EIGHTY YEARS WITH THE MARINE STEAM TURBINE

BY

DR. A. W. DAVIS, C.ENG., PRESIDENT I.MAR.E.

(Technical Director, Marine Turbine Division in Europe, Westinghouse Electric)

This paper, the 39th Parsons Memorial Lecture, was delivered on the 19th November 1974 at the Royal Institution of Naval Architects to the Institute of Marine Engineers by the Author, by whose permission it is reproduced here.

The Parsons Memorial Lecture was instituted in 1935 and is delivered annually under the auspices of the Royal Society. The range of Sir Charles Parsons's activities was very wide and included almost all branches of engineering and optics, and each Memorial Lecture deals with one of the subjects in which his interests lay and in which his genius played a part.

It is indeed an honour to be invited to present a memorial lecture commemorating the life work of a great engineer. As the years pass, such individual lectures inevitably stray further from the immediate triumphs of the man whose memory is being honoured, both because rapid developments can only be expected to obscure earlier achievements oft praised, and very properly lectures on topical associated subjects are chosen as being best worthy of commemorating past greatness.

The general intention of this lecture, which takes rather a different form, is to recollect the origins of the marine steam turbine, to show the heredity of current designs and the reasons why the marine creation of Parsons is no longer directly linked with his name in any current marine manufacture. A combination of circumstances developing in the years shortly after the First World War provided the basis for what followed twenty years later, and the author must be one of the last memorial lecturers who knew some of the personalities involved at that time and who later participated in some of the consequent drama with its less than happy conclusion. It is now perhaps well that events be recorded in broad outline.

Early Days

It is well known that *Turbinia* made her famous debut at the Review of the Fleet at Spithead in 1897, but the original turbines and the ship were constructed in 1894—hence the justification for the title of the lecture, despite the fact that the demonstration using improved turbines was delayed by understandable difficulties with the propellers.

Study of the history of the marine steam turbine becomes inextricably mixed up with inventions more particularly directed to land turbines, and around 1890 there were over a hundred relevant patents on the general subject. The need for a turbine was brought about by the development of the electric generator. As the quest was successfully pursued, the possible application to marine use was mooted in a few quarters—notably by Parsons and also by De Laval—but it was Parsons who had the initiative and the facilities to fight his way through the problems of the propellers. His marine action seems to have been particularly inspired by the first successful application of a condenser to a unit built by the C. A. Parsons Company for the Cambridge

Electricity Supply Company in 1891, and this gave promise of the possibility of the turbine becoming more efficient than the steam reciprocating engine.

It was long ago acknowledged that five names are bracketed as the basic inventors of the modern steam turbine. The names are those of Parsons, Curtis, Rateau, De Laval and Ljungstrom. Their heredity in relation to marine steam turbine manufacture is shown in FIG. 1, which progresses downwards in chronological fashion and terminates with full arrows pointing onwards to the future, representing firms in current production, turbo-electric manufacture being disregarded. Where the history is inseparable from land products, events relating to these are included and shown by broken lines. A few words of explanation will help to classify the inventions. The two-row velocity compounded impulse stage was the invention of Curtis. The single-row impulse stage was invented by Rateau, but could not be effectively patented in the U.S.A. because Curtis's invention embraced this simpler alternative. It is, however, a nice gesture to the French inventor that, in the U.S.A., such a stage is always known as a Rateau stage. This accounts for the fact that Rateau seems to play an obscure part in some of the events to be described, but with an odd sequel. In Sweden, there was De Laval who ran an almost parallel course to Curtis. In 1904, he was instrumental in setting up the American company that bears his name and which still flourishes. Later, in his own country, the company he founded was amalgamated with one that had been formed by Ljungstrom, who pioneered the double-rotation turbine, the new company being Stal-Laval whose product, a conventional axial flow machine, is so well-known in the marine world today. The impingement of these companies upon their competitors' history happened to be minimal and reference to them is minimal only for this reason.

Reference is rarely made today to the distinction between reaction and impulse turbines, but an appreciation of the difference in their principal characteristic is essential to a better understanding of what follows. The reaction turbine was really shared in conception between Parsons and Ljungstrom. The latter worked on a radial flow concept and so did Parsons at a fairly early stage. The first set of turbines for *Turbinia* were radial flow, but by 1897 these had been replaced by axial flow machines which Parsons understandably regarded as superior. Expansion of the steam takes place equally both in the fixed and the moving blade channels, which are of similar profile. Actual blade efficiency is superior to that of any impulse turbine and these maximum values were achieved by Parsons almost from the beginning —in fact the blade section of Parsons's reaction turbines remained almost unaltered as long as they were built, at least for marine use. Many constructional and probable operational problems were avoided by restricting the pressure drop over each row and providing the machines with a multitude of rows, usually divided between two or three casings operating over ranges of falling pressure. Blade construction was remarkably simple and the large number of blades even in each row provided a continuity of flow which produced only a very small fluctuation in steam force on passing blades. These, in general, had a vibrational frequency so high that fatigue failures were unusual—an example of Parsons's rare intuitive flair for settling on the most apt solution of a mechanical problem. An almost necessary feature of the single-flow reaction turbine is the provision of a steam-tightened dummy cylinder and rotating drum arranged to offset the axial force arising from the pressure drops across the moving row of blades. This always led to some loss of efficiency, but its presence became more disadvantageous as steam temperatures became higher. In fact as this happened the attractiveness of the reaction turbine for marine use became more restricted because of the high thermal inertia usually met with in conventional construction.

