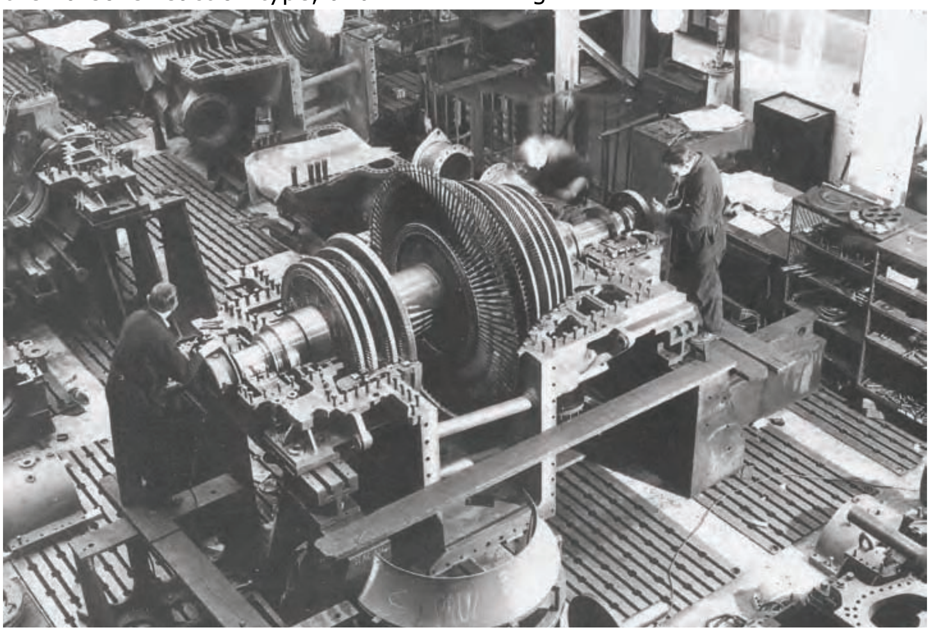
Significant success at home enabled Parsons to establish worldwide licensees and a virtual monopoly, except for a brief period from 1910 when Brown-Curtis turbines made a rapid, if short-lived, penetration of the marine turbine market.

The attraction to ship designers was that Brown-Curtis manufactured an impulse design which was more compact and lighter than the Parsons reaction type, and for the same blade speed an impulse design has only half the number of stages.

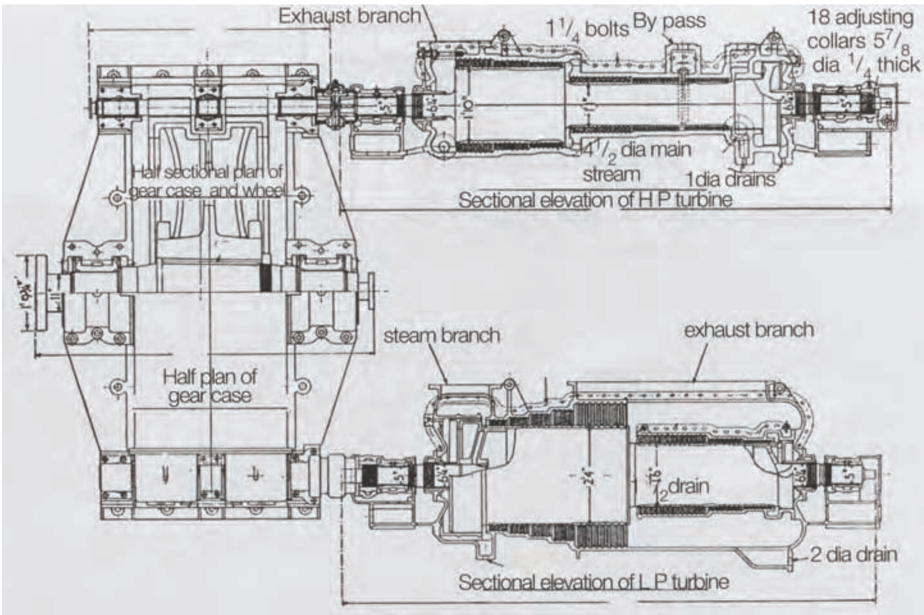
Within an impulse stage the pressure drop takes place entirely in a circle of nozzles which direct high speed jets of steam at a circle of blades attached to the rotor. There is a specific relationship between the steam speed in the jets and the speed of the rotor blades for best efficiency, and hence if high steam speeds are used then the blade speed must also be high.

