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Review of the marine steam turbine over the last 40 years

D G Nicholas, BSc, MIMechE, FIMarE
GEC Alsthom Turbine Generators Ltd

SYNOPSIS

The last 40 years have been as turbulent as any in the 100 year history of the marine steam turbine. For a short period in the 1970s it achieved dominance over the diesel engine for merchant ship propulsion in terms of new tonnage, only to rapidly fall to its present position of being virtually out of contention. As a result, over the last decade,only a handful of ships have been built with steam propulsion, but a high level of research and development has continued for land turbines and this work will benefit future generations of marine turbines.

Steam temperatures were on a plateau of 950°F virtually throughout the period under review due to boiler limitations, but this restriction on cycle efficiency was removed by the advent of fluidised bed boilers.

Low alloy steels, which have good temperature/strength properties, were introduced very early in the period. Although little further progress was made in basic material properties, the development of metallurgical techniques which enabled large, high quality monobloc rotor forgings to be produced, resulted in remarkable progress in reducing the size of the high powered machinery fitted to VLCCs and fast container ships.

The use of steam propulsion for naval vessels has remained constant throughout the period and 30% of naval ships under construction at the present time are steam powered. Salient designs are reviewed and comment made on the inconsistent attitude to the use of cruise turbines.

INTRODUCTION

Presenting a paper on the marine steam turbine at the present time is regarded in some quarters as being akin to introducing yet another theory for the sudden and mysterious disappearance of the dinosaur. Certainly there is a similarity in the way that both species vanished from the scene after achieving a position of dominance, but this is very superficial as the marine turbine is only one variant of an enormous and very healthy family of steam turbines which today contribute over 75% of the world's generation of electricity and, in fact, also provide 30% of the installed power in new naval vessels currently being built. The dinosaur only left an exciting collection of enormous fossilised footprints and vertebrae, but the steam turbine is currently in extensive use over a power band which extends from a few hundred kW to 1.5M kW and is linked to the utilisation of a wide range of fuels, some of which are unusable by any other prime mover.

The marine turbine has benefited enormously in the past from receiving a technical input from the large scale R&D carried out by the power station turbine builders.

Much effort is continually being applied to increase turbine and cycle efficiencies and these improvements will be available to be applied for marine use. They will increase the prospects for the use of steam for ship propulsion in a world where, quite soon, liquid and gaseous fuels will only be economically feasible for air or road transport and where emissions will be ever more strictly controlled.

To switch now from conjecture about the future to look at the subject of this paper, which is to review the marine steam turbine over the last 40 years, it is necessary first to establish the state of things at the start of this period which, to all intents and purposes, begins at the end of World War II. Also, to simplify the structure of the presentation, the author would like to separate the naval from the mercantile application, starting with the latter.

The author joined the English Electric Co at Rugby as a graduate apprentice in 1951. After experience in the construction, technical service and design departments, he was appointed Chief Design Engineer in 1965 in the Industrial Turbine Division. Following the merger with GEC in 1968, he became Engineering Manager of the Industrial and Marine Steam Turbine Division at Trafford Park when VLCC and container ship machinery was being produced. In 1973 he was made Manager of the Naval Department at Rugby, becoming Assistant General Manager of the IMSTD in 1984 and Deputy General Manager of the Medium Turbo Machines Group of GEC Alsthom in 1989.

MERCANTILE PROPULSION

Background

Sir Charles Parsons recognised from the very beginning that the appropriate use of steam turbines for ship propulsion was to provide very high power, and he supplied turbines with outputs totalling 73 000 shp for the *Mauretania* in 1906, these turbines being significantly more powerful at that time than the largest land turbine built for power generation.

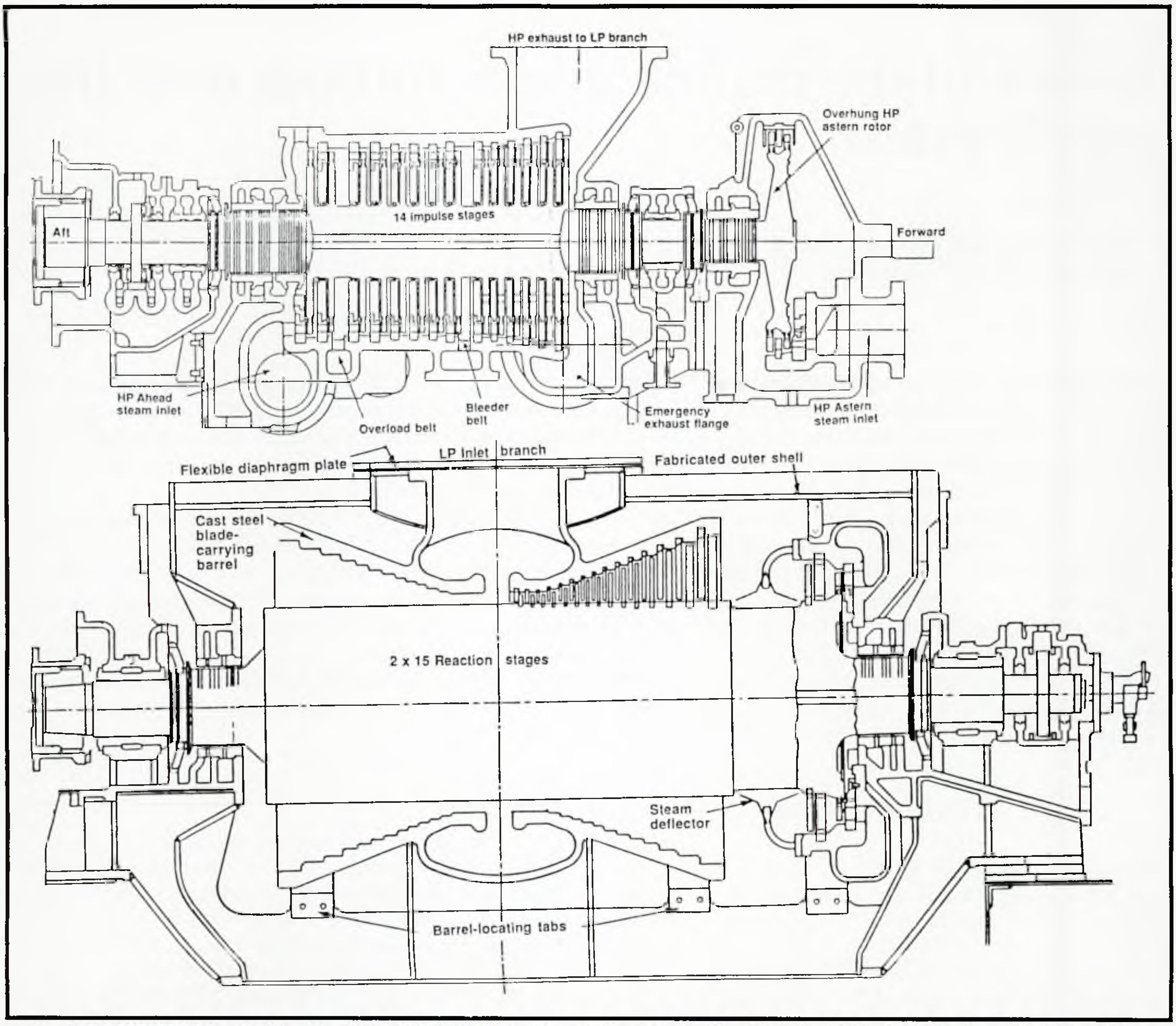


Fig 1: PAMETRADA 12 500 shp 420 lb/in²/740°F machinery, for *British Venturer* in 1951 showing impulse HP turbine and fully reaction LP turbine

This impressive achievement of Sir Charles set the pattern for over 60 years when steam turbines were generally used for the large passenger ships, fast ferries, cargo liners and oil tankers. The bulk of steamships were powered by reciprocating engines, the dividing line being about 3000 shp, as in fact a reciprocating engine is more efficient than a turbine at these low powers, particularly if it makes use of an exhaust turbine which can expand the steam to a much better vacuum than the engine alone.

However, since the *Selandia's* appearance in 1912, steam propulsion steadily lost ground between the wars to the diesel engine, so that by 1939 two out of three ships ordered were diesel powered. At this time diesel engines were unable to make use of the rough residual oil being burnt under ships' boilers, and the decisive factor was the difference in the ratio of the prices of diesel fuel and residual fuel to the ratio of the diesel and steam system efficiencies. The most efficient turbine propulsion systems were in fact very competitive against these distillate burning diesels, but unfortunately this was not the case for all turbine ships. Sir Charles had established worldwide licensees and the Parsons reaction design marine turbine dominated the market after the debacle of impulse designs in the 1920s due to rotor disc failures. Thus a very large proportion of turbine ships built anywhere in the world were likely to be fitted with Parsons' marine turbines and, whilst these turbines are well remembered for being durable and reliable, they were not very efficient. This was primarily as a result of the built-up shrink fit construction of the typically large drum type rotor which imposed a limit on steam temperature of about 650°F, and attempts to operate at higher temperatures were unsuccessful due to vibration. A reaction turbine relies on small running clearances between the rotor blades and casing to minimise leakage as 50% of the stage pressure drop takes place across the moving blades. It was not possible to maintain these small clearances in the marine environment and this factor, combined with the low steam temperature, contributed to the low efficiency.

It must be said that very little development work appears to have been done on these Parsons' marine turbines as the general layout showed very little change from the earliest designs. Additionally, the scattered marine engineering shops, where they were built, would undoubtedly have been a mixed

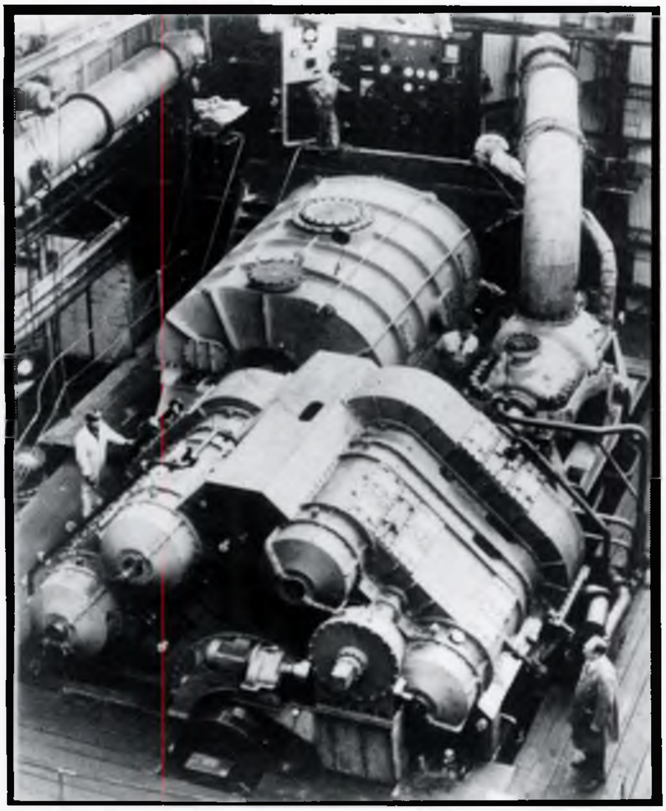


Fig 2: QE2 machinery on test, 55 000 shp (It appears to be running in emergency steaming mode with the HP turbine exhaust bypassing the LP)

bunch, some with inadequate ancient machine tools with an inevitable damaging effect upon the quality of the build.

The lead towards better efficiency came from the USA where President Roosevelt had initiated an extensive naval shipbuilding programme in the early 1930s as a contribution to his efforts to get the country going again after the Depression. This led to a tremendous and highly political struggle between the protagonists of modern propulsion plant and the vested interests of the shipyards which were Parsons' marine licensees and wanted to build their own turbines. This episode is entertainingly recounted in Admiral Bowen's book, 'Ships Machinery and Mossbacks',[1] which tells how the modernists won through and the outcome was that the power station turbine builders, General Electric (GE), produced a first class range of impulse turbines for the new classes of naval ship. This led to a spin-off of mercantile designs from Westinghouse and de Laval, in addition to GE, which operated on typical steam conditions of 400lb/in²/750°F and set the standard for marine turbine design at the start of the era we are now considering.

The post World War II situation

The superior performance of the US impulse turbine design during the war finally broke the virtual monopoly of the Parsons' marine reaction turbines upon the world market and it could be said that the impulse design principle had finally won through after a false start in earlier times. It is very fitting that GE should have been such a protagonist in this victory as Wilfred Campbell made a major contribution to the analysis of turbine disk and blade vibration when he was a Senior Engineer at GE in the 1920s, and it was the lack of knowledge of this aspect of design that had led to the earlier downfall of the impulse marine turbine.

There was clearly going to be a sustained world demand for ships at the end of a war which had been enormously destructive of shipping and within this demand there would be a good market for steam turbine propulsion, particularly as a result of the increasing size of tankers.

Development in Britain

PAMETRADA

Despite the enormous wartime build up of shipbuilding capacity in the USA using advanced designs and welding techniques, high labour costs prevented the USA from being competitive in the peace time market and Britain reassumed its prewar position of being the leading shipbuilding nation in the world. The need to produce a modern marine turbine design was recognised and resulted in the formation of the Parsons and Marine Engineering Turbine Research and Development Association, better known as PAMETRADA, which would produce designs and have extensive test facilities. The Association initially consisted of the 16 British marine turbine licensees of Parsons Marine, the Parsons Marine Turbine Company itself, together with CA Parsons who also provided invaluable managerial assistance in getting the new organisation under way. The Admiralty were important collaborators as they were interested in the capability to test new naval designs.

Expertise in the design of impulse turbines was injected into this reaction turbine stronghold by the recruitment of their new Senior Design Engineer, H G Yates, from the English Electric Co at Rugby. The first designs emerged in 1945 and although these were reaction, the influence of H G Yates was soon apparent when a new cross compound turbine emerged which developed 7000 shp with steam conditions of 400lb/in²/815°F, an appreciable advance on the 650°F limit of the earlier all reaction machines (Fig 1 illustrates a typical example). The HP turbine was an impulse design coupled to a separate HP astern turbine, but although the LP turbine was still a reaction design the problems associated with built-up rotors were avoided by manufacturing it from a monobloc forging. However, in the author's view this reaction type LP rotor would still pose operational problems in marine use because the massive drum construction would cause it to lag behind the casing in warming through and so tend to give rise to axial rubs if the operator was too adventurous with the throttles, and later PAMETRADA designs embraced single and double flow impulse type LP turbines which would give much better operating characteristics.

PAMETRADA maintained a programme of research and development, which is well described in Dr T W F Brown's paper presented at this Institute in 1957,[2] and included full scale test facilities at Wallsend. This resulted in a continual improvement in the designs which were built in large numbers by the member firms of the Association during the 22 years of its existence. The situation by 1967 was that Britain had slipped well down in the league of shipbuilding nations and this, combined with the seemingly remorseless advance of the marine diesel engine which could now burn residual fuels, led to the decision to disband PAMETRADA. The last significant design to provide 2 x 55 000 shp for the QE2 (Fig 2) was unfortunately flawed and suffered the well publicised blade failures, but subsequently the machinery performed well enough until subjected to the ignominy, shared with many other steam installations, of being replaced in recent years with diesel engines.