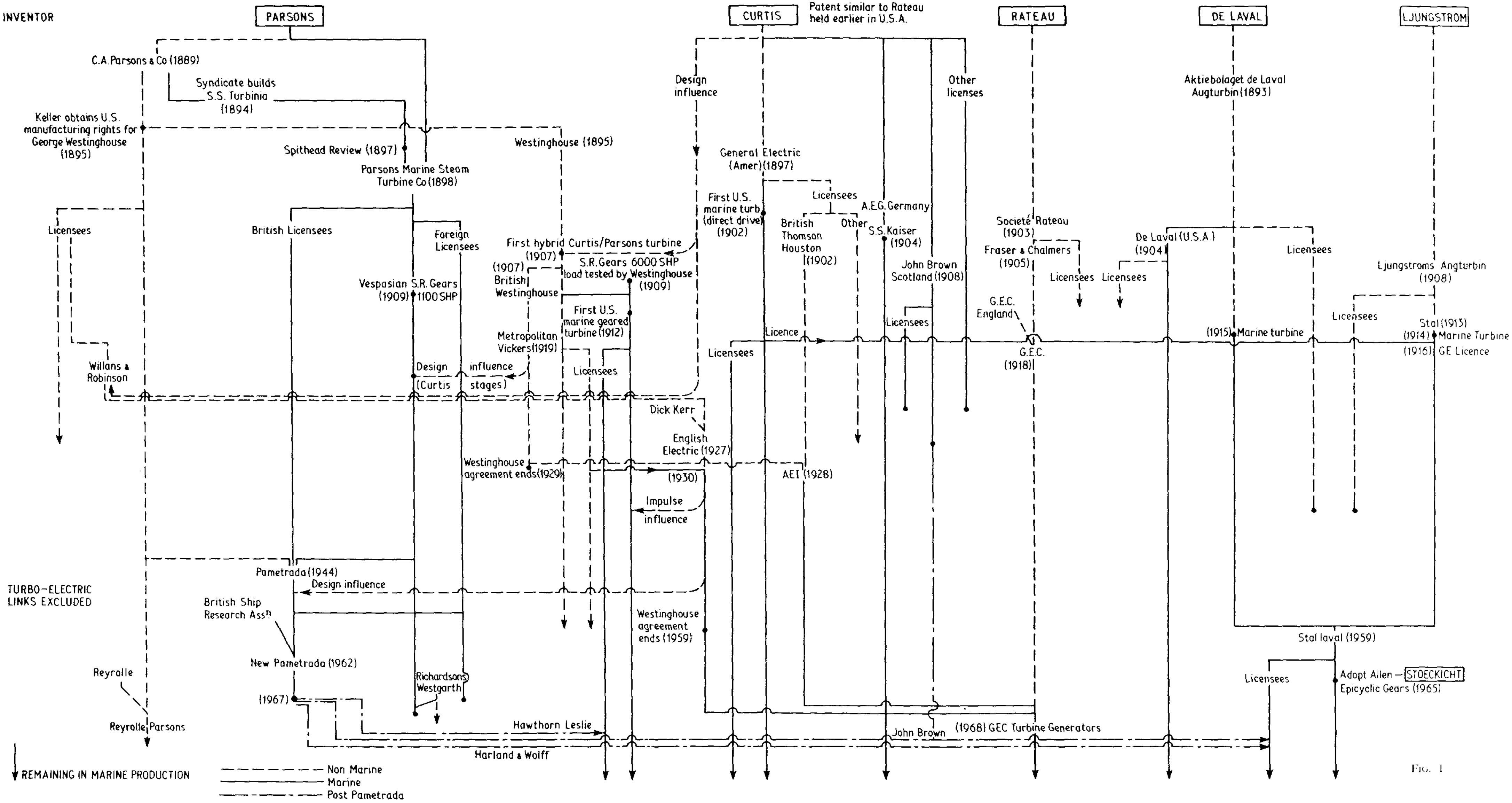
INVENTOR
PARSONS
CURTIS
Patent similar to Rateau held earlier in U.S.A.
RATEAU
DE LAVAL
LJUNGSTROM
C.A. Parsons & Co (1889)
Syndicate builds S.S. Turbinia (1894)
Keller obtains U.S. manufacturing rights for George Westinghouse (1895)
Spithead Review (1897)
Parsons Marine Steam Turbine Co (1898)
Westinghouse (1895)
Design influence
Other licenses
General Electric (Amer) (1897)
Aktiebolaget de Laval Augturbin (1893)
Licensees
British Licensees
Foreign Licensees
First hybrid Curtis/Parsons turbine (1907)
First U.S. marine turb (direct drive) (1902)
Licensees
A.E.G. Germany
British Thomson Houston (1902)
Other
S.S. Kaiser (1904)
Societé Rateau (1903)
Fraser & Chalmers (1905)
De Laval (U.S.A.) (1904)
Licensees
Ljungstroms Angturbin (1908)
Vespasian S.R. Gears (1909) 1100 SHP
(1907) British Westinghouse
S.R. Gears 6000 SHP load tested by Westinghouse (1909)
John Brown Scotland (1908)
Licensees
Licensees
First U.S. marine geared turbine (1912)
G.E.C. England
Licensees
Licensees
Stal (1913)
(1914) Marine Turbine
(1916) GE Licence
Metropolitan Vickers (1919)
Licence
(1915) Marine turbine
G.E.C. (1918)
Licensees
Willans & Robinson
Design influence (Curtis stages)
Licensees
Dick Kerr
English Electric (1927)
Westinghouse agreement ends (1929)
(1930)
AEI (1928)
Impulse influence
Pametrada (1944)
Design influence
TURBO-ELECTRIC LINKS EXCLUDED
British Ship Research Assn
Westinghouse agreement ends (1959)
Stal laval (1959)
New Pametrada (1962)
Reyrolle
Richardsons Westgarth
Licensees
Adopt Allen — STOECKICHT Epicyclic Gears (1965)
(1967)
Hawthorn Leslie
(1968) GEC Turbine Generators
John Brown
Reyrolle Parsons
Harland & Wolff
REMAINING IN MARINE PRODUCTION
Non Marine
Marine
Post Pametrada