Thus the compactness of the Brown Curtis designs was at the expense of using higher blade speeds and stresses, and this was accentuated when gears became available enabling the designers to use much higher turbine speeds than the cautious Parsons. This underlined their advantage in weight .and size but led to their total undoing since no proper understanding of blade and rotor vibration characteristics existed at the time. A series of turbine-wrecking disasters led to the demise of the Brown-Curtis company in the early 1920s.

Prior to World War 1 turbines were operating on low pressure steam at 200 to 250 lb/ in² with no superheat, so efficiencies were correspondingly low. Mauretania consumed 1.5 lb of coal per HP hour - equating to an overall efficiency of barely 11. 5 per cent - and 200 stokers were required to feed the boilers until she was converted to oil firing in 1921.



The only British designer of marine steam turbines after PAMETRAOA dropped out in 1967 was GEC Ltd which incorporated Met-Vick and the English Electric Co. Low pressure turbine cylinders for a Ben Line container ship are shown under assembly at GEC's Trafford Park factory in 1970



Parsons' turbines and gearing of the Vespasian (1910), the first vessel fitted with geared turbines

During the 1920s steam conditions increased as boiler designs improved and took advantage of the availability of better materials, so that by 1930 pressure/temperature ratings of 350 lb/in² and 650°F became the norm.

Land power stations had developed plant utilising steam at 750°F, and the British Ministry of Defence made an attempt to improve the fuel rate of naval vessels by ordering machinery from Parsons to run on similar steam conditions. Unfortunately; the resulting turbines of traditional Parsons reaction design, which were installed in the destroyer Acheron, proved incapable of running on steam at this temperature, heavy vibration forcing the attempt to be abandoned.

The Royal Navy, wholly equipped with such machinery, was then committed to enter World War II with rather inefficient if reliable machinery. The demands of warfare were to highlight this deficiency and bring to an end the reign of the Parsons Marine Turbine Company.

In the inter-war period merchant ship machinery followed a similar slow rate of development and steam ships requiring less than about 3,000 shp would be powered by triple-expansion engines, which at this end of the power range were more efficient than turbines.

Turbines were typically used for fast ferries, cargo liners, oil tankers and - of particular interest, because of the high power levels - for the propulsion of a series of large and luxurious transatlantic liners, starting with Bremen in 1930 and followed by others such as *Rex*, *Normandie* and Cunard's two Queens.

Most were fitted with Parsons turbines manufactured under licence by the shipbuilder and driving through single-reduction gearboxes. *Normandie* adopted a different approach by using impulse turbines and electric drive, but running on similar steam conditions of 350 lb/in²/700°F with an installed power of 165,000 shp, compared with the 160,000 shp of the Queens, all on four shafts.

The massive machinery in the Cunard ships illustrated the effect on size and weight of the continued conservative design policy followed by the Parsons company. as each of the four turbines expanded the steam through 70 equivalent stages in four cylinders. In contrast, the impulse turbines of *Normandie* ran at much higher speed and required only 15 stages located in two cylinders.

Steam propulsion suffered a steady loss of competitiveness against marine diesel engines following the appearance of the motor ship *Selandia* in 1911. By the late 1930s engine outputs up to 12,000 shp were available and by the outbreak of World War II two out of three ships ordered were powered by diesel engines.

Significant technical advances in marine turbine design took place in the USA in the mid -1930s as a result of a major expansion of the navy. Against opposition from the domestic shipyards which were Parsons licensees, the decision was taken to power the new warships with impulse turbines designed by the General Electric Company and capable of operating on steam conditions, identical to contemporary land power stations, of 600 lb/in²/825°F.

A standardised design was produced in which a high and a low pressure turbine were positioned side by side, with each inputting to a 'locked-train' double-reduction gearbox.

In a locked-train gearbox the input pinions each mesh with two primary wheels, which are connected to the secondary pinions. Thus the drive to the low speed wheel, where the biggest meshing forces occur, is divided between four pinions. Their manufacture depended on high accuracy gear cutting machines which had been developed in America and enabled high turbine speeds to be employed.

The high pressure turbine ran at 6,000 rpm, the steam then passing via cross-over pipes to a 5,000 rpm low pressure turbine where the steam continued its expansion down to a vacuum established by a condenser located beneath longitudinal beams supporting the LP turbine. The high blade speeds allowed a high efficiency to be attained with only 18 stages, despite the high inlet steam conditions; typically, the HP turbine had 11 stages and the LP turbine had seven stages.