Metropolitan Vickers and GEC

This company which was, and still is, the only other source of marine turbines in Britain, has a very long history of producing propulsion turbines of impulse design. These operated successfully thanks to the contributions made by outstanding engineers like H L Guy and D M Smith who pioneered the analysis of disk and blade vibrations and so avoided the trauma suffered by the Brown-Curtis machines.

The position post World War II was that the company had supplied sets of turbines for the wartime national shipbuilding programme and this design, which gave a 6% better fuel rate compared with Parsons,[3] provided a basis for future activity. It must be remembered that an enormous pent-up demand for power station turbines existed when the war ended, so the MV shops were full of work and there appears to have been little incentive to chase after marine contracts as very few orders were taken, and unfortunately the company management also had no interest in establishing licensees for their marine designs. Landmark machinery was supplied for three Alfred Holt ships in 1953 when state of the art power station technology was used to design turbines operating on 950°F steam. These were of three cylinder design with running speeds of 6000, 4500 and 3000 rev/min for the HP, IP and LP respectively.

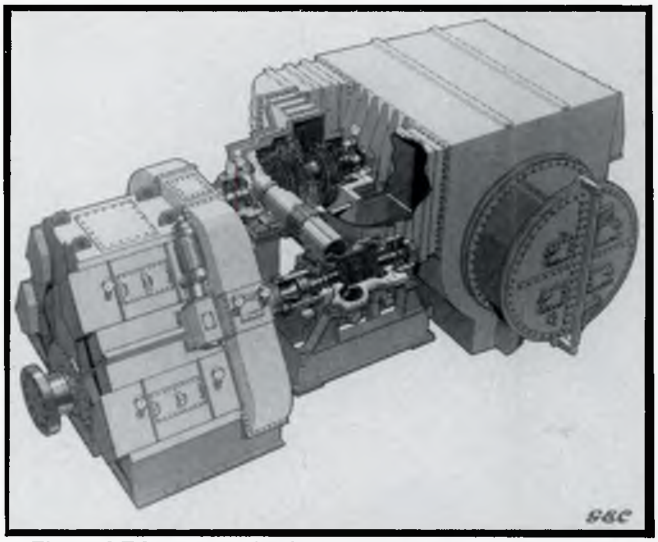


Fig 3: GEC 44 000 shp in plane condenser design for Ben Line container ships, 1971

Significant progress was also made in the gear design when case hardened pinions meshing with through hardened wheels were introduced on the third ship, the *SS Thesius*, to counteract the wear experienced on the low speed wheels of the earlier *Nestor* and *Neleus* which had through hardened pinions. This 'hard on soft' principle was very successfully used, but with nitrided pinions on later sets of machinery supplied for the VLCCs and large container ships during the steam boom of the 1960s and early 1970s.

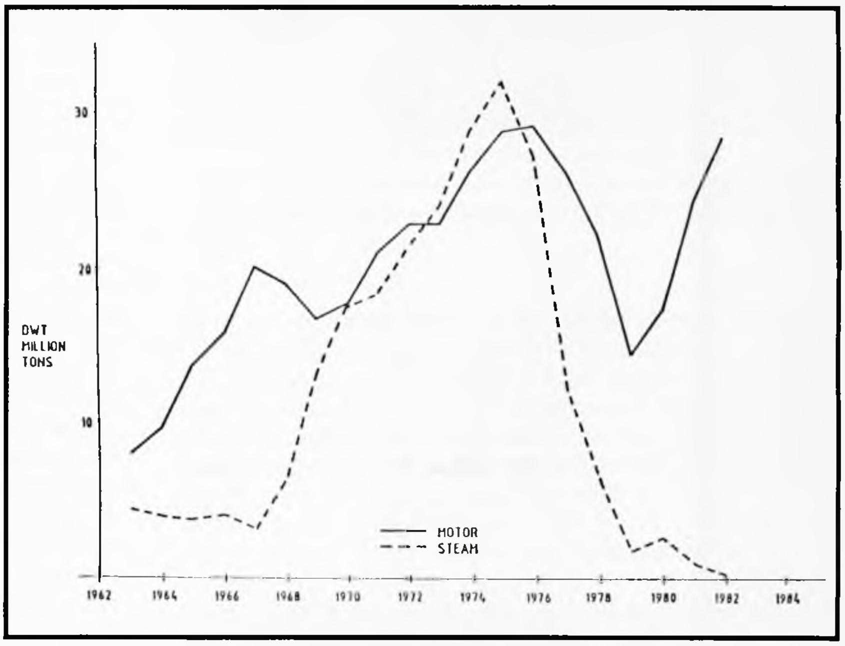


Fig 4: The steam ship boom in the 1970s

The VLCC and container ship boom

The rapid escalation of oil supplies from the Middle East which began in the late 1950s led to the development of VLCCs by the mid 1960s capable of carrying 0.25M t of oil and requiring 32 000 shp to give an operating speed of about 15 kn. In the 1970s this exploitation of the economies of scale, obtained by using these enormous ships, was pushed even further with a new class designated as ULCC with sizes going up to as high as 0.5M t.

Almost coincident with this tanker development came the evolution of the big fast container ships led by OCL and ACT (the British lines within the OCL/ACT consortium) in the late 1960s with the Encounter Bay and ACT 1 Classes, which were followed by designs produced by many of the world's shipyards.

The installed power in these container ships ranged from 32 000–120 000 shp (Fig 3) to give a typical service speed of 23 kn, but some ships had a maximum speed capability of up to 32 kn which enabled close schedules to be maintained even if delays had been experienced.

Diesel engines were not initially able to supply the power levels required for either the VLCCs or the container ships, and for a time a tremendous boom period existed for marine turbines which was so extensive that for the first time since the 1920s a greater tonnage of new ships was powered by steam than by diesel. This heady period for the proponents of steam unfortunately only lasted from 1973–1976 when the effect of the OPEC oil crisis in 1973 brought it rapidly to an end as shown in Fig 4. However, the demand resulted in some very interesting and successful developments in turbine design, and also in the perfecting of bridge control systems and machinery data loggers which were linked to unmanned machinery spaces (UMS) for steam ships which contrasted with the earlier engine room control stations (Figs 5 and 6).

The reduction in engineer manning levels required to operate these ships was reinforced by very high levels of reliability which were achieved by the machinery. The author has personal experience with very hard worked container ships which operated without a break for 8 years with virtually no maintenance required for the boilers, turbines or the systems.

These qualities were insufficient to counter the overwhelming economic advantage of using diesel engines which had attained fuel rates as low as 0.27 lb/hp h (0.163g/kW h), and with the addition of complex heat recovery systems operated at levels approaching half the overall fuel rate of the steam ships.

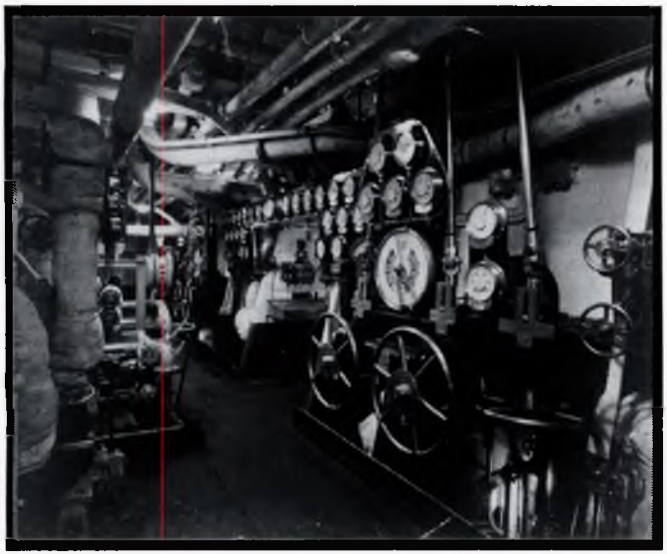


Fig 5: The starting platform; *President Peron*, 1950

Fig 6: Bridge control; Shell tanker, 1966

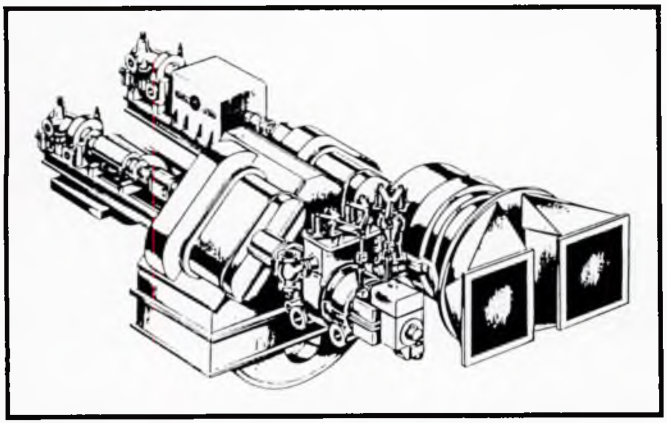


Fig 7: General Electric MST14 main propulsion turbine

The effect of quadrupling the price of oil in 1973 and again of doubling it in 1979 changed the proportion of fuel costs from about 8% in 1970 to almost 70% of the overall cost of operating the ship by 1980.[4] Clearly steam systems burning the same fuel as diesel engines were totally outclassed and many were removed and replaced, as already referred to in the case of the QE2 machinery.

The major turbine builders

General Electric

As recounted earlier, GE was the pioneer of the modern marine turbine and, after supplying over 800 cross compound machines between 1940 and 1946, emerged after the war as the biggest marine turbine builder in the world. High home labour costs led to progressive design development to minimise these costs and the company also established a policy of setting up licensees who could manufacture the static elements of the turbines and gears, but received the dynamic parts from GE. This had the double effect of reducing the content of US scale labour costs whilst retaining the high skill activity within GE, and contributed to GE's success in obtaining at times as much as 50% of the market.

In order to better compete with diesel engines, which had become virtually dominant by the early 1960s, GE introduced the MST13 range of standardised turbines in 1961, designed to operate on steam at 850lb/in^2 g/950°F with an axial exhaust to an in-plane condenser and linked to a locked train gearbox. The power could be specified from 18 000–32 000 shp. The scheme minimised weight and space requirements and provided mechanical drive for the feed pump from the HP pinion shaft which ran at 6500 rev/min. A generator was similarly linked to the LP shaft which ran at about 3600 rev/min.

The appearance of this design was well timed to meet the rapid rise in demand for the tanker boom and it was built in considerable numbers by GE licensees.

A later version, the MST14 (Fig 7) also available in reheat form operating on steam at 1450 lb/in^2 g/950°F/950°F, appeared in 1965 with the maximum power capability extending to 45 000 shp and giving a fuel rate of 0.39 lb/hp h, an improvement of 4–5% in fuel rate over the non-reheat version (Fig 4).

What transpired to be the final development of the post World War II GE marine turbine came with the announcement in 1970 of the MST19 range which offered shaft powers from 45 000–120 000 shp in either non-reheat form to run on 850 lb/in^2 g/950°F or reheat with steam conditions of 1450 lb/in^2 g/950°F/950°F. These MST19 turbines were produced following a study by GE into the power ranges needed for the ships of the future but this era, when the prospect of bigger and faster ships seemed endless, was brought to a precipitous conclusion by the OPEC fourfold increase in the price of oil. The result was that the only ships to which the MST19 turbines were fitted were the class of giant Sealand 33 kn container ships. These utilised 60 000 shp units from the lower end of the MST19 range, but even so had the highest shaft power of any merchant ship yet built.

Stal Laval

Stal Laval and General Electric took the lion's share of the market during the period we are reviewing, but whereas GE started with an impeccable pedigree in the marine turbine field and with a massive engineering and manufacturing capability, the de Laval resources were minimal. As a result, their early designs were outdated and used shrink on disk construction for both HP and LP rotors, which ran at very low speed because gear cutting limitations restricted peripheral speeds to 70 m/s. Professor Ingvar Jung was appointed Chief Engineer in 1950 and under his direction modern designs were eventually produced culminating in the AP (Advanced Propulsion) range which appeared in 1963, when the de Laval company joined with ASEA Stal to form Stal Laval (Figs 8a, 8b and 8c).

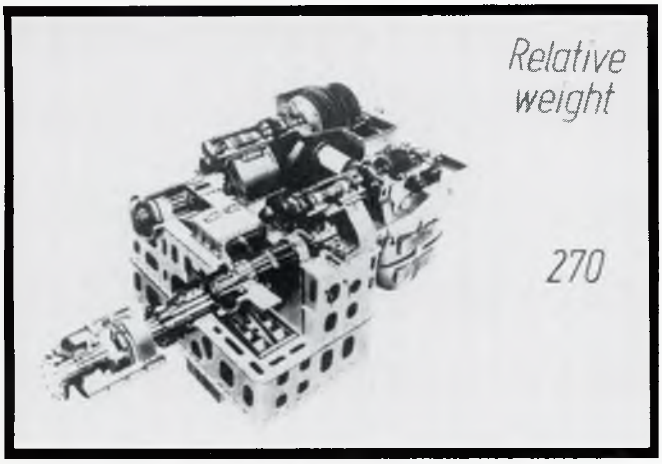


Fig 8a: Stal Laval progress; P2, 1956, 900 lb/in²/932°F

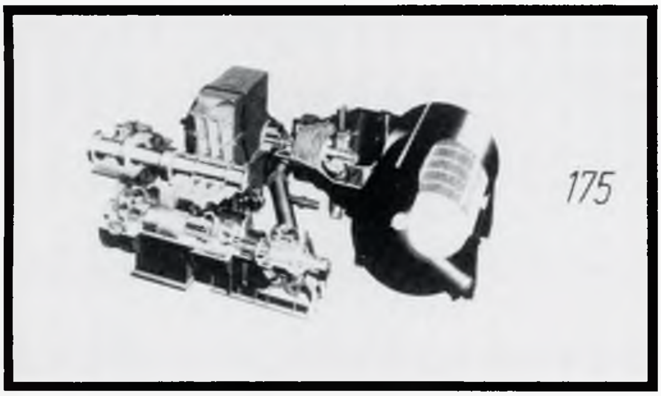


Fig 8b: Stal Laval progress; AP, 1963
(Note use of epicyclic gears and in plane condenser)

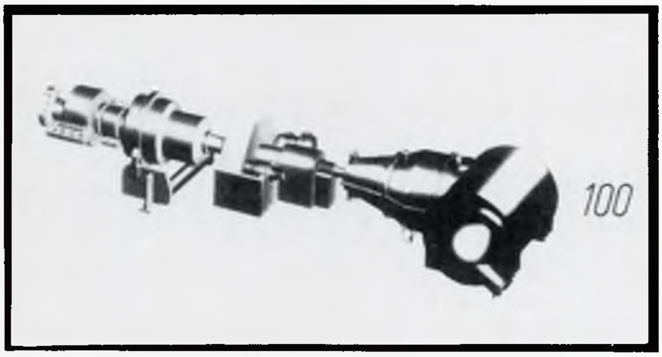


Fig 8c: Stal Laval progress; VAP, 1981, 126 bar/600°C/600°C
(Only built in prototype form)