FIG. 1

In the impulse turbine, the whole of a stage pressure drop occurs across fixed nozzles and the moving blades have to be sturdy to accept high velocity jets of steam. All nozzles other than the first stage have to be steam tightened with the rotor and, to keep leakage to a minimum, stationary steam-tightened diaphragms are interspersed between discs or wheels carrying the moving blades, the associated nozzles being termed diaphragm nozzles. This represents a degree of constructional complication that demands a minimization of the number of stages, great ingenuity in mechanical design, and, as the whole set-up is prone to possible serious vibrations which are hard to avoid entirely on a variable speed machine, great applied mathematical ability in adjusting the design to meet operating conditions. These circumstances provided a difficult basis for the original inventors. High-speed machines with constant-speed operation presented fewer difficulties and it is therefore seen that substantial development took place in power-station units before marine application was seriously pursued.

Nevertheless the first impulse marine turbine, having of course direct drive, was put in operation by General Electric in the U.S.A. in 1902, this being the company which had undertaken to develop Curtis's patents in that country. In 1904, the German firm AEG obtained a licence and forthwith engined the steamship *Kaiser*. In 1908, John Brown and Company of Clydebank, Scotland, obtained manufacturing rights in the U.K. from Curtis, who sent Stephen Pigott (later Sir Stephen) to assist in developing the turbine for marine use. Curtis is on record as having expressed his pleasure at the basic help given by John Brown in making a success of the marine application far in advance of the earlier work.

Another subject that requires special reference, to help in an understanding of events as they unfold, is that of geared drive. With outstanding ingenuity, Parsons made a success of direct drive, but its future was regarded with some scepticism which is best illustrated by referring back to George Westinghouse's actions. He was an American inventor with broad interests and had a deep intuitive sense much in the manner of Parsons. He had experimented with some forms of displacement rotary engines having relatively poor efficiency and was quick to recognize the value of Parsons's early work. In 1895, following a single interchange of letters, he arranged for a Mr. Keller to come over and negotiate for sole manufacturing rights in the United States and accompanying him on his homeward journey was the young technician Francis Hodgkinson who did much to develop the Parsons turbine in America. Possibly impelled by competitor GE's initiative in applying the Curtis turbine to propel a boat with direct drive, and perhaps wondering whether he was not missing out in not taking fuller advantage of his Parsons licence, Westinghouse, in 1904, sent Admiral Melville and John Macalpine to Britain to study the development of marine turbines, which by that time had been installed in 26 ships totalling 147 000 s.h.p. The crucial sentences of their report read: 'If one could derive a means of reconciling in a practical manner the necessary high speed revolutions of the turbine with the comparatively slow speed of revolution required by an efficient propeller the problem would be solved and the turbine would practically wipe out the reciprocating engine for the propulsion of ships. The solution of this problem would be a stroke of great genius'. As a consequence of this judgement a set of single-reduction gears transmitting 6000 s.h.p. was designed, built and finally shop tested under load in 1909. The forgings were supplied by Krupp of Essen and the teeth were cut by Schuchardt and Schutte of Chemnitz.

No doubt the American turbine industry also benefited in the early days from the competitive enthusiasm of De Laval at Trenton, where a very high quality hobbing machine commenced building in 1904, based on work done by De Laval in Sweden.

Meanwhile in 1909 Parsons had engined the now famous *Vespasian* with single-reduction gears and compound turbines developing 1100 s.h.p. The gears were supplied by the Power Plant Company, and the serious pitch errors in the teeth led to Parsons inventing the creep drive mechanism for hobbing machine tables, whereby the destructive potential of the errors of the master dividing wheel was minimized by their effect being spread in humps and hollows over the surface of the helically cut gear so that the axial uniformity of the errors was greatly reduced. It was in 1912 that Parsons wrote to Lord Fisher: 'I have come to the conclusion that gearing between engines and screw shafting will be essential, thereby reducing weight'.