The rotors of these impulse machines were of a fundamentally different shape to the drum configuration of reaction turbines, having a number of discs spaced out along their length. These discs were shrunk on to a shaft in earlier designs but machined from a monobloc forging in the later high speed designs. The blades were attached to the peripheries of the discs by 'roots' of various types, the simplest being a T-shape machined in the bottom of the blade and fitting into a corresponding T-groove in the periphery of the disc.

Steam nozzles were located within circular plates called diaphragms which fitted into circumferential grooves machined in the casing and positioned between the rotor discs, so that the jets of steam they produced entered the passages formed by the blades.

A significant pressure drop takes place in these impulse nozzles to produce steam velocities approaching sonic, and the diaphragms have to be strongly constructed to limit the amount of deflection that results from the difference in pressure between their upstream and downstream faces. The diaphragms are split in two halves, the bottom halves being inserted into their grooves before the rotor is dropped into position.

Plates retain the diaphragm top halves and so allow the complete top-half casing assembly to be lowered into place and the casing main joint bolts tightened up. A labyrinth gland minimises leakage where the rotor passes through the centre of the diaphragm.

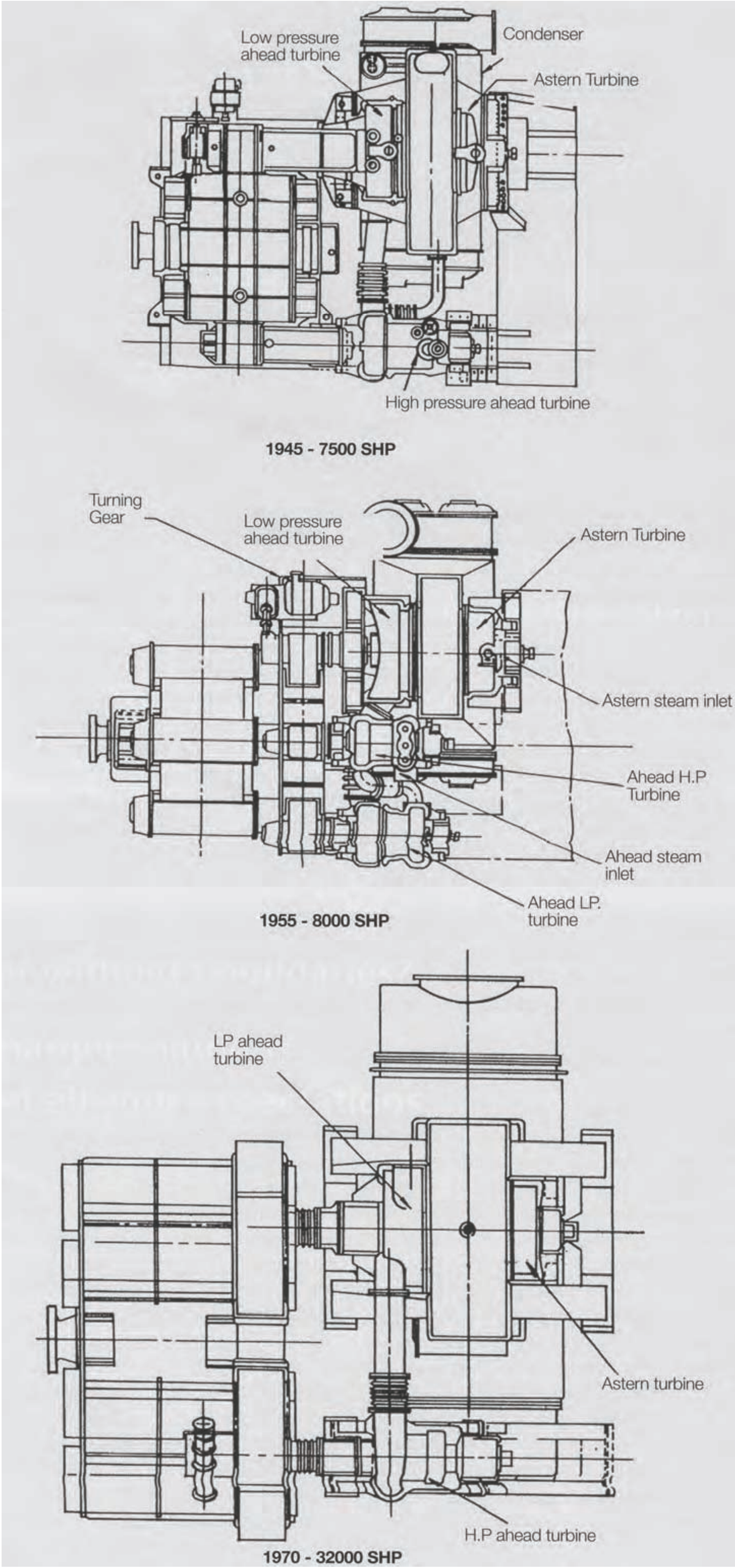
General Electric supplied 804 sets of these 'cross compound' turbines with power outputs from 25,000-53,000 shp between 1940 and 1946, the machinery achieving a considerable reduction in size and weight over earlier marine designs.