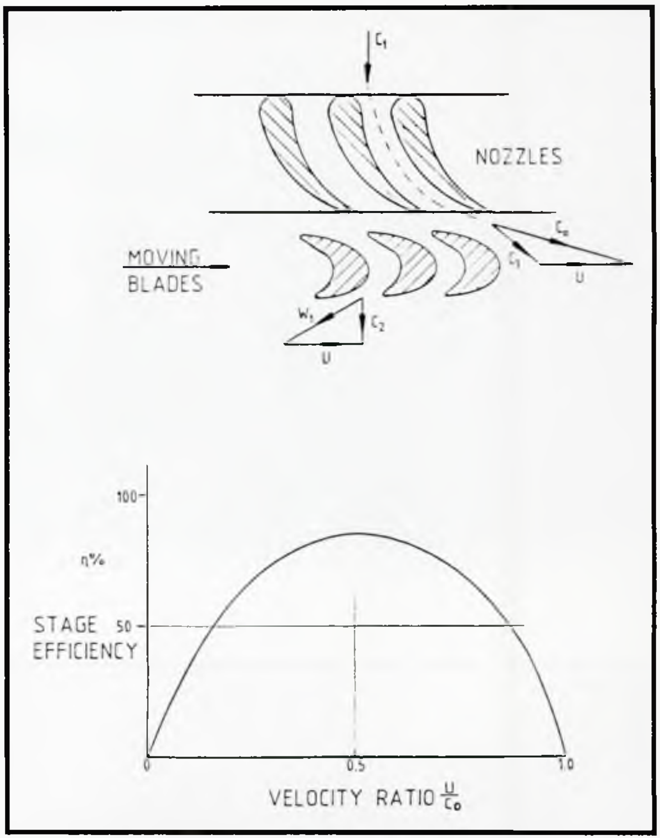


Fig 9: U/CO diagrams for impulse stage

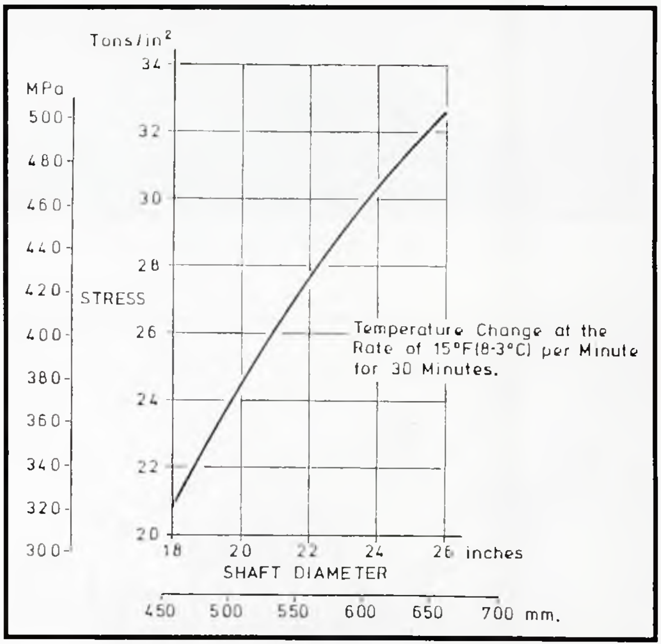


Fig 10: Thermal stress vs rotor diameter

The new AP design was produced to counter the progress being made by diesel engines in the early 1960s and also to provide competition against the new General Electric MST13 turbine system. Like GE, de Laval had followed the principle of appointing licensees, but in their case this was initially because of the lack of production facilities at their own factory. The main spur in designing the AP range was the need to reduce cost and Professor Jung recounts that it was successful in achieving a 25–30% reduction,[5] together with a 30% reduction in weight compared to the previous P type. An important contribution to these improvements resulted from the use of epicyclic gears for the first reduction gearing, which were supplied by W H Allen,[6] and designed on the Stoeckicht principle which was originally developed for use on German submarines in World War II.

The turbines operated on inlet steam conditions of 900 lb/in² g/950°F (63 bar/510°C) and provided a competitive all-in fuel rate of 0.441 lb/shp h from the 32 000 shp frame as fitted to VLCCs. In addition this machinery was very compact and could be installed in an extreme aft position in the ship, a point

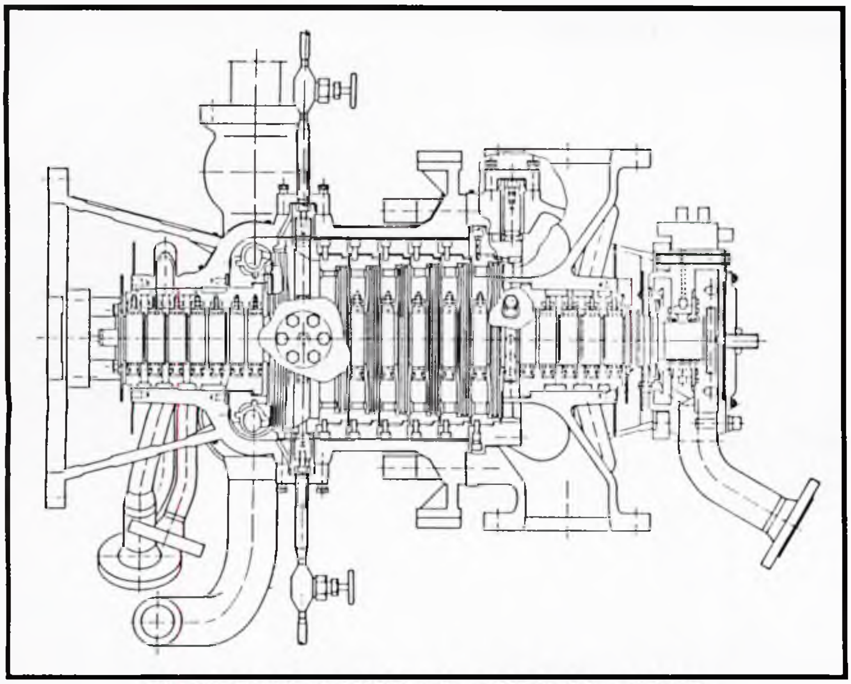


Fig 11: Stal Laval VAP; reheat HP turbine, 600°C (Note use of barrel casing)

emphasised in Stal Laval advertisements which showed their steam systems installed in a VLCC and completely dwarfed by the superimposed profile of an enormous cathedral diesel engine of the same power output.

Triple reduction was used in the HP turbine line for some VLCC installations, thus allowing very low propeller speeds with an attendant improvement in propulsion efficiency.

In all over 300 sets of AP machinery were produced mainly by the 12 licensees, but with Stal Laval providing a variable proportion of the build depending on the licensee's capability.

By a combination of innovative engineering and good commercial acumen, Stal Laval had built up a successful very large scale business, but the effects of the OPEC oil shock threatened to bring it to a sudden end. The development of slow speed diesels having an ultra long stroke provided a tremendous challenge in fuel rates to the existing steam systems, particularly as these engines ran at such low speed that they could match the 85 rev/min propeller speeds achievable by turbine ships but without the need for gearing.

In the new environment of the mid 1970s, where fuel costs had become the major constituent of ship operating costs, it looked like the end for steam unless a very radical improvement in efficiency could be achieved. Marine propulsion had become so important to Stal Laval that the company decided to make a major attempt to achieve such an improvement and, in conjunction with Babcock Power Ltd, produced the VAP machinery design which was tested in prototype form in 1981 in the Stal Laval factory (Figs 8a, 8b and 8c).

A reheat cycle operating on extremely high steam conditions was vital to obtain the level of efficiency necessary to match the diesel fuel rates. The collaboration with Babcock was essential as the maximum steam temperature produced by marine boilers had been limited to 950°F (510°C) by the danger of corrosion in the high temperature zones of the boiler. This problem was overcome by operating the boiler at orthodox temperatures and adding a separate superheater in series with it to boost the inlet and reheat steam temperatures to 600°C with the intention of making a further increase to 650°C at a later date. This latter temperature is significantly higher than the current limit of 565°C for land power stations and would represent a major step forward in steam technology. The series superheater was fired by means of a fluidised bed which, because of the high heat transfer rates, could be operated at a very moderate combustion temperature of 800°C, and the exhaust gases then passed into the main boiler. The steam pressure was 126 bar, or 1812 lb/in^2 at the turbine.

The design of the turbine showed a classic adherence to the aim of achieving maximum efficiency whilst producing a machine that would be reliable and easy to operate. The HP and IP turbines were separate and not combined as in earlier General Electric and Kawasaki reheat designs. This minimised the rotor length and so allowed the high rotational speeds of 14 000 rev/min for the HP and 12 000 rev/min for the IP, without any attendant problems with rotor dynamics. Tilting pad journal bearings were used to contribute also to high speed stability. The small steam volume commensurate with the high operating steam pressure led the Stal designers to use a small blade mean diameter of the order of 12 in, in order to allow the use of reasonably long blades to provide the required flow area. This is desirable in order to minimise the losses in the steam passages through the blades and nozzles. The small diameter involved the use of high rotational speeds in order to obtain a sufficiently high blade speed to give good stage efficiency as blade speeds and stage heat drop are related by the need for the ratio

$$\frac{\text{blade speed}}{\text{steam velocity from nozzle}}$$

to approach a value of 0.5 to give the maximum efficiency for an impulse stage (Fig 9). The high blade speeds allowed the stage heat drops to be large and reduced the number of stages, so helping to maintain short bearing centres.

The interaction of some of the design features are illustrated above, but another very important aspect in view of the high inlet temperatures was the minimising of thermal stress. This is achieved by maintaining symmetry and by making the turbine as small as possible as thermal stresses are size related, as shown in Fig 10. To achieve symmetry both the HP and IP turbine cylinders were of barrel construction with no half joint. These turbines are assembled by entering the rotor and diaphragms axially into the cylinder and then threading on an end cover, and so require very accurate manufacture as it is not possible to check the running clearances which need to be small to minimise losses (Fig 11).

The HP and IP cylinders were made by welding together forged sections as the high nickel alloy was not suitable for casting, and the rotors were made from similar material. Only six stages were required on each rotor and the HP rotor weighed just 140 kg. The diaphragms were fabricated in 12% Cr steel by electron beam welding and the inlet nozzles were made by investment casting.

The LP turbine was similar to previous Stal Laval designs, but the astern turbine was different as it required three Curtis wheels in place of the usual two. The increased efficiency was necessary due to the fact that the steam for astern running was

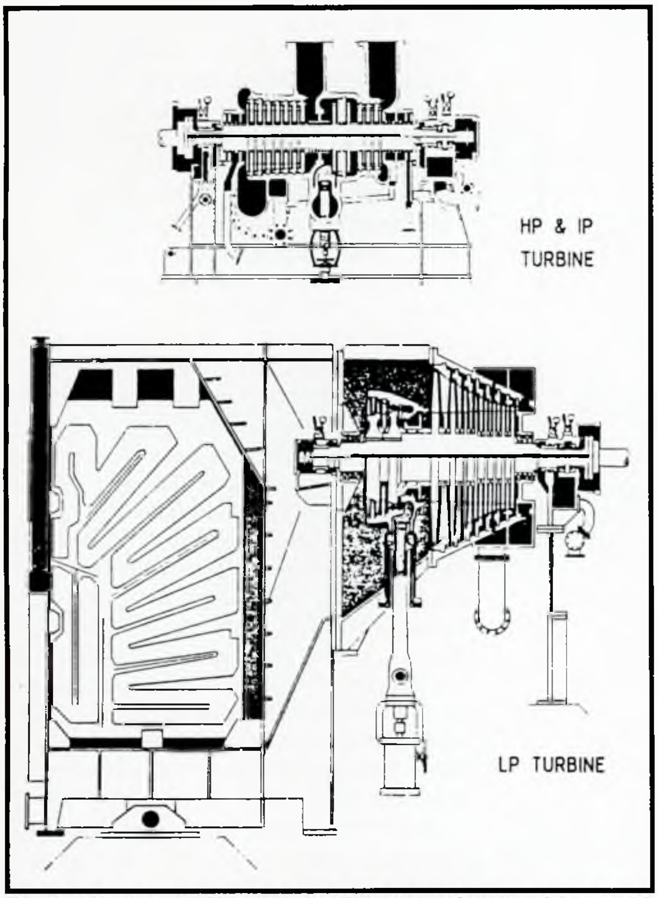


Fig 12: Kawasaki UR 315; 31 500 shp reheat turbine 1420 lb/in²/1000°F/1000°F

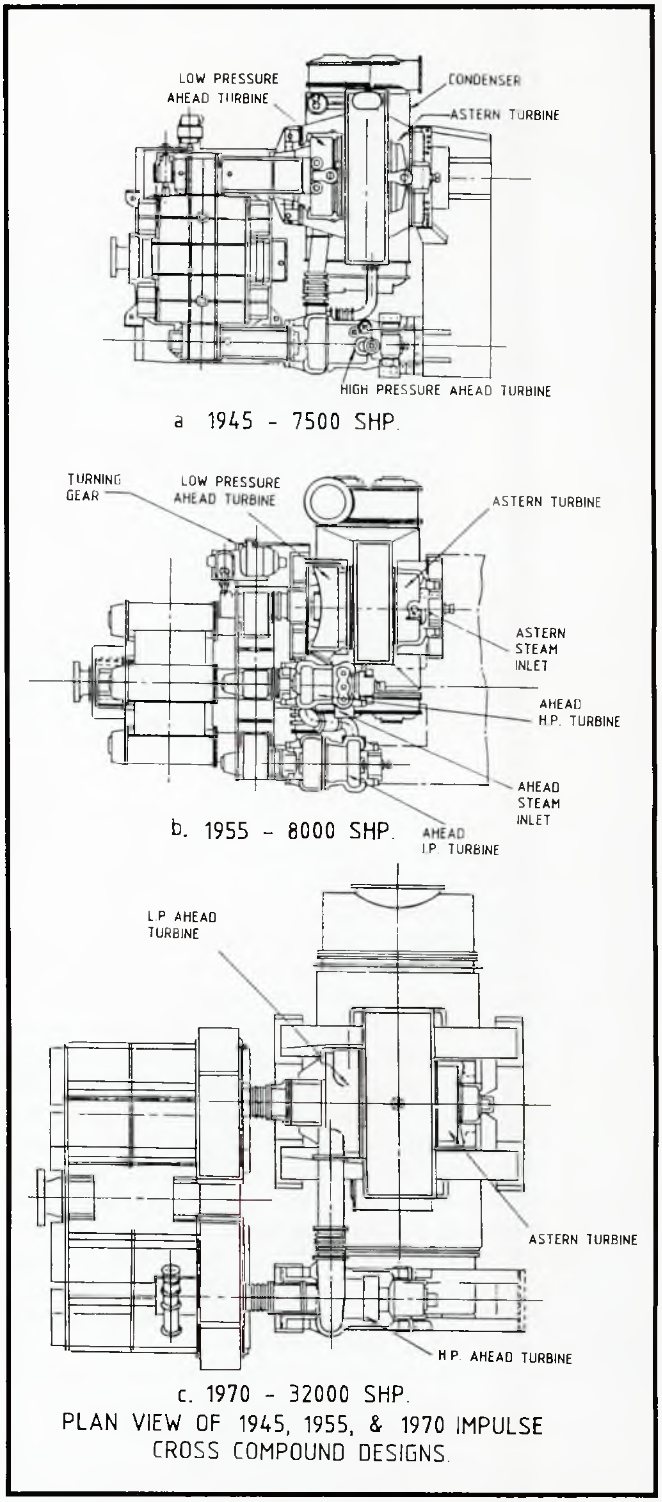


Fig 13: AEI/GEC cross compound designs 1945-1970 (Drawn to the same scale showing compactness of modern design)

limited as a result of the steam rate for the ahead turbine being so much lower than in previous designs.

Triple reduction gearing was employed in the form of a first stage parallel gearbox, which also combined the outputs of all three turbines into the first of the two planetary further reductions.

The target set by the Stal Laval designers was for this machinery to achieve a fuel consumption rate of 0.23–0.24 kg/kW h with additional potential gains from the ability to operate with ultra low propeller speeds. This would make it very competitive with typical diesel plant consumption rates of 0.24 kg/kW h which included lub oil and auxiliary power requirements. Unfortunately for Stal Laval the development of diesel engines was also continuing apace and by 1981, when the VAP system was given its press release, the current ultra long stroke diesel engines, with attendant extensive heat recovery systems, could offer an equivalent fuel consumption rate as low as 0.18 kg/kW h and not a single VAP plant was sold. Although this marked the end of Stal Laval's valiant attempt to beat the diesel in a straight fight, all was not completely lost as the VAP turbine design was adapted for use as an industrial land turbine and has sold very successfully on the basis of being more efficient than the competition. The concept of a separate series superheater made a very important contribution to moving steam systems forward from the limitation imposed on the attainable cycle efficiency by high temperature corrosion in the boiler.

Mitsubishi, IHI and Kawasaki

Japan built up her shipbuilding capacity with incredible speed and overtook Britain as the major country in this field by the late 1950s. Mitsubishi, IHI and Kawasaki were the main suppliers of steam machinery and their combined output represented between 30–45% of world production during the peak years from 1967 onwards.

Kawasaki produced its own designs which were similar to GE in concept and with licensees had supplied over 100 units of its standardised UA type by 1975. A reheat version, the UR operating on 100 bar/520°C/520°C, was introduced in 1969 (Fig 12) but, despite operating satisfactorily, only eight sets were ever delivered, as presumably the shipping companies could not overcome their suspicions that reheat systems were

Table I: GEC/AEI design development 1945–1970

Design references	*Inlet steam conditions*		*Power*	*Number of stages*	*Average enthalpy drop per stage BTU/lb*			*Maximum blade tip speed ft/s*			*Rotor bore stress at last stage*	*Non–bled steam rate*
	lb/in²	*° F*	*shp*		*HP*	*IP*	*LP*	*HP*	*IP*	*LP*	*t/in²*	*lb/shp*
National shipbuilding programme (1945)	430	740	7500	11	11.47	–	31.5	450	–	685	8.15	7.55
Blue Funnel Line (1955)	615	950	8000	30	14.19	15	26.2	600	518	718	9.27	6.20
Ben Line Container Ships (1970)	900	950	44 000	15	33.00	–	45.4	715	–	1293	16.11	5.30

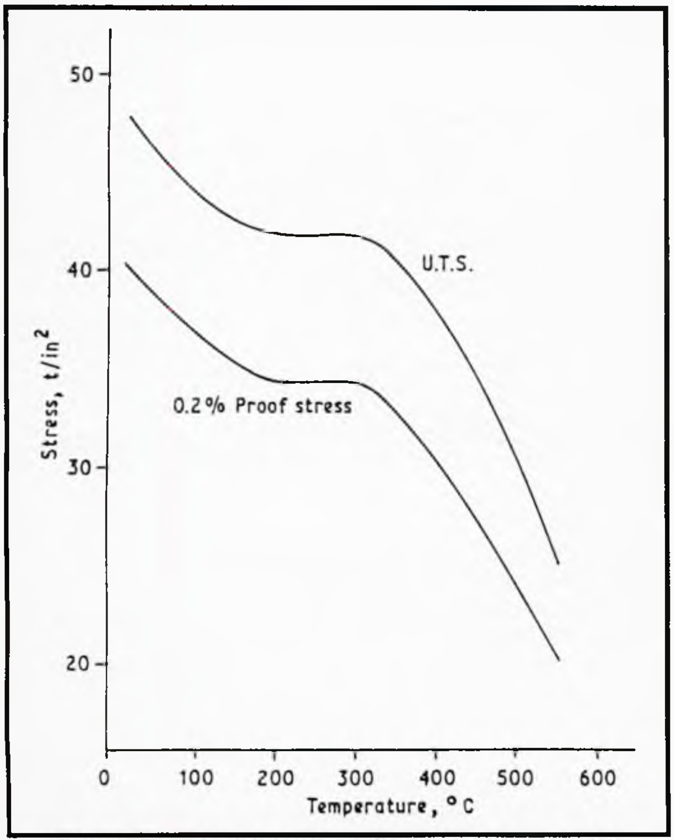


Fig 14: Typical properties of low alloy rotor steel

too difficult to operate on a ship, or else could not make the economic justifications for the increased first cost.

Other world suppliers

There were several other worthy suppliers of marine turbines who produced excellent designs, particularly Westinghouse, de Laval, Alsthom, Franco Tosi, Brown Boveri and AEG, but who, in company with Metro Vick/GEC, failed to set up a significant number of licensees. As a result their market share was minute compared with General Electric, Stal Laval and the Japanese companies.

40 years of design progress

Steam turbines have been in use for over 100 years and such an old technology is not likely to be subject to dramatic improvements. Over the period we are considering the biggest influences have been due to metallurgical development, together with the very significant effect of an increasing use of computers in the design process.

Progress up to 1970 is illustrated in Table I which utilises design data available from historical AEI/GEC mercantile designs. The availability of a range of low alloy steels for casings and monobloc rotor forgings has allowed the use of higher steam conditions which, together with improved blade and nozzle design, has resulted in a reduction in steam consumption of 30% for non-reheat machines. The better material properties have allowed the last stage bore stress to double between 1945 and 1970 and blade speeds to increase by 60% in the HP and 67% in the LP. The work done per stage has trebled in the HP and increased by 50% in the LP and the number of stages has been correspondingly reduced. This has resulted in large gains in the compactness of the machinery as shown in Fig 13. Figure 14 illustrates a typical strength/temperature characteristic of a low alloy rotor steel.

At the beginning of the period we are reviewing the mass of design work, covering all the various stress calculations, blade and nozzle performance, glands, steam thrust, critical speed, blade vibrations, diaphragm deflection, control valve characteristic etc, was all carried out by hand, usually by slide rule and mechanical calculator. Today the work is covered by the use of suites of computer programs which deal with the analysis in a far more detailed manner than would ever have been possible by hand calculation. A good example is the use of computer software to examine the rotor dynamics by assessing the response to an out of balance applied to various positions on the rotor. Accurate results are now produced which compare with the methods used 30 years ago which were based on graphical methods to establish the static deflection of the rotor. The critical speed calculated from this deflection was then given an arbitrary adjustment to allow for bearing oil film flexibility.

Even by 1970 the adoption of these methods and improved materials had led to the gains in compactness and efficiency referred to earlier and had also resulted in the virtual elimination of mechanical failures.

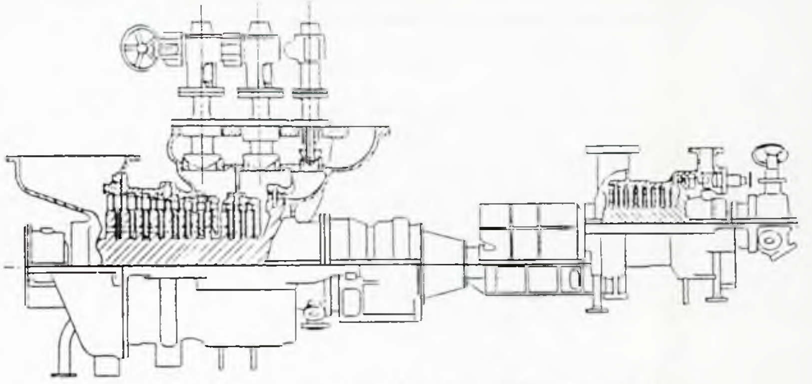
Research and Development has continued at a high level and mathematical modelling techniques, in conjunction with laboratory work, have led to a further 4–5% improvement in turbine stage efficiency since 1970, as well as enabling the designer to carry out the accurate stress analysis of the components of complex shapes.

THE COAL FIRED SHIP AND FUTURE PROSPECTS

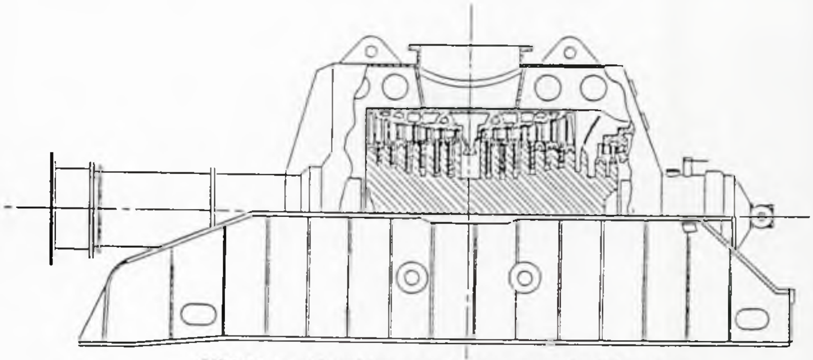
Oil is a finite resource estimated to run out in about 40 years and the future of the marine steam turbine, apart from naval applications, undoubtedly depends on the capability of steam systems to burn any fuel. Coal is the obvious main alternative to burning oil,[7] and in the early 1980s there was an enormous interest in the coal fired ship as a result of oil prices in some parts of the world becoming five times the price of coal on an equivalent energy basis. Ten ships were built and went into successful service operating UMS (unmanned machinery spaces) and with entirely automated coal handling from the bunkers to the boiler. Subsequently the price of oil came down and no more coal burners have been built as a consequence of their higher initial cost compared to diesel ships.

An additional factor was the use of stoker fired boilers which made the ships inflexible in regard to the type of coal which could be burnt.

Some interesting papers were presented at the First International Coal Fired Ship Conference in 1980 organised by the Shipping World & Shipbuilder. One, from Kawasaki, described their development of a marine reheat boiler which incorporated a fluidised bed boiler and so overcame the problem of fuel inflexibility, and also enabled the steam conditions to be increased to 100 kg/cm²/540°C/540°C using a development of their UR type reheat turbine. A paper from Hitachi demonstrated that a bulk carrier engined either by coal fired steam or oil fired diesel had equal volumetric and dead weight carrying capacity for the same overall measurements, power and endurance, but that the first cost of the steam ship would be higher.



USS *Mahan* – general electric HP turbine and geared cruise turbine circa 1933; 600 psi/850°F



USS *Mahan* LP turbine – notable early use of solid rotor construction and beam support

Fig 15: General Electric machinery for USS *Mahan*, 1933

It would appear that a fluidised bed coal fired system is the most likely development, which could become economically attractive if and when oil prices escalate to about three times the price of coal of the same energy equivalent. From the turbine aspect this would be an extremely interesting situation as undoubtedly, under the pressure of competition, steam conditions would escalate dramatically with the disappearance of the boiler gas side corrosion problem. Marine turbines would then lead land turbines in the use of high temperature steam, as the small high speed HP and IP units, of the type pioneered by Stal Laval in the VAP design, would avoid the size related thermal stress problems which would be faced by the large central power station turbines. Figure 10 illustrates the relationship of rotor diameter to thermal stress.

The development of fluidised bed boilers will also enable steam ships to operate within environmental legislation, as well as having the capability to burn waste products like petroleum coke which has a calorific value similar to coal.

The conclusion must be that the mercantile marine turbine is far from dead and will emerge from its present dormant state to meet an economic need as soon as it arises.

NAVAL PROPULSION

Background

Virtually all significant naval vessels have been powered by steam turbines since the early years of the century when Parsons supplied destroyer machinery, some with installed power as high as the 49 000 shp installed in HMS *Viper* in 1907. Early impulse turbines suffered catastrophic disk failure and Parsons' reaction designs became almost universal between the wars until, as already recounted, the American builders, General Electric, set the pattern for the future with a superb range of propulsion machinery designed before World War II. A full description of this development was given in great detail by G B Warren in a paper presented to this Institute in 1947.[8] The principles upon which these turbines were designed have not changed and a contemporary designer could do no better than to introduce improvements resulting from the research and development carried out in the intervening half century whilst sticking to the same basic theme.

Naval machinery has to be efficient, compact, lightweight, capable of withstanding shock, reliable and able to operate at low noise and vibration levels, but in addition, in contrast to mercantile machinery, it must offer its best economy at about 20% rated power. Warships spend about 85% of their time at less than 2/3 maximum speed, which, with a typical hull, requires about 20% of full power. At the same time good efficiency at full power is important as it enables the size and weight of the boilers and auxiliary plant to be minimised.

The GE design (Fig 15) achieved this aim by the use of high steam conditions of 600 lb/in²/825°F for the day and the use of separate efficient cruise turbines, which were small diameter high speed devices giving a reduction of nearly 17% in steam rate at cruise, compared with straight throttling of the main engines. The size of the main turbines was minimised by running them at high speeds – in the case of 27 000 shp turbines for destroyers the rotor speeds were 6000 rev/min for the HP

Table II: Comparison of Daring III with preceding classes of naval propulsion machinery

	Daring III	*Battle class*	*Improvement*
Full power	27 000	25 000	–
Steam conditions lb/in^2/°F	550/825	350/650	–
Steam consumption at 20% power lb/shp h	7.25	9.8	26%
Steam consumption at 100% power lb/shp h	7.52	8.4	11%
Specific wt of turbine lb/shp	2.45	4.83	49%
HP rotor bearing centre	4' 9"	9' 4"	49%
LP rotor bearing centre	7' 10"	12' 6"	37%

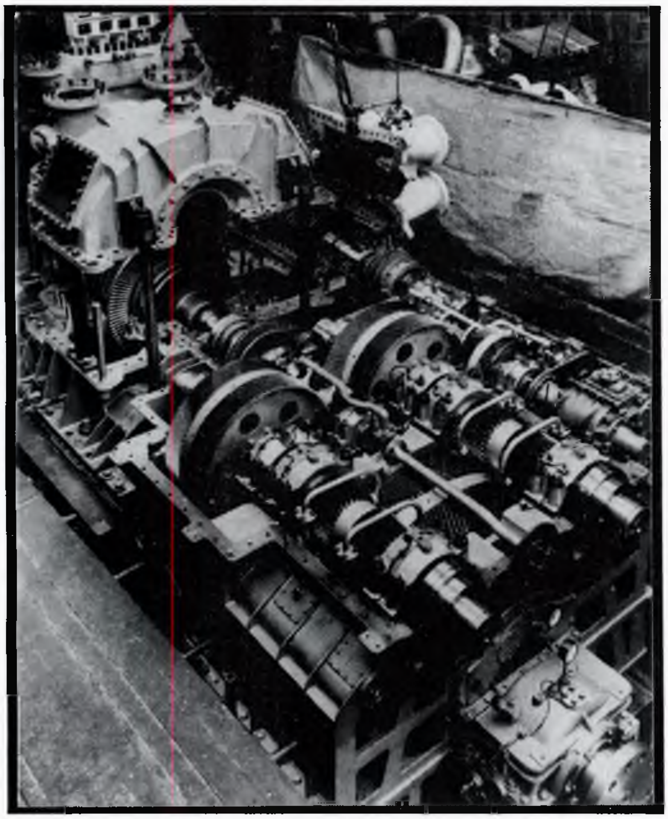


Fig 16: English Electric Y100 machinery on test at PAMETRADA, 1951; 15 000 shp 450 lb/in^2/825°F (Note cruise turbine, later abandoned)

and 5000 rev/min for the double flow LP. These speeds were made possible by the availability of monobloc rotor forgings and by the pioneering use of double reduction locked train gearboxes. The HP casings were 0.5% Mo castings with fabricated LP casings.

The war demonstrated the superiority of this American propulsion equipment which, according to G B Warren, was used in 95% of the main US Navy combatant ships and most post war naval designs were based on it.

Post World War II naval designs

Britain

A new start with the Darings: World War II had demonstrated that although British propulsion machinery was reliable, it was inadequate in providing the ships with the required operating range,[9] and this led the Admiralty into setting up a propulsion committee, with a turbine sub-committee, whose brief was to improve future designs by co-opting the major British land turbine builders. The procurement of the machinery for the first post World War II warship, the Daring Class destroyer, was used to initiate this policy and, in order to evaluate the various potential suppliers of naval machinery, a design competition took place in which five designs were submitted and evaluated by the turbine sub-committee. The outcome was that the English Electric Company, which built impulse turbines, had put forward the proposals which were adjudged to be the best, one, as to be expected being an impulse turbine, but the other, surprisingly, was a reaction design based on details supplied by the US Navy.

The Admiralty then continued with their evaluation of propulsion turbines by ordering three different sets of machinery to be fitted to the ships in the class, to provide 54 000 shp on two shafts and with steam conditions of 565 lb/in^2 A/825°F. These were:

1. Daring I – An all reaction design developed by PAMETRADA and C A Parsons.
2. Daring II – An impulse HP turbine by BTH linked with a Daring I type LP cylinder.
3. Daring III – All impulse type designed and developed by the English Electric Company.

This latter English Electric design was a two cylinder cross compound turbine, closely modelled on the American concept, with high rotor speeds made possible by the use of monobloc rotors forged in 3% Cr/Mo steel to an Admiralty specification. The design was the most compact and proved to be only two thirds the weight of the other two types, although steam consumptions were closely similar.[10] In retrospect, the Admiralty must have taken a very conservative approach to the machinery selection as five of the ships in the class were fitted with the all reaction design, one with the BTH impluse HP turbine and only two with the modern impulse machinery. A surprising omission was that no cruising turbines were specified, despite their successful use in US destroyers, cruisers and light carriers and the specified steam conditions were not very imaginative as they were exactly those established by the Americans before World War II. Nevertheless, the Daring III showed a major advance compared with the wartime Battle Class destroyers as shown in Table II.

YEAD 1 and YEAD 2: In conjunction with Yarrow, English Electric then carried out a wide ranging investigation for the Admiralty into the use of advanced steam conditions with temperatures up to 1100°F which showed potential 20% reductions in steam consumption compared with Daring III, but were impractical because of the non-availability of rotor materials capable of maintaining the required strength properties at the temperatures being considered. The intention, following this study, was to build two sets of experimental turbines designated YEAD 1 and YEAD 2 (Yarrow English Electric Advanced Designs) to investigate the influence upon design of available rotor materials. YEAD 1 was intended to operate with a boiler giving a reducing steam temperature with increased output, which would thus reduce the problem with rotor materials by avoiding the highest temperature coinciding with the high stresses at maximum power. YEAD 2 was a long term project to take advantage of the availability of better rotor materials in order to allow the use of the high steam conditions examined in the study.

In the event, an order was placed in 1950 to design the YEAD 1 machinery to be capable of an output of 30 000 shp

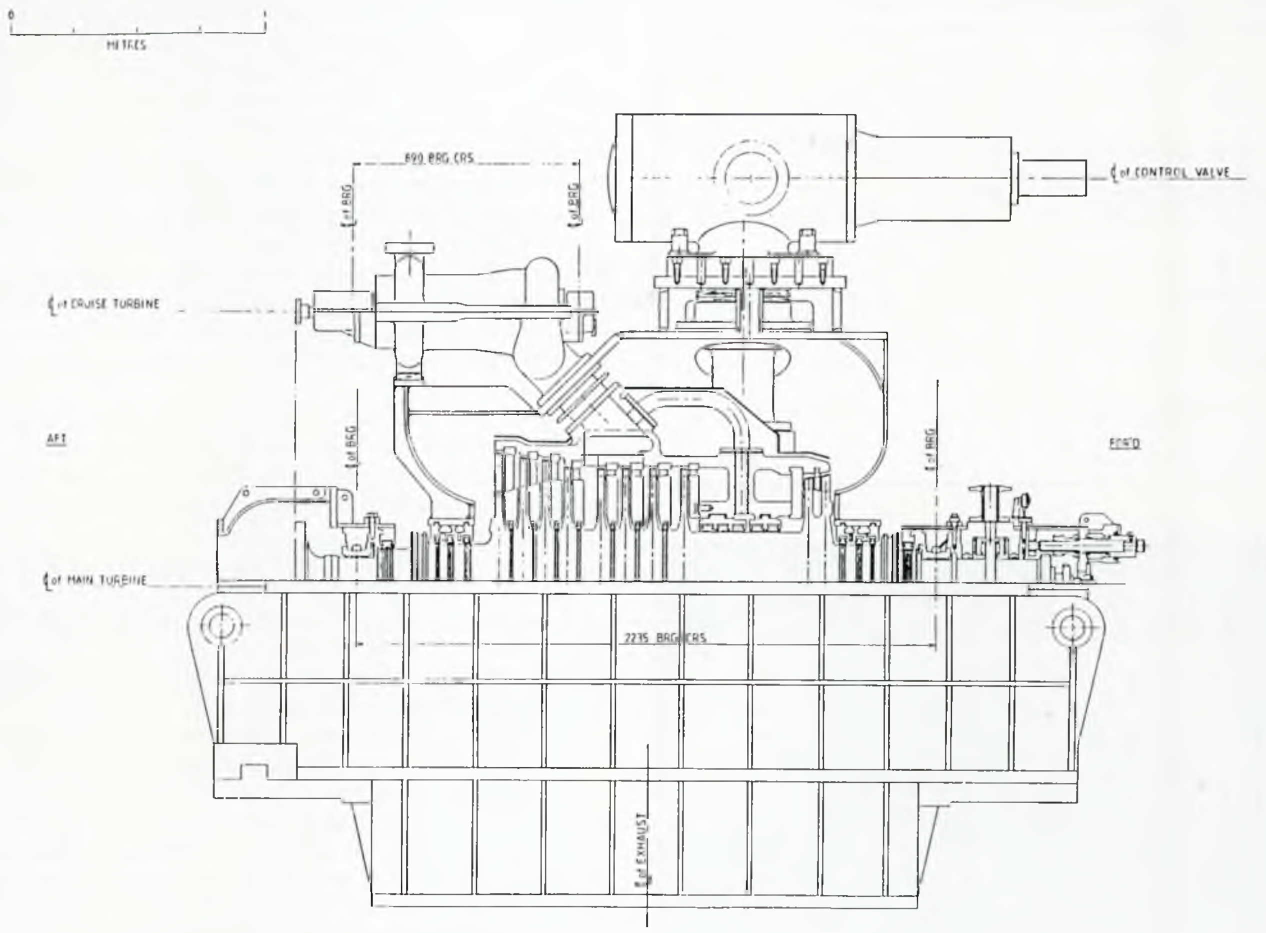


Fig 17: Proposed piggy-back cruise turbine arrangement for Y100; 3000 shp, 30 000 rev/min

with steam at 550 lb/in^2 A/825°F and 26.5 in of mercury, and this machinery was then tested at PAMETRADA but never installed in a ship. The lowest calculated steam rate of 6.3 lb/shp h compared with 6.5 lb/shp h for the prewar GE turbines running on 525 lb/in^2 g/825°F. YEAD 2 was never proceeded with presumably because suitable rotor materials never became available.

The Y100: The next design embarked on by English Electric once again was as a result of winning a competition open to British turbine builders to supply the machinery for a 2000t anti-submarine frigate requiring 30 000 shp on two shafts. A reduction of 30% in machinery weight was being looked for in conjunction with good cruise economy, and because of its combination of good qualities the ship and the machinery design, designated Y100, became an all time classic.

Messrs Cowlin and Veitch, the English Electric designers in 1950, would have been amazed and delighted if they had known then that these turbines would not only still be in wide use 40 years later, but actually still be manufactured - as they are, in India, for the Godavari Class of frigates. Well over 200 of these turbines have been manufactured to date which makes them one of the most successful naval turbines ever designed.

As with most classic designs, the Y100 turbines (Fig 16) are very simple and straightforward because an important requirement was that they had to be suitable for manufacture by lincensees. The steam conditions were moderate at 450 lb/in^2 g/825°F and the ahead section comprised eight impulse stages whilst the astern element consisted of a single Curtis wheel. The exhaust chamber and turbine support structure was a lightweight fabrication integral with the condenser shell and the four nozzle valves were cam operated. An essential part of the concept was to design for maximum efficiency at 60% power, with a very poor vacuum of 23 in at full power, as this enabled the size of the exhaust annulus of the turbine and the condenser to be reduced in order to achieve the compactness and lightness required by the Admiralty specification. These turbines were meant to operate in conjunction with cruise turbines in order to achieve the desired cruising range, but the design approach was seriously flawed on two accounts. This led to the cruise turbines being abandoned after being fitted to the original Blackwood and Whitby classes and the subsequent Rothesays, Leanders and the Leander based Canadian and Indian frigates were all built without cruise turbines.

In view of the enormous success of this family of frigates it could well be deduced that the absence of the complication of cruise turbines was proved to be of benefit, but this is to ignore the very real improvement in capability that was lost by the inadequacy of the original design work.

The dominant reason for the abandonment was the failure of the clutch to operate satisfactorily in all sea conditions – this was before the SSS clutch became available and removed all such problems from contemporary machinery designers. The other reason was the rather uninspired design of cruise turbine

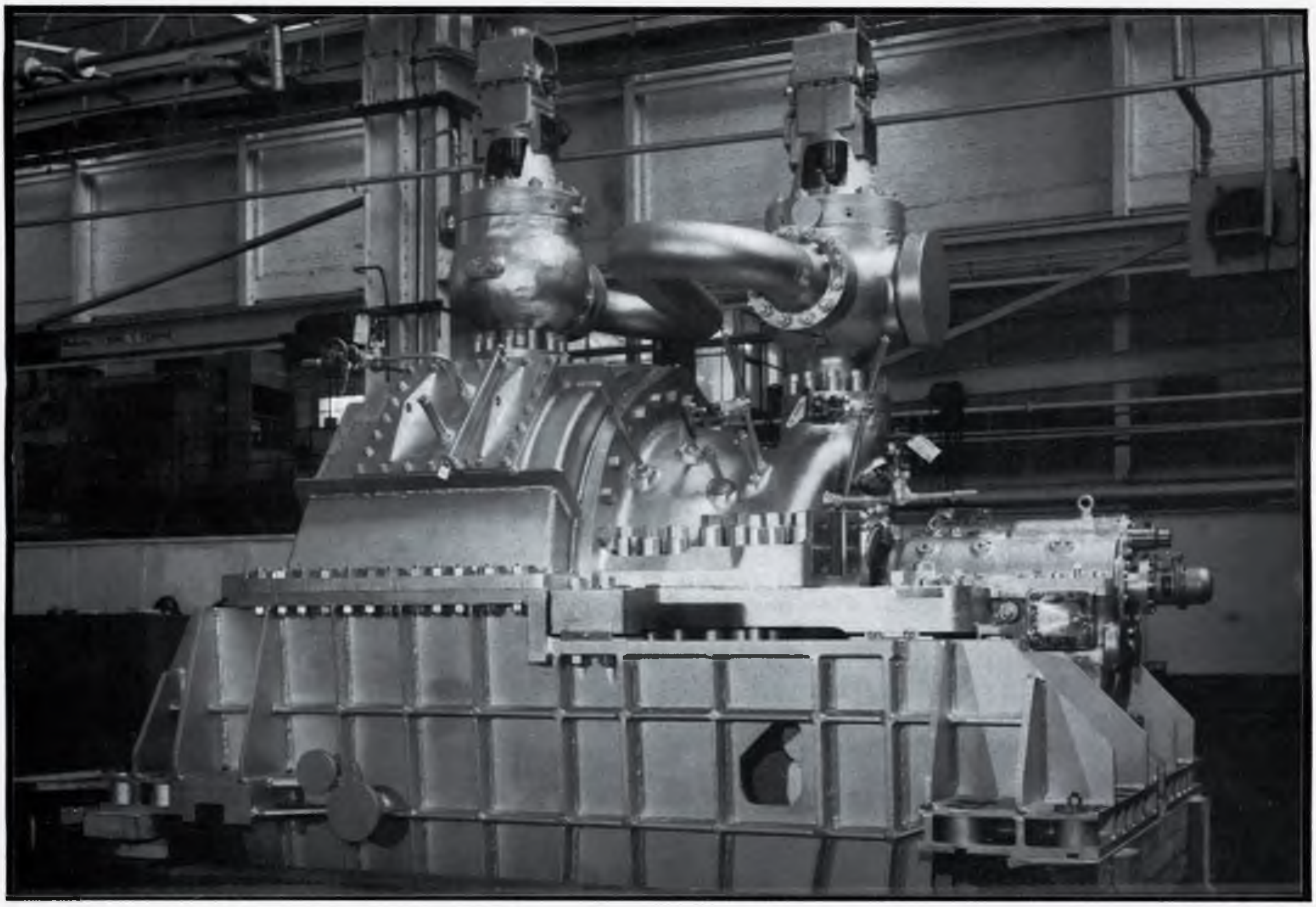


Fig 18: GEC Alsthom main propulsion turbine for British nuclear submarine

which resulted in the steam consumption at cruise being disappointingly high.

In view of the importance to a warship of good cruise economy, it is of interest to examine the Y100 cruise turbine design and compare it with a proposal made fairly recently to uprate the Y100 design in the light of its continued production.

The basic cycle efficiency is established by the inlet and exhaust steam conditions and overall efficiency results from the product of the cycle and turbine efficiencies. Important sources of loss in the turbine are:

1. *Leakages.* These are minimised by ensuring that leakage paths are small compared to the flow area through the blades and nozzles.
2. *Partial admission losses.* The flow area at any point in the turbine is proportioned to match the specific volume and velocity of the steam at that point. If the full 360 deg annulus is not used, this is termed partial admission and losses occur as a result of the high velocity steam at the ends of the active arc entraining with 'dead' steam.
3. *Passage losses.* These losses are proportional in some way to the wetted surface of the flow passage in the blades and nozzles. The areas of the roof and platform of the passage remain constant regardless of the height and hence these losses increase as the blades become shorter. Turbine design rules usually exclude the use of blades shorter than some prescribed size.

It can be deduced from the above factors that the designer's aim is to achieve a well proportioned steam passage through the machine with a minimum use of partial admission. The flow area = circumference x blade height x % admission .

As referred to earlier, the ratio

$$\frac{\text{blade speed}}{\text{steam speed}}$$

also has to be maintained at a value approximating to 0.5 in order to maximise the stage efficiency (Fig 9).

Thus, if the designer reduces the diameter in order to obtain an acceptable blade height, he has to increase the rotational speed in order to maintain the blade speed, the limit then being the rotor stress which varies as $(\text{speed})^2$.

In the case of the Y100 cruise turbine the designer chose a mean diameter of 22 in for the blading with a speed of 8510 rev/min at its maximum output of 3200 shp. A blade height of 0.81 in was selected for the first stage and the required flow area was obtained by using only 10 nozzles out of a potential full circle of 80, ie only 12.5% admission. As the steam expanded through the subsequent stages, full admission was not achieved until stage 5 with a blade height of 0.79 in. The cruise turbine exhaust entered the main turbine ahead of stage 5.

A better concept would have been to use a much smaller diameter of say 6 in running at 30 000 rev/min. Even in this case partial admission is necessary as the steam volumes are so small, but full admission is achieved by stage 3. The rotor stresses are only 12t/in^2 compared with 17t/in^2 for the 1950 design and the turbine would be so small that it could have been mounted piggy-back fashion on the main turbine casing (Fig 17). The result is to achieve a steam rate of 7.2 lb/shp h at 20% power, compared with 8.24 lb/shp h for the original design at 27% power. Thus a cruise turbine of the revised design would have given a 27% reduction in fuel rate compared with running the main engine at 20% power and this surely would have provided the incentive to persevere and overcome the clutch problems.

COSAG: Combined steam and gas turbine systems (COSAG) were introduced for the Tribal Class frigates and County Class destroyers in the early 1960s and this represented an innovative approach by the MOD(N) to the problem of obtaining good fuel economy at cruise. The gas turbines were available to provide the boost power for maximum speed and this allowed the steam turbines to be designed to be at their best efficiency close to the cruise power level. This philosophy also meant that the steam turbines would be designed to operate at much higher vacuum than would be the case for an all steam installation.

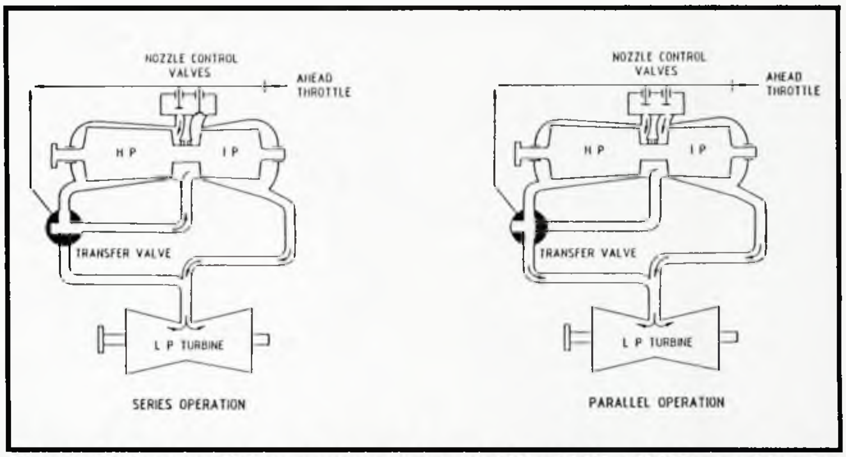


Fig 19: Series/parallel arrangement on post World War II US warships for cruise/full power

A steam consumption curve presented in a paper given by Capt Raper RN,[11] illustrated that this scheme was very successful and gave a specific steam consumption for the Tribal machinery at 20% power (ie typical cruise output) which was 22% lower than for the Y100. The debit side was represented by the need for an expensive gas turbine and a very complex gearbox, although good reliability was achieved in service by this machinery which was designed in its entirety by AEI, now part of GEC Alsthom. It is worth noting that the improvement in consumption at cruise obtained by the COSAG arrangement as compared with the Y100, was not as great as if the latter had been fitted with a well designed cruise turbine. It should also be noted that the COSAG arrangement was only made practicable by the newly available SSS clutches which allowed the gas turbines to be engaged or disengaged without drama under any sea conditions.

A similar COSAG system was installed in HMS *Bristol* with two Rolls Royce Olympus gas turbines providing boost power to two single cylinder AEI steam turbines, each of 15 000 shp. HMS *Bristol* proved to be the last RN surface ship to be fitted with steam turbines and all subsequent surface ships were propelled by either all gas turbines or with the combination of diesel for cruise as for the Type 23s.

Nuclear submarines: British expertise in the design of naval steam turbines has fortunately been kept alive by the nuclear submarine programme. Whilst nothing can be said about the performance of these turbines (Fig 18), the designs are generally in line with traditional naval requirements, but with an even greater emphasis upon reliability, compactness and silence.

USA

The US Navy emerged from the war with a well proven range of propulsion turbines with power outputs extending from 25 000–53 000 shp and which operated at steam conditions of 550 lb/in²/825°F. In order to further development, the USN embarked on a programme which made use of the destroyer *Timmerman* to investigate more advanced propulsion systems.[12] As an experimental ship, machinery operating on steam at 815 lb/in²/1040°F was installed in the starboard engine room whilst the port engine received steam at 1805 lb/in²/1040°F.

Both turbines were rated at 50 000 shp and in both cases the HP and LP rotors ran at very high speed for units of this power output and high operating temperature. On the starboard turbines these speeds were extremely high at 10 000 rev/min and 7500 rev/min for the HP and LP respectively, with 7513 rev/min and 6502 rev/min the corresponding figures for the port set.

It is difficult to comprehend the logic of this experiment as Cdr Phillips quotes the turbine efficiency for the starboard turbines as being only 3% better than the wartime designs and the port set only 1% better, a figure which is smaller than the measurement tolerances.[12] This does seem an amazing outcome for two turbine designs which encompass inlet temperatures at the limit of land power station use and rotational speeds which must have meant the acceptance of factors of safety significantly lower than normal.

A further mystery was the decision to link the cruise turbine directly to the HP rotor of the starboard turbine and so make it impossible to optimise its design. The port turbine had a cruise turbine linked through gearing in the same manner as the wartime machinery and ran at 14 000 rev/min at full power. G B Warren's paper,[8] read in 1947, contains curves which illustrate the advantages of using cruise turbines, the biggest gain of 22% being obtained by a de-clutchable unit. The reason for this is that if the cruise speed is 2/3 of maximum speed and the cruise turbine cannot be de-clutched, it will be subjected to over twice the rotor stresses at full ship's speed and this imposes a limit on blade speed at the cruise design point. To maintain the same stage efficiency twice as many stages would be needed, with attendant size and weight penalties as well as increased losses. Some of the resources devoted to the *Timmerman* experiment would surely have been better spent in developing a suitable clutch.

Unfortunately, future American machinery dispensed with a separate cruise turbine and utilised a combined single HP/IP rotor in two sections, which operated either in series or parallel when in the cruise or high power mode respectively (Fig 19). It is not possible, for the reasons given earlier, for this design to give as good results as a separate cruise turbine and there is also a further disadvantage. Combining the rotors in this way results in much bigger hub diameters being necessary to give acceptable rotor dynamic characteristics to a rotor having a greatly increased span between bearings. This heavy rotor will have a greater thermal inertia, thus making the turbine less amenable to temperature changes during start up and power changes. Thermal stresses relate to the size of the component

Fig 20: Soviet Sovremennyy Class destroyer powered by 2 x 55 000 shp steam turbines

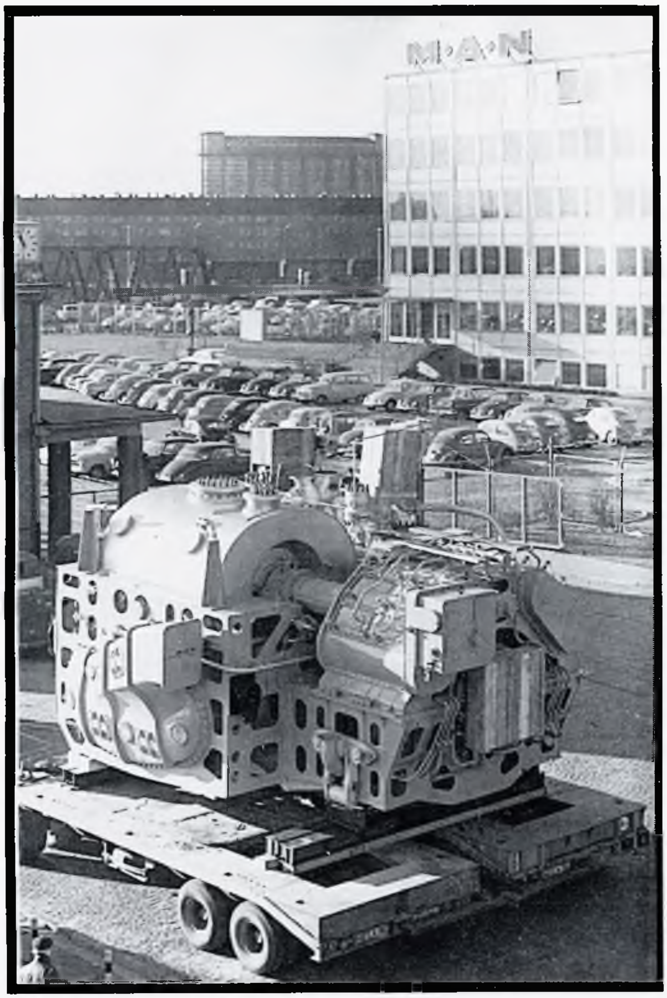


Fig 21: Hamburg Class machinery; West German destroyer powered by 2 x 34 000 shp MAN turbines, 900 lb/in^2/850°F (Note packaged unit construction)

and a small high speed separate cruise turbine is not only better able to receive the hot inlet steam, but is also beneficial in that the HP turbine is preheated by the cruise exhaust passing through it.

Classes of destroyers, cruisers and aircraft carriers were fitted with turbines having this series/parallel arrangement, which were built by both General Electric and Westinghouse, and operated on steam with conditions moderated from the levels used in the *Timmerman* experiment to 1200 lb/in^2/950°F. In 1968 the Spruance Class destroyers introduced the use of gas turbines for destroyers and frigates and all subsequent classes of these types of vessel have used gas turbines rather than steam for propulsion. Steam turbines utilising steam generated in PWRs are used in classes of cruisers and carriers with installed power levels of 60 000–100 000 shp for the cruisers and extending up to 280 000 shp for the monster Nimitz Class aircraft carriers. The turbines operate on 700 lb/in^2 saturated steam with unit sizes up to 70 000 shp.

A large fleet of nuclear submarines has been built up since *Nautilus* was commissioned in 1954 and these can now be regarded as the capital ships of the modern US Navy. The steam turbine used for their propulsion will have been the subject of continued development to give continued improvements in compactness, low weight and the ability to operate with extremely low levels of noise and vibration. The Ohio Class are immense vessels 171m long displacing 18 750t submerged and are reported to be propelled by 80 000 shp turbines to give underwater speeds of over 40 kn.

USSR

The Soviet Union has established a navy which is technically very advanced and, in the words of the editor of 'Jane's Fighting Ships' has 'a vivid programme of new construction'.[13] This extract is only referred to in the light of the much wider use of steam propulsion in the Soviet Navy compared with Western navies which have switched extensively to aero gas turbine propulsion. Thus, despite the fact that the Soviets were the first to use an all gas turbine drive for a major warship with the Kashin Class destroyers in 1962, their latest destroyers, the Sovremennyy Class (Fig 20), have an oil fired steam system reportedly utilising pressurised combustion chamber boilers, whereas the equivalent US Kidd Class ships are fitted with four gas turbines. The 23 400t Kirov Class battle cruisers use an innovative combination of nuclear generated steam for cruise with oil firing to provide boost for full power. The Kiev VSTOL carriers use a straight oil fired steam system.

No details of the steam turbines used in these very impressive modern ships have been made available, but in line with the innovatory features displayed by Soviet warships and by the evidence of their land power station turbine designs at very high steam conditions, it can be safely assumed that their design will be equally advanced.

This wide use of steam turbines for surface ships is supplemented by their application to the large fleet of Soviet nuclear submarines.

Other countries

Turbines have been designed and supplied during the period under review by world ranking companies, other than those referred to earlier, but only in very small numbers for their own navy and it is not possible to review their design in this paper. Typical of these are Rateau, Franco Tosi, Ansaldo, Mitsubishi and Wahodag (MAN). The latter introduced an interesting concept for the machinery for the four ships comprising the Hamburg Class destroyers whereby the turbine gearbox and condenser were unified into a monobloc structure which was pre-assembled and installed into the ship as a unit (Fig 21). The author put forward a similar scheme a few years ago thinking that it was an original idea which could have benefits in reducing radiated noise and vibration.

CONCLUSION

The future of the steam turbine for naval propulsion appears to be assured, partly because of the enormous advantage of using nuclear propulsion for submarines and other vessels, but also for other reasons as demonstrated particularly by their widespread use in the Soviet Navy. The continued development of aero gas turbines will make them even less suitable for use in warships than they are today. Increased gas temperatures, in the search for higher efficiency, will incur the need for even greater stringency in regard to fuel purity, difficult to achieve in a warship and to conformance to specification. This will amplify the difficulties already experienced and will be in contrast to the fuel flexibility possible with steam power ships. Similar points can be made in regard to high speed diesel engines which also require more space in the ship.

It is not believed that the use of extremely high steam conditions will be attractive for naval turbines and the successful designs will achieve the best compromise between a wide range of conflicting parameters. In some ways the principles established by the General Electric designers in the 1930s were ignored during the period reviewed and the inadequate use of cruise turbines by the two major Western navies remains a mystery to the author.

ACKNOWLEDGEMENTS

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Discussion

Cdr E Tyrrell (Retired) I was an Engineer Officer of an 'E' class fleet destroyer from March 1940 to March 1942 when that ship was sunk by a superior Japanese force in the Battle of the Java Sea. During the manoeuvres prior to and during the battle itself the superiority and economical performance of the US destroyers in company was all too apparent.

As the author has rightly said the reliability of the main turbines was good but unfortunately the same could not be said of the auxiliary machinery. The steam driven extraction pumps were a constant source of trouble as they used to trip out if a bomb was dropped within about a quarter of a mile of the ship.

As in the Mediterranean this was an almost hourly occurrence when the ship was at sea, the only answer was to lash the trip gear down with wire, accepting the danger that if the pump lost suction it would overspeed, fly into pieces, killing some if not all the engine room crew. The trip gear in HMS *Encounter* was lashed down for some 20 months. HMS *Ark Royal* (2) lost suction on the extraction pumps during trials although fortunately the ship was operating on electrically driven pumps at the time and the trip gear operated satisfactorily. On one occasion HMS *Encounter* lifted a main safety valve during high speed operations 5 miles off the Sardinian coast – the valve stayed open. Most of the boiler feed water was lost. Force H had no alternative but to leave the destroyer dead in the water to look after itself.

Fortunately hostile aircraft did not appear until the ship was under way at reduced power – the bombing that followed was possibly some of the most inaccurate the Italian Airforce was capable of.

The expertise and dedication of the Chief ERA was praiseworthy. The two of them kept cool by stokers playing sea water on them and they had that safety valve off the boiler, refitted and operational again in $6^1/_2$h. The ship, steaming at 32–34 kn, got back to Gibraltar 2h after the main fleet with 14t of fuel left.

Cruising turbines were fitted in both the 'E' and 'F' class destroyers. Operationally they were a dangerous nuisance. The synchromesh equipment did not operate satisfactorily so that cruising turbines could only be clutched in or out at very low speed. It was unacceptable to have to stop and declutch cruising turbines if a U-boat had fired a torpedo at you or the dive bombers were coming down. The cruising turbines did not seem to make much difference to fuel consumption and most Captains and Engineer Officers did not use them during war time.

After the war in Europe ended Churchill persuaded the US Navy to accept help from the Royal Navy in the far east. This the US did very reluctantly. The fuel consumption of the KGV battleships was, at the US Navy's operational cruising speed of 20 kn, almost twice that of the comparable Washington class. Hence the Royal Navy had to operate as a separate unit with its own fleet train and oilers because it required to take in fuel more frequently than the Americans.

After the war I was posted to the Admiralty for 4 years. There I found that those Engineer Officers who had operated HM Ships during the war were very bitter that they had been forced to fight with ships engined with machinery that was inferior to that available to their allies and enemies. The Admiralty were determined to improve the performance of British marine steam turbines. After a brake capable of absorbing 30 000 shp, which had been used to test the *Schasnhorst* and *Bismarck* machinery, was found in Germany and transported to this country, PAMETRADA was set up and the Y100 machinery tested on this German brake. I was posted to PAMETRADA to oversee the testing of the Y100 machinery and eventually accepted it for use in the Royal Navy (see p 94 of the author's paper). The troubles experienced during these trials were not with the turbines but with cruising turbine clutches. As mentioned by the author these were eventually abandoned. Also the employees in the Marine Engineering Industry seemed to have no idea that strict mechanical hygiene was necessary with highly rated machinery.

In 1956 I joined the Research Committee of PAMETRADA where I proposed that epicyclic gearing be used on the HP pinion of turbine machinery. This was rejected by the shipbuilders who maintained that work would be transferred from their own engine shops to WH Allen. This development was taken up by Stal-Laval whose generally advanced designs then took the larger proportion of the market.

After about a year I resigned from the Research Committee and in 1963 took up a post with the Department of Scientific and Industrial Research, later to become the Ministry of Technology. PAMETRADA was heavily financed by the Admiralty and the Ministry of Technology. Many of the marine engine builders were going out of business at that time and the contribution of the Marine Engineering Industry to PAMETRADA was falling while research costs were escalating rapidly. PAMETRADA was in serious financial difficulties and the Ministry of Technology consequently advised the Chief Engineer of Cunard that it might be advisable to seek a turbine manufacturer other than in the marine industry for the QE2 as PAMETRADA might not be in existence when the QE2 went to sea. This advice was ignored. The Council of PAMETRADA requested greatly increased grants from the Ministry of Technology in 1967. This request was refused in view of the small number of marine steam turbines then being built in the UK.

The QE2's turbines experienced blade failures on the maiden voyage by which time PAMETRADA had been disbanded. The Ministry of Technology placed and paid for a contract with Metropolitan Vickers turbine design team at Trafford Park led by Alan Beale, now Sir Alan Beale, to advise what should be done to put the turbine right. The Metro-Vic proposals were adopted and there have been no further reports of blade failures in the QE2's turbines.

The decision to set up PAMETRADA was a disaster. The land turbine industry, with its far greater research expertise and experience, had been unable to break into the marine turbine industry, and UK industry was unable to participate in the upsurge of demand for steam turbines which occurred with the construction of the large tankers and fast containerships.

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) Cdr Tyrrell's reminiscences of some of his wartime experiences with steam machinery are enormously interesting and contribute to a fuller understanding of why the Propulsion Committee was set up by the Admiralty at the end of World War II. His comments on the poor steam rates achieved by the cruise turbines on the 'E' and 'F' class destroyers undoubtedly indicate that their design lacked the fundamental approach indicated as necessary in my paper, ie I very much doubt if they were the small diameter high speed devices demonstrated to be capable of giving steam rate reductions of over 20%, compared with throttling the main engines. In the circumstances it did not make much difference that the clutches would not work either.

His direct confirmations of the high fuel rate of the *King George V*, one of our newest battleships, when compared with its USN equivalents, emphasised the urgent need to modernise British naval machinery.

I also found his comments on PAMETRADA to be extremely interesting and must agree with him that if the available Government funding had supported either Metropolitan Vickers or the English Electric Company, the outcome could well have been that Britain would have supplied a significant proportion of machinery during the boom years. Avoidance of the unnecessary blade failures on the QE2 machinery would have been a further bonus, but it must be acknowledged that PAMETRADA in its prime was highly successful and over 450 ships were powered by turbines of its design.

K Brownlie (Stone Vickers Ltd)

1. In the early days of World War II Metropolitan Vickers Electrical Co Ltd were manufacturing three sets of steam turbines for the Soviet Union. Following Dunkirk these turbines were shipped to the USSR before completion. It was not know at Metro-Vick whether they were completed and put into service.
   Perhaps British turbine technology originally helped in some small measure to establish the present wide use of steam plant in Soviet warships?
2. I wish to clarify one matter concerning the advanced machinery installed in the USS *Timmerman*. Cdr Phillip's paper,[12] does not quote fuel rate, or cycle efficiency or non-bled steam rates, but only refers to small improvements in the turbine efficiencies achieved in comparison with the conventional machinery. Taking the usual definition of turbine efficiency as useful work output divided by heat energy input, the designers of these high inlet condition turbines did well to achieve small increases in turbine efficiency.
   The higher steam conditions give a large adiabatic heat drop through the turbine and a turbine of the same efficiency produces more work output per unit mass of steam. Assuming a condenser vacuum of 25 in Hg in each case, the non-bled specific steam consumptions will have been reduced to about 73% for the port and 70% for the starboard turbines.
   Although more heat is needed to produce each unit mass of steam at the higher conditions, there will have been gains in the thermodynamic cycle efficiency and significant reductions in fuel rates when compared with the conventional machinery.
3. I would like to ask the author if he sees any future for combined cycle gas steam plants for marine propulsion?

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) Referring to the three points raised:

1. No doubt many of the excellent design features of Metropolitan Vickers' turbines found their way into Soviet machinery, but I think their wider use of steam machinery in their latest very advanced warships stems from strategic aspects, probably associated with the ability of steam machinery to operate on a wide range of fuels compared with gas turbines.
2. Keith Brownlie was a senior steam turbine designer earlier in his career and his comments on the *Timmerman* machinery are very relevant to the interpretation of the phrase 'turbine efficiency' as used by Cdr Phillips.

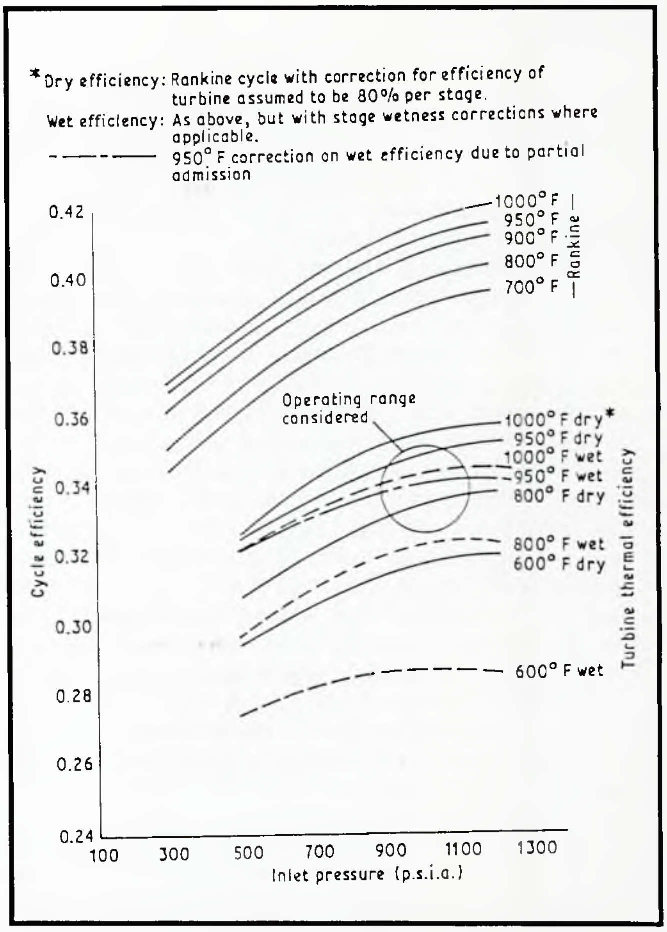

Fig 22: Effect of inlet pressure on efficiency for varying temperatures (28 in Hg vacuum)

   In my comments I interpreted the small improvements quoted by Cdr Phillips as relating to steam rate or turbine thermal efficiency rather than the as stated 'turbine' efficiency, and I should have made this clear. Taking the 'Brownlie' view that they were genuine improvements in turbine efficiency, then the experimental machinery would have given the reductions in steam rate he quoted of 27% and 30% respectively for the port and starboard turbines, this being the product of turbine efficiency x Rankine efficiency. If such improvements had been obtained, I feel sure Cdr Phillips would have referred to them rather than the minute improvements in efficiency actually quoted. I append curves showing turbine thermal efficiency, ie

$$\frac{\text{power output}}{\text{heat in the steam}}$$

   plotted against inlet steam pressure (Fig 22), from which it can be seen that an optimum pressure exists which depends on steam temperature. The optimum pressure for 1040°F steam would be about 1300 psi, whereas the *Timmerman* starboard machinery used 815 psi and the port side used 1805 psi. My guess is that both turbines were seriously understaged in the interests of compactness and the turbine operating on the 1805 psi steam suffered a further reduction in turbine efficiency, compared with earlier designs, as a result of the small specific volume of the steam. The greater available heat drop allows a higher Rankine efficiency which balanced out these reduced turbine efficiencies so that the turbine thermal efficiencies came out as 3% and 1% better than previous designs.
3. To the best of my knowledge the only merchant ships to be built which utilise combined cycle propulsion machin-

ery are the Soviet *Kapitan Smirnov*, which appeared at Tilbury in 1980, and its sister ships, these being 20 000 dwt ro-ro vessels. The fuel rate was quoted as 0.386 lb/shp h burning marine diesel and as this is not competitive with diesel and would be compounded by a high first cost and by the short life between overhaul for gas turbines burning a liquid fuel, it is unlikely to be repeated.

In the very long term a combined cycle system, incorporating a compact coal gasifier plant, could well become the coal burning propulsion system of the future in line with the likelihood of its wide adaption for land power stations. It offers a combination of high efficiency, low emissions and coal burning capability, but with the disadvantages of bulk and high first cost. Its main competitor would probably be a coal burning steam system operating with a fluidised bed at very high steam conditions.

A F Hodgkin (Retired) Thanks are due to Mr Nicholas for his review of the marine steam turbine which must cause a significant adrenalin flow in the veins of all steam buffs.

In the past I have co-operated with the author on many occasions, particularly with regard to steam driven fighting ships, and a comment on this section of the paper is that until a breakthrough in the combustion process is made it is wise not to utilise all of the size reducing potential of reduced turbine steam flow in cutting the volume of the combustion chamber. I know Mr Nicholas realises this but I like to remind him from time to time. The coal fired merchant ships built in the early 1980s proved that modern coal fired steam technology, by then in wide use ashore, could be successfully taken to sea. None of these ships, however, utilised the high steam temperature which coal firing would have permitted. Indeed in all cases the temperature level adopted was less than that on contemporary oil fired steamships so that unattractive efficiency comparisons were bound to occur. The reason for this choice of low steam temperatures did not appear to have any connection with the use of mechanical stokers which, as the author points out, do restrict the choice of coals for bunkers. It must be acknowledged, however, that some stokers are more flexible in this regard than others. Even the fluidised bed is not entirely free from restriction in choice of fuel. Admittedly much more flexible than stokers, it is still necessary to know at the design stage the likely range of fuel supplies so that proper design features are included, enabling trouble free operation to be achieved. Fuel taken out with the range for which the plant was designed is likely to cause difficulty whatever method of combustion is used.

Whilst agreeing with the author about the future for steam propulsion, I express the fond hope that someone somewhere is ensuring that sufficient development effort is being applied to the steam generator and combustion system to fit them for duty in the harsh marine environment of the next century.

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) Mr Hodgkin makes some very appropriate comments upon the influence of the boiler upon the overall steam plant. In replying to his final point, it is unfortunate but virtually certain that no development work on marine boilers and combustion systems is being carried out in this country. It is more likely that such work is being continued in Japan.

C R Berridge (GEC ALSTHOM Turbine Generators Ltd) Those concerned in the quest for better machinery for the Royal Navy after 1945 must have been convinced that reliable impulse turbines could be produced in Great Britain. It must have been a brave decision, after the history of troublesome impulse turbines in the 1939–45 war, although these were designs dating from the immediate post-1918 era. HMS *Hood* suffered stripped blades in 1940 during a chase in the Mediterranean, HMS *Enterprise* suffered engine defects, presumably blade or disc faults, while chasing German destroyers in the Bay of Biscay in 1943, and Dr Davis referred to HMS *Berwick's* machinery problems in his 1974 paper. But some of the Parsons turbines of the 1939–45 era and after suggested better designs were possible. Very early memories include engine room breakdowns in two Black Swan class sloops and these were probably drum distortions causing ‘rubs’. In 1957, HMS *Ark Royal's* programme had to be changed after machinery defects involved, it was said, three out of four sets of engines.

The success of the English Electric engine Daring class ships can be judged by their sale abroad after Royal Navy service, and they are still in service; a recent report states that they are about to undergo refit. Some of the Daring I ships are said to have suffered blade-vibration problems which must have made them less attractive for sale abroad.

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) Mr Berridge referred to problems with Royal Navy impulse machinery in World War II, but these related to turbines designed in the 1920s and should not be compared with postwar designs.

F A Manning (Retired) I am sure that many of us of the older generation who attended the presentation of this paper will have experienced a reliving of old memories. My own connection with marine engineering started in 1940.

The second speaker, Cdr E Tyrrell, mentioned in passing the Pacific Fleet Train, a mobile support group used to extend the operational range of UK fighting ships in World War II. I served as a Junior Engineer on a 1929 vintage cargo vessel converted to a fleet supply ship serving in this task force. The author may be interested to learn that this ship's main steam reciprocating machinery, typical of its time, had a power of 4800 IHP plus a Bauer-Wach turbine giving a total of 6200 hp. This figure is considerably higher than the 3000 hp upper limit stated in the paper.

During October 1945 I spent a brief period on a lease/lend escort carrier powered by a US Westinghouse geared steam turbine. The steam conditions for this plant were 450 psig at 750°F with a final feed temperature of 350°F which was to me, a 21 year old, right at the forefront of technology.

My subsequent career took me both in and out of marine engineering and the electrical power industry, and my experiences in both industries do not allow me to hold up either industry as a model for the other to follow. I believe that at the grass roots level both industries had a lot to learn from each other and that their respective blinkered managements have a lot to answer for in terms of the poor service performance and loss of reputation this caused our nation. Government reports, circa 1970, highlighted extensive machinery breakdowns to CEGB plant, together with delays in construction on site.

The author's disparaging remarks about reaction turbines, particularly those using built up methods of HP rotor construction are curious when examined in the context of CEGB purchases of 500 MW turbine generator units (650 000 shp). To my knowledge power stations at Ferrybridge, Fawley, Radcliffe, Rugeley and Pembroke numbering 18 machines totalling 9000 MW are still in service and therefore must be suspect to the author.

As a former marine turbine designer at PAMETRADA I would agree that Fig 1 represents machinery entering service in the 1950s. In parallel with this design another type of LP turbine was produced at the end of 1950 with disc and diaphragm construction and impulse reaction/blading, and first entered service in 1953. Over 60 repeat sets of machinery from this design were constructed mainly for 18 000 dwt tankers which were popular at the time. One reason for placing the HP astern blading in its own casing, overhung from the HP rotor, was to get away from the old Parsons Marine Turbine HP and IP cylinder with the diaphragm gland between ahead and astern blading. From my records I see that most cases of bent marine turbine rotors in the 1950s were rubs caused by deformation of this gland. I should be interested to know how many cases of axial fouling in LP turbines of the *British Venturer* type Mr Nicholas is aware of as I know of only one, which was due to a leaking astern steam manoeuvring valve.

My knowledge of United States GE marine turbines is somewhat limited as I have investigated failures in only two sets of their machinery. The first was a turbo-electric set in a T2 tanker and the second a geared set built about 1960 which failed in about 1962. The second case is, I think, the most interesting in that it highlights the disadvantages of having only one set of astern blading in a large single screw tanker. When steaming at full power the LP rotor fractured at mid-span with the fracture slightly saucer-shaped. Due to excessive vibration the watchkeeping engineer tried to stop the engine by shutting off the ahead steam supply, and then applied braking steam to the astern turbine in the LP forward end of the casing. I leave the details of what happened to the imagination. To bring the machinery to rest the ship was steered in a circle for about a quarter of an hour. The vessel duly entered the nearest port for repairs, which fortuitously for me happened to be in the UK. A new LP rotor from stock was delivered to the ship and the two piece fractured rotor was whisked away to the US in great haste but not before it was photographed by me.

Despite the glowing reference to GE(US) by the author, I find myself in a similar position to one who has bought a new dud car or washing machine and is being told that all other identical models are trouble free.

My final comment concerns the Daring class turbines referred to on p 93. In the merchant ships section of the paper it is implied that reaction turbines in general are very much less efficient than impulse machinery for the same power and steam conditions. It is stated that the Daring steam consumptions were closely similar for the impulse and reaction turbines tested.

Is the author able to shed any light on this peculiar result? Is it possible that the introduction of the 600 Series Parsons Blading, which was superseding the old pre-war 400 Series Profiles, could have finally bridged the efficiency gap?

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) Mr Manning raised a number of most interesting points on which I would like to comment.

The combination of LP turbine with a reciprocating engine gives an efficient prime mover, but a modern steam turbine would be more efficient as a much higher inlet steam temperature could be used than would be possible with a reciprocating engine. I did not suggest a 3000 shp limit for the latter, but maintain the view that the turbine is more efficient above that level of power.

Mr Manning has totally misconstrued my remarks about reaction turbines as the points I made referred to their inferiority compared with impulse turbines for the marine application and to the steam temperature limitations which resulted from the Parsons Marine shrink fit rotor construction. In my presentation I made the statement – 'the fact that both impulse and reaction turbines are both currently being built over 100 years after Messrs Curtis and Parsons had built the first practical examples of each type, is a clear indication that there is little to choose between them for land use'. However, NEI Parsons most definitely do not use shrink fit rotor construction for their current power station reheat designs operating on 565°C steam and these use monobloc forgings for all rotors.

Mr Manning refers to the very successful adoption of disc and diaphragm construction by PAMETRADA for their LP rotors and only the early designs used the *British Venturer* type of drum rotor. My criticism of this early rotor design stemmed solely from my own experience and I clearly expressed it as a 'personal viewpoint', which I think is a correct one, corroborated by the fact that PAMETRADA found it necessary to change to the disc and diaphragm arrangement.

Mr Manning's reference to a catastrophic LP rotor failure in a GE geared turbine in 1962 is very surprising in view of the high standards of control which were being applied to the production of turbine rotor forgings by that time. One can probably assume that that particular rotor suffered some very extreme form of abuse – possibly a sequence of prolonged astern running when extremely high temperatures would be reached, followed by rapid build up of ahead power when temperatures would plummet. A rotor temperature cycled in this way could build up high tensile stresses at the surface until sudden brittle fracture could occur, possibly with some slight surface damage or machining mark acting as a starter. I have absolutely no connection with the General Electric Company of America, but I have the greatest regard for their standards of turbine design and manufacture and particularly to the important contributions to turbine design technology which they have made over many years.

Finally, in reply to Mr Manning's question on the Daring class destroyers it must be noted that both the reaction and impulse turbines fitted to this class operated on the same steam conditions of 565 psi/825°F, far higher than the limit of 650°F imposed on the Parsons Marine designs by their poor design features. Thus the basic cycle efficiency was identical for the two types and Mr Manning may well be right in that modern blade profiles were used which improved the turbine internal efficiency.

E A Bridle (Retired) The author's excellent review will have caused many a sigh among those, like myself, who wielded a cudgel on behalf of the marine steam turbine in its long struggle for supremacy with the pressure-charged diesel engine.

The author clearly believes that all is not lost and that we may yet see the coal-fired steamship rise like a phoenix from its fluidised bed.

One must assume, however, that the diesel engine manufacturer will not be taken unawares by any major escalation in the price of oil and that he will make strenuous efforts to maintain an economic supply of liquid fuel, possibly making use of the author's speculative cheap coal. What are the author's views on this?

In acknowledging the contribution from the land turbine, the author has omitted mention of one requirement that is peculiar to the marine turbine, namely its need to operate on load over a range of different rotational speeds. In this respect, the design of marine turbines with acceptable blade and disc vibration characteristics is perhaps more demanding than that of the very much larger, but constant speed, land turbine.

On a point of detail, the later stages of the PAMETRADA 'impulse-type' LP turbines were, in fact, designed for nominally 50% reaction. The 'impulse-type' feature was their disc-and-diaphragm construction, which reduced both thermal inertia and leakage losses.

It is worth recording that many of the efforts in the mid-1960s to improve the competitiveness of the marine steam turbine, including the use of reheat and/or main engine-driven auxiliaries, sprang from a joint UK initiative by PAMETRADA and the Esso Petroleum Company described in Refs 1 and 2. A marketing drive in 1965 resulted in an internationally enthusiastic response and a spate of enquiries to PAMETRADA from a number of interested shipowners and some overseas shipbuilders. Unfortunately, most of the UK marine turbine manufacturers on whom PAMETRADA depended for its existence had been used to supplying only their parent shipbuilders and were unable (or unwilling) to respond to the opportunity to export their wares.

It is ironic that in 1967, the year in which PAMETRADA was dissolved, the UK shipbuilding industry received its first ever orders for a class of 250 000 dwt steam turbine-driven oil tankers from Esso.

References

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2. N J H D'Arcy, 'The prospect for steam propulsion', *Trans IMarE*, Vol 78, pp 409–425 (1966).

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) The diesel engine manufacturers are already engaged in development programmes with the aim of producing engines capable of burning fuels derived from coal and of burning coal directly. The latter is showing little sign of being successful and the cost of producing liquid fuels obviously introduces an economic handicap which hopefully will make direct coal burning steam systems viable.

Mr Bridle is correct in pointing out that as marine turbines operate at variable speed the blading has to be capable of withstanding a much wider range of vibration excitation frequencies than is the case for constant speed land turbines. Modern design methods ensure that marine turbine blades meet these requirements.

In regard to his next point, all modern impulse turbines utilise varying degrees of reaction for all stages of blading ranging from about 5% at the inlet end to 50% for the last stage at its mean diameter. I agree that, as Mr Bridle suggests, it is more accurate to describe LP cylinders as being of disc and diaphragm or drum rotor construction, rather than being of the impulse or reaction type.

Mr Bridle's reference to the collaboration between PAMETRADA and Esso was most interesting and the lack of follow-up is a confirmation of Cdr Tyrrell's comments on the limited capability of the PAMETRADA concept.

P B Welbourn (Fellow of Selwyn College, Cambridge) As the first manager of the Allen-Stoeckicht epicyclic gearing department, I was privileged to see some of the work described in this paper from the sidelines. Tribute should be paid to the two naval officers who were responsible for defining the problem facing the Service in its machinery development, and for initiating the work which led both to the founding of PAMETRADA and also the bringing of Herr W G Stoeckicht to work at Allens. These were Capt I G MacLean and Cdr W H B Lane. Our country owes a great deal to their drive and vision.

Before World War II, the turbines for the Royal Navy had been designed to have their point of maximum efficiency at full power. Analysis of ships' logs at the end of the war showed that only about 2% of their time was spent steaming at full power, and most of it at half power or less. When the American power station turbine designers had started work on marine turbines, the first question which they had posed was that of what were the normal operating conditions for their plant.

A further and important point in MacLean and Lane's analysis was that they considered in detail what proportion of the steam went to the propulsion machinery, and what to the auxiliary machinery.

This point is unfortunately not touched on in this otherwise admirable paper. They recognised that the auxiliaries were taking a large proportion, particularly when the steam lost by leakage at all the joints in the pipe runs was taken into consideration. As a result I was instructed, as an Acting Lt-Cdr (L), to persuade Professor K Röder to work at W H Allen Sons & Co Ltd. He had designed the turbines in the peroxide U-boats. A turbine to his design, of high efficiency with two Curtis wheels followed by reaction stages with unusual blade profiles, was unfortunately never built, since Capt MacLean had been superseded by a less imaginative officer. Some years later Allens was to license his designs from a German firm.

The Navy had also of course investigated the high pressure/temperature machinery in the German destroyers, and had been surprised to discover that the overall steam consumption had not been better than ours, primarily due to additional leakage at the joints due to the higher working pressures.

The state to which the art of Parsons type steam turbine design had fallen may be illustrated by the fact that in 1947/48 I was asked by one of John Brown's turbine designers how to estimate the efficiency of one of their turbines both at full and at part load.

The development of advanced thinking at Alfred Holt also owed much to MacLean and Lane. We designed epicyclic gears clutched to change them from sun gears to star gears for reversing the ships. These unfortunately were never built, although approved by Mr Archer of Lloyd's (they were so small that he suggested that a spare gearbox might be carried on the first ship), due to loss of nerve on the part of Allens.

On a point of fact, Stoeckicht gears were developed before the war, and two 1000 hp 1:5 step-up gears were fitted to the boiler feed pumps in Mannheim power station. They were also used in the Jumo 222 warplane.

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd) The reference to the early emphasis made by Capt MacLean and Cdr Lane on the proportion of steam absorbed by auxiliaries and leakages is of great importance to steam systems. Modern mercantile and naval machinery arrangements utilise auxiliaries which are either driven by electric motors or directly from the main engines or turbogenerators. Apart from avoiding the inefficient use of steam, this approach enormously reduces maintenance and simplifies the controls for unmanned operation.

The reference to Professor Röder's association with W H Allen is interesting as is the idea of using an epicyclic reversing gear, but presumably the cost of the latter is uncompetitive with the currently available hydraulic reversing coupling produced by Franco Tosi.

Professor E F C Somerscales (Rensselaer Polytechnic Institute, USA) The author is to be congratulated on providing an outstanding review of marine steam turbine developments during the last 40 years. This is a major contribution to engineering history, which has been compiled by one who has been directly involved in the activities he describes.

The main point that the author has brought out for this reader is the relative roles, in marine steam turbine history, of the disc type turbines and the drum type turbines. The former are most usually associated with the name of Curtis and the General

Electric Company in the US (this is not intended to slight these machines that are derivatives of the original concept of Rateau), and are typically of the impulse type. The drum type of construction is usually connected with the name of Parsons and characteristically is of the reaction design. The catastrophic effect of the disc failures experienced by the GE turbines in the 1920s and the consequent lack of competition experienced by the Parsons turbines appear to have had much to do with the limited improvement that was observed in this type of turbine in the 1930s (the author mentions particular construction features as playing a role, and surely the economic depression of the 1930s must also have played a role). However, GE recovered from their setback thanks to the important discoveries of Wilfred Campbell and this, together with a timely injection of government aid by way of the US Naval shipbuilding programme, ultimately led to the development of some outstanding marine steam turbine designs.

As the author recounts it, there was apparently no comparable advance in British naval machinery and this was amply demonstrated by direct comparison in World War II. However, it is surprising to learn from the author that a conservative frame of mind persisted among naval personnel and steam turbine designers even after the war. An insight into the thinking that led to this situation would be fascinating for those of us with an interest in the historical side of engineering.

Although more directly concerned with business history than engineering history, it is interesting to note the role of licensing in ensuring that the companies that originally developed steam turbine technology could maintain an economic market share. There is clearly an important lesson here.

D G Nicholas (GEC ALSTHOM Turbine Generators Ltd)
I thank Professor Somerscales for his comments on my paper.