It is thus seen that in America relatively few direct drive turbines were ever fitted, and it was into the second decade of the century before marine turbine production was widely undertaken. In this country by 1910 about 3 000 000 s.h.p. had been built with direct drive, including installations on famous liners such as *Mauretania* (74 000 s.h.p.).

The First World War

It comes almost as a surprise to reflect that nearly half the turbines installed in ships of the British fleet during the first war were built by, or under licence from, the John Brown Company, being of Brown Curtis design. The builders in every case were also licensees of the Parsons Marine Company. The author has records to show that the entire wartime output of naval turbines by the old Fairfield company was of Brown-Curtis type, and learns that John Brown and Company had a similar record. Some other licensees also produced this type in large proportion. An Engineer-in-Chief of the day is on record as having expressed the view that Brown-Curtis turbines had the advantage at all powers.

Despite personal contact with many of the people directly involved in those relatively early days, the author was surprised to discover in his recent researches how little seems to have been said later about this division of effort. Few engineers remembering the famous H.M.S. Hood recall that she was propelled by Brown-Curtis single-reduction turbines. The forgetfulness—and for a later generation, ignorance—may have been induced by the calamitous downfall of the Brown-Curtis turbine in the early 1920's, but the reasons for wartime popularity can be deduced from contemporary records. When war broke out, geared drive had only very recently come into production and the number of gear hobbing machines available must have been minimal. The Parsons Marine Company were in the driving seat and it was only right that they themselves should make best use of the facilities until they could be expanded. This meant that, early in the war, the bulk of naval tonnage would have to incorporate direct drive turbines. Because the speed of rotation was low with direct drive, the average blade diameters had to be proportionately large to maintain the blade speed required by the steam pressure drop per row. Blade heights were correspondingly shorter than would be the case with geared drive. The number of rows of blading was determined by the allowable pressure drop per row which was a function of mechanical strength. These facts apply to any type of turbine. But if the Parsons turbine had any obvious disadvantage compared with the Curtis, it was the much greater number of rows it contained. The undesirability was enhanced by large diameters and, therefore, the need for geared drive was more urgent for the Parsons turbine.

Not that the Curtis turbine did not show the need for just the same increase in diameters, but because it affected a shorter length of turbine the lack of gears was less objectionable (cruising turbines commonly incorporated drove through small gears that were readily available, but this was not the main issue and mention of them is included only to keep the record straight).

An actual advantage for direct drive to the Curtis turbine lay in the short blades which were less prone to vibration, regarding which so little was yet known. The fact that this was not readily appreciated was shown by the immediate adoption of single-reduction gears with Brown-Curtis turbines when such gears became available. It seems probable that the above-mentioned comment of an Engineer-in-Chief in favour of the Brown-Curtis turbine was made before the faster running turbines with longer blades on smaller pitch diameters came into operation; as these developed, their tendency to suffer blade fatigue failures (aggravated by an offset root fixing) and also loosening of disc wheels on the rotor spindles, demonstrated a weakness which began to undermine the popularity of the Brown-Curtis turbine.

All the same it was strategically sound that the nation's fleet should not be tied to one general design of turbine for propulsion where a good alternative was available.

The troubles that had later become prevalent led the Admiralty, after the war, to ask John Brown and Company to satisfy them on the establishment of the natural frequency of bucket wheels by test; but this the Company was unable to do and, perhaps more than anything, this led to the demise of the Brown-Curtis turbine, although they continued to be fitted for a number of years to come. Their ultimate extinction was confused with massive gearing failures more associated with bad gear cutting than with defective design, but before referring to these last troubles it is necessary to take another look at the concurrent situation in the United States.

Reference has already been made to the enthusiasm with which the Americans attacked the gearing problem once the need became clear, and their search for means of accurate production extended from Germany to Sweden. It could also be said that, entering the war three years later, they had nearly twice as long as European countries to develop the art before they became involved in mass manufacture. This time was by no means wasted and, although they had a small number of direct drive, single calibre battleships and destroyers building in the meantime, in 1917 and 1918 they placed orders for no fewer than 238 twin-screw, single-reduction geared destroyers, 107 having Parsons type turbines and 131 Curtis. At the same time, Westinghouse alone had on order turbines for 271 merchant ships with double-reduction gears. The turbines were of Parsons type, although it will be appreciated that by that time the Westinghouse-Parsons designs had been greatly modified to increase the work done by each stage and thus reduce the number of blade rows. That the facilities for gear cutting had been developed is shown by the fact that Westinghouse, as an example, had 16 high quality gear hobbing machines and 17 machines under manufacture, 13 to their own design based on the German experience and 4 from Gould and Eberhardt who, it is believed, were encouraged by General Electric and who made a massive contribution to the success of American gears in the following quarter century. There is evidence that by 1915 it was seen that adequate gear cutting capacity would be forthcoming, for it was in that year that General Electric introduced double-reduction gears in s.s. *Pacific*.

No more need really be added to point out American determination to avoid direct drive as far as possible, but it would be remiss not to refer to the fact that, to make the growing gear-cutting facilities available for the smaller ships, the battle-cruisers building were arranged for turbo-electric drive.

Looking now at the American situation at the end of the First World War, surely they had started to experience with their single-reduction Curtis turbines the same kind of troubles that Brown-Curtis had found. It could be said that, as the American turbines were designed in close conjunction with power station practice, earlier experience would have benefited the marine turbines, and yet operating conditions at sea are so much more severe that any such benefit could only have been marginal. It is likely that seagoing experience prompted the manufacturers to undertake massive research on the problems. Only this could have established the reliability that was achieved with the Curtis turbine by 1940.

And before returning from the American scene, let it be emphasized that double-reduction gears had become a proved success in the merchant fleet. Probably there was in fact quite a lot of trouble with early units, but there was seemingly no dismay and news of the achievements clearly made more of an impact on Brown-Curtis ears than any troubles. Britain was a war-weary country, while American inspiration was on the crest of the wave, and the effect of this might be seen in tendencies affecting the rebuilding programme of the merchant fleet.

Between the Wars

Despite known shortcomings, Brown-Curtis retained many of its adherents among the builders; and, although gear-cutting facilities were so limited (and so poor) in this country, it nevertheless happened that such turbines together with double-reduction gears were installed in some of the larger of the new ships building. How many of those responsible were rightly impressed with the American application of double-reduction gears without being aware of the dismal prospects attending the production of such gears in this country?

Parsons turbines were also being installed in conjunction with double-reduction gears, the first being in 1918 in s.s. *Somerset*. This particular installation gave satisfactory results for many years, but the general experience, as with Brown-Curtis turbines, was quite unsatisfactory.

Britain had survived the war with a large proportion of the fleet operating with direct drive and in its latter years the *Vespasian* enterprise had borne sufficient fruit to allow the new classes of destroyers, light cruisers and the K class submarines being built to take advantage of single-reduction gears. Indeed, as early as 1913, Scotts had engined the liner *Transylvania* with single-reduction geared turbines. Yet 1920 showed us unable to build satisfactory double-reduction geared installations while the Americans had scores at sea.

The interpretation of the problem lacked incisiveness and the action taken was to abandon double-reduction gears rather than to tackle the cause of the trouble. This had the most devastating consequences leading ultimately to the collapse of the Parsons Marine Company's position in the industry. The subject in its different aspects has been covered by many erudite papers once the consequences started to become apparent 20 years later. At the late stage of this review, only the highlights can be covered and this itself can be done in the briefest way by comparing British and American actions in tabular form as in TABLE I. This makes no reference to Diesel competition and there is no doubt that the demands so made on development capacity were great, although this should not have deterred the Parsons Marine Company from following the path it never took on its own initiative.

Reverting to the more general picture in the 1920's, one of the last Brown-Curtis turbine installations must have been the four single-reduction shaft sets in the County class cruiser H.M.S. *Berwick*, ordered from Fairfield in 1924. Perhaps the choice was influenced because the company was, at that time, still out of touch with design and construction of Parsons turbines but, with the Admiralty's knowledge, their own intentions seem obscure when looked at

TABLE I—*Gear development*

Item	*American Action*	*British Action*
Direct Drive:		*Parsons*
Production	Avoided as far as possible but about 160 naval shaft sets ordered during 1917–1918 war	Used extensively 1894–1916
Single-reduction Gears:		*Parsons*
First ship	*Neptune* 1912	*Vespasian* 1909
First liner		*Transylvania* 1913
Production before 1920	About 520 naval shaft sets ordered during war	Used increasingly 1915–
Quality	Good	Indifferent
Double-reduction Gears:		*Parsons*
First ship	*Pacific* 1915	*Somerset* 1918
Production before 1920	About 600 shaft sets for cargo ships ordered during war	
Type	Nested	Interleaved (nested)
Quality	Good	Seemingly acceptable
Production 1920–23	No specific information	Known to be for several ships including liners
Type		Interleaved
Quality		Disappointing
Further policy	Continue nested type	Revert to single-reduction
Further policy	Develop articulated type for flexibility of heavier parts for higher powers	—
Further policy	Develop locked train type for naval work	—
Production 1941–45		
Type—Naval	Locked train	Single-reduction
—Merchant	Nested	S.R. or nested
Quality	Excellent	Good
Production 1950–		*Pametrada*
Type—Naval	Locked train	Locked train
—Merchant	Articulated	Articulated
		QE2—Locked train
Quality	Excellent	Excellent

half a century later. The vessel survived through the Second World War and repeatedly provided the author with his only first-hand experience of the troubles to which such turbines were prone. TABLE II is included to show the abrupt changes reflected in turbine output as typified by the old Fairfield company. For simplicity of reference, the table is extended into a period yet to be described in this article, but it will be noted that despite its adherence to Brown-Curtis during the first war, as much as 49 per cent. of the total turbine horsepower it ever produced was to be built under licence from the Parsons company, within the years between 1925 and 1945. The outputs given in the table represent, on average, nearly 9 per cent. of the marine output of the country as a whole.

TABLE II—*Total powers of different types of turbines built by a company representing about 9 per cent. of U.K. output.*

Cumulative total s.h.p. completed through year	*Parsons Design*			*Brown-Curtis Design*			*Pametrada design Double reduction*
	Direct drive	*Single reduction*	*Double reduction*	*Direct drive*	*Single reduction*	*Double reduction*	
1907	33 500	—	—	—	—	—	—
1910	278 000	—	—	—	—	—	—
1912	327 000	9 500	—	—	—	—	—
1914	460 000	,,	—	280 000	—	—	—
1916	479 000	,,	—	781 000	—	—	—
1918		,,	—		413 000	—	—
1924		11 000	—		598 000	79 200	—
1930		151 000	—				—
1936		274 000	—				—
1940		654 000	—				—
1944		2 212 000	—				—
1965							346 000

Perhaps the supreme example of the change in thought which occurred in the 1920's is given by the case of the C.P.R. liner *Empress of Canada*, completed in 1922 with twin-screw, double-reduction Brown-Curtis turbines and re-engined five years later with single-reduction geared Parsons turbines. This reflects not only the troubles referred to above, but also the fact that in the interval Parsons had established a growing reputation for success with high powered, single-reduction geared units. Due to retention of existing Scotch boilers, albeit with smoke tube superheaters added, the steam conditions for the new turbines were 190 lbf/in^2 and 580°F (although two years later *Empress of Japan* was to have steam at 375 lbf/in^2 and 700°F). The new turbines corrected back to exclude the advantage of superheat were $3\frac{1}{2}$ per cent. more efficient than the Brown-Curtis units they replaced.

This represented the surge of engineering opinion of the day back towards Parsons. The author served his apprenticeship in this atmosphere and recalls that not only had Brown-Curtis acquired a poor reputation but, by reason of the connexion, American turbine practice was mistakenly at a discount in marine circles. Although the great advances made in the U.S.A. in the next ten years or so were far from being lost on the land turbine builders in this country, they were very largely, if not completely, disregarded by the marine community so recently attracted back to Parsons. The British marine turbine industry had in fact become introverted.

The latter half of the 1920's saw Parsons making two outstanding attempts to develop turbines suitable for higher steam conditions.

1926 brought the installation of a twin-screw, high-pressure, single-reduction geared unit operating at 550 lbf/in^2 and 750°F fitted in *King George V*, a vessel built for passenger service on the West Coast of Scotland. The design incorporated high-pressure turbine elements that could be removed if unsatisfactory. The turbines were in fact a success, but water tube boilers were unsuited for the service and suffered, it was found, from being supplied with impure water. After two sets of boilers supplied by different makers had failed, conventional boilers were fitted and the high pressure turbine elements removed.

Meanwhile in 1927, years before the possibility of a re-armament programme was envisaged, construction was under way for an advanced installation in the destroyer H.M.S. *Acheron*. This was a twin-screw set of single-reduction geared turbines operating with boiler steam conditions of 550 lbf/in^2 and 750°F and developing 34 000 s.h.p. The vessel was three years in building and it was unfortunate that the trials turned out to be disappointing. Vibration occurred in the H.P. turbines and was thought to be caused by either a movement at the shrunk joint of the drum type rotor due to thermal

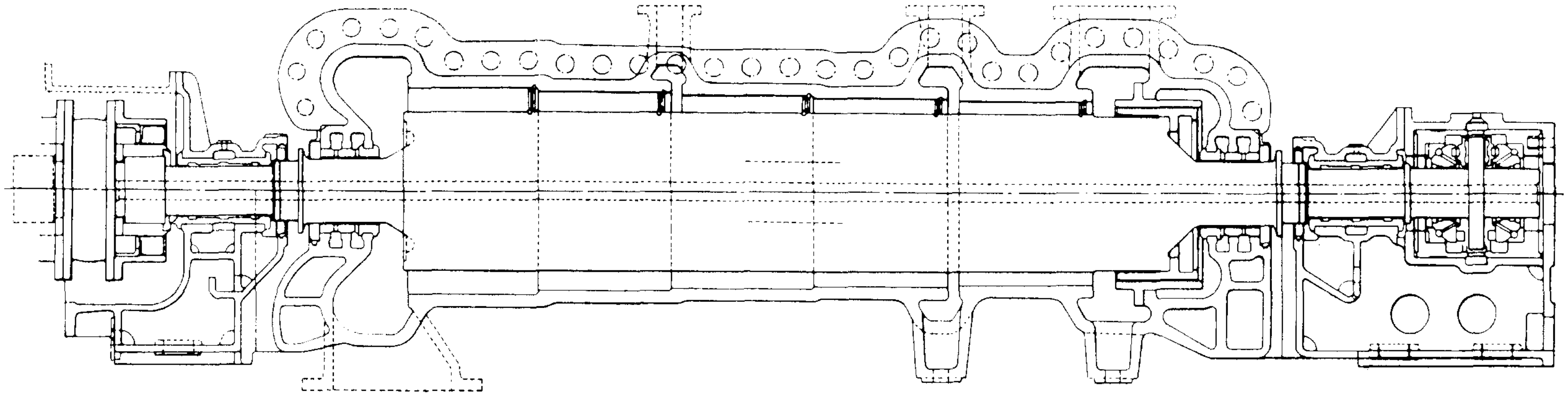

FIG. 2—H.P. TURBINE

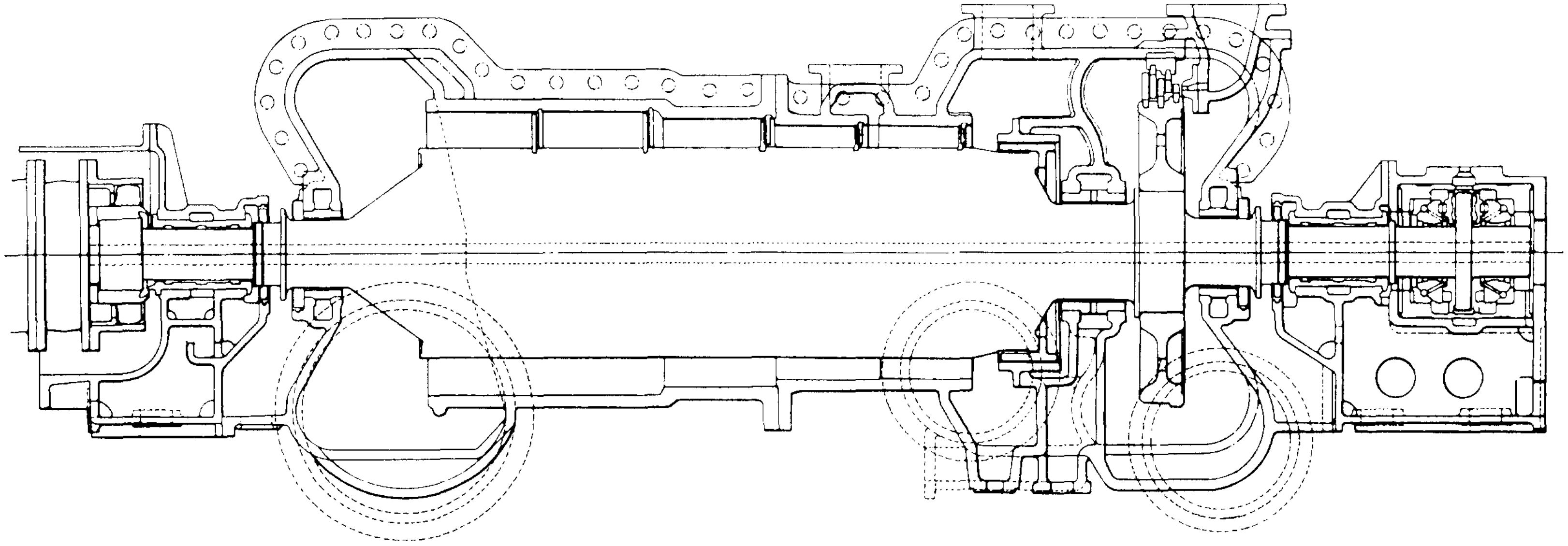

FIG. 3—I.P. TURBINE

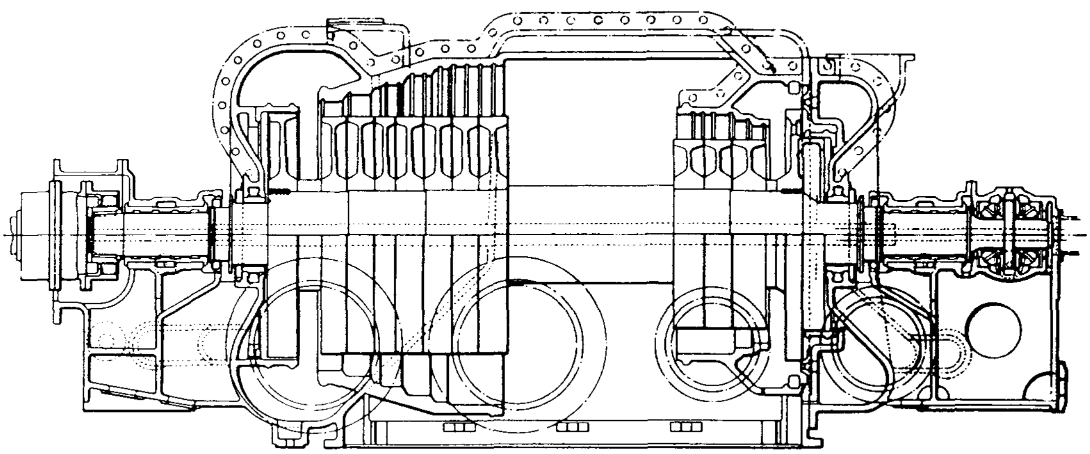

FIG. 4—L.P. TURBINE

inertia under transient conditions or by a rub due to distortion of the hot end of the turbine casing. Either cause was enough to cast doubt on the soundness of the design but, eight years later, the late Engineer Vice-Admiral Sir George Preece said, in opening the discussion on the late Mr. S. S. Cook's paper (dealing in part with the design), that the difficulties were no reflection on the designers and could not reasonably have been expected to be foreseen. Be this as it may, and despite success with merchant installations at this temperature, the Admiralty was not disposed for further research of this nature. The year 1931 saw the death of Sir Charles Parsons at the age of 76, with all that that meant to his Marine Company. It was also the year of the Depression. A policy was established in new building that steam pressures should be limited to 400 $\mathrm{lbf/in^2}$ and temperatures to 700°F, and long before circumstances could justify second thoughts on so vital a decision the re-armament programme had become a reality.

A damaging habit that developed in the following years was the adoption of a large margin in control pressure to obtain the guaranteed power. Apparently to obviate complaints of failure to obtain full power because of careless blade segment manufacture, the Marine Company developed the practice of providing this margin in control pressure, so that if blades were correctly made the steam would have to be severely throttled if the desired power were not to be exceeded. The Marine Company was always adamant that its designs were correct in this detail, regardless of any evidence the licensee might have which satisfied him that this was not so. Licensees and customers alike became embarrassed.

The Second World War

Re-armament commenced in 1935 and construction was thereafter based on designs of 1930 enlarged to meet progressively higher powers. Single-reduction gears were still employed. When war again broke out in 1939, there must have been very few engineers in the country who realized that the Parsons marine turbine was outdated, and the author does not recall any conversation whatever that made the suggestion. In any case, the vital matter was production, and this was surely achieved in tremendous measure. FIGS. 2, 3 and 4 show H.P., I.P. and L.P. turbines typical of high-power merchant units produced in the immediate pre-war days. Compound turbines of a rather similar design, but with double-flow L.P. turbines and no astern reaction blading were built to the extent of possibly 20 000 000 s.h.p. for warships in the period 1939–1945.

For a full appreciation of the position of the naval turbines, one has to look again at the developments that took place in America during the approximate period 1925–1940. Westinghouse are treated separately from other foreign licensees of Parsons because their marine turbines developed from their land experience and with the coming of gearing they adopted divergent features of design. Nevertheless, with the growing superiority of the impulse system, General Electric and De Laval were ahead on turbines, but all were employing pressures and temperatures well above British practice. In the realm of double-reduction gears, all three of these companies were producing a high quality product embracing locked trains driving a common main wheel, but Westinghouse, having earlier adopted the shaving finishing process, were producing a higher standard of finish than their competitors. The use of the divided (locked) train gears allowed in the limited available space for the higher turbine speed of revolution required by higher steam conditions, therefore showing a lower consumption rate and, vital for warships, a greater endurance.

The difference in performance arising from such an arrangement was only clearly shown when America entered the war and U.S. and British destroyers were engaged on similar duties in the Pacific, although it must be added that superior endurance was only made possible by better husbandry of the American boiler plants.

At this time the Admiralty concluded that the Parsons Marine Company were not adequately in touch with modern land practice, and set up an Advanced Steam Conditions Committee to vet competitive designs in this country. This was perhaps intended as a less hurtful way of saying that the reaction turbine was outdated for marine use. The response of the marine industry's technicians was that land turbine designers, whatever their virtues, were ignorant of the requirements of a marine turbine to accept quick changes of temperature and to run astern. Nor were they enamoured of the impulse turbine except for an initial relatively rugged Curtis stage.

The committee was asked in particular to study designs prepared by English Electric, to whom experience was available from Westinghouse, who by this time were also producing all impulse turbines. Moreover they had designers of exceptional ability. It had to be conceded that the design looked attractive if one accepted the claims for its immunity from vibrational failures and if the manufacturing facilities for the turbines and the divided train gears were available—which they were not in this country. In fact, starting in 1944, it took five years to raise the standard of the highest quality gear-cutting machines in a manner necessary for the hobbing of locked train gears. In this country they had become known as divided train gears, but the American description is more vivid because it emphasizes that, the divided trains being locked together, any tooth pitch error upsets the equal division of power between them—a fact overlooked when at one time it was thought we might catch up with U.S. practice under wartime conditions.

The representatives of Parsons Marine were understandably hard to impress, as they seemingly saw no reason to depart from the practices established by Sir Charles so many years earlier. Apart from that company, all the marine engineering manufacturers were owned by shipbuilders who technically were guided by their engineering associates and who moreover were not disposed to see their turbine business pass into other hands.

As emphasis continued to be placed on land turbine builders' abilities, it was felt that the marine industry's best ally was C. A. Parsons (now part of Reyrolle-Parsons) who were asked by the marine industry to join in forming the Parsons and Marine Engineering Turbine Research and Development Association, Pametrada. The Association was also to be responsible for turbine and gearing design. Apart from its advantages and inevitable disadvantages, this arrangement also had the expressed virtue of preserving the name of Parsons in marine turbine manufacture. The Association was formed in 1944 and originally comprised all the 16 British marine turbine licensees of Parsons Marine, the Marine Steam Turbine Company itself and C. A. Parsons, and also had Admiralty representation on the board and on the various technical committees.

The Rise and Fall of Pametrada

The success of getting such an organization off the ground was largely due, from the managerial point of view, to the untiring efforts and assistance of C. A. Parsons who were a sound and technically well equipped company. Their lack of marine experience was offset by the ability of the Research Director, transferred from one of the marine member firms, and the technical experience of the member firms themselves—but the whole set-up still lacked the impulse turbine expertise which the Admiralty knew was needed.

This shortcoming was, however, largely met by inviting a most able designer from English Electric to fill the post of Chief Designer, and it was this move that really made way for the ultimate break with the all-reaction tradition. It was perhaps a little hard on English Electric, and must have placed the Admiralty's