During World War II, particularly in the long range actions in the Pacific, the GE turbines additionally demonstrated such an improvement in fuel rate that they led to a wholesale adoption of similar impulse designs for both merchant and naval ships after the war.

A solution to the problems of disc flutter and destructive resonances in turbine blades, experienced earlier in Brown Curtis turbines, had been initiated by an Englishman, Wilfred Campbell, who had joined the General Electric Company. His paper published in 1924 by the American Society of Mechanical Engineers led to the development of design procedures vital to the success of modern impulse turbines.

To meet demand for marine turbines the Parsons company was instrumental in 1944 in setting up a new organisation - The Parsons & Marine Engineering Turbine Research and Development Association (PAMETRADA) - with the aim of producing modern impulse designs for its licensees.

PAMETRADA proved to be a successful venture (post-war Great



Plan view of progressive impulse cross compound turbine designs

Britain was still the largest shipbuilding nation) and turbines of its design, built by licensees, were fitted to 450 ships until the operation was closed down in 1967.

Closure was partly due to the penetration of the turbine market by diesel engines, which gave a fuel rate 30 per cent lower than steam, but also because the decline in British shipbuilding forced PAMETRADA licensees out of business.

Post-war naval turbine designs were developments of the classic General Electric model but usually with increased steam conditions and making use of better materials and improvements in design methods. Steam conditions of 1,200 lb/in²/950°F were employed by the Americans.

Quite wide use is made of nuclear steam power, mainly in submarines but also for surface vessels, by the Russian and US navies, the latter fleet including classes of large aircraft carrier having an installed power of 280,000 shp on four shafts. Steam has otherwise been displaced from naval surface ship propulsion by aero-derived gas-turbines, although the Soviet navy surprised pundits when a steam system was employed in the Sovremennyy-class destroyers in the 1980s.

Rapid escalation of oil supplies from the Middle East led to the emergence of VLCCs in the mid - 1960s requiring 32,000 shp to yield an operating speed of 15 knots. This demand was almost co-incident with the evolution of large, fast container ships with an even higher power requirement.

Together, these new commercial tonnage types presented a substantial market for marine turbine builders as contemporary diesel engines were unable to meet the necessary power levels. *Remarkably, for a period from 1972 to 1976 a greater tonnage of new ships was powered by steam than by diesel: a situation not experienced since the 1920s.*

Meeting this demand, the major suppliers - The General Electric Company and Stal-Laval developed standardised designs which operated on steam conditions of around 900 lb/in²/950°F, which gave a fuel rate of about 0.44 lb/shp h.

These well-developed cross-compound impulse machines exploited modern materials and production methods to enable high blade speeds to be used, contributing to very compact configurations. Stal-Laval reduced size and weight further by using epicyclic gearboxes. Both companies at different times supplied as much as 50 per cent of the market, almost entirely through licensees, and Japanese firms like Mitsubishi, IHI, and Kawasaki were also major suppliers.

During this era the propulsion system became automated, engine rooms were unmanned, and complete control could be exercised from the bridge. Very high standards of reliability were achieved and machinery would operate for many years without any remedial work being required other than statutory boiler inspections.

Nevertheless the revived market for steam turbines came to an abrupt end in the late 1970s as a result of the price of oil quadrupling in 1974 and doubling again in 1979. An overwhelming focus on low fuel rates made steam totally uncompetitive against new long stroke, low speed diesel engine designs developed to yield fuel rates of around 0.31 lb/shp h.

A niche market developed for the steam turbine in powering LNG carriers, whose cargo boil-off gas can be burned as boiler fuel, but even this sanctuary is now threatened by the arrival of dual-fuel diesel engines and reliquefaction systems.

It is possible that steam power will re-emerge in the wider arena when oil supplies diminish and prices escalate to the point where a steam system, relatively inefficient but able to exploit cheaper fuels, will become viable. There was a brief flickering in the early 1980s when the high price of oil relative to coal led to the commissioning of a dozen large coal-fired ships.

Source: Marine Propulsion April/May 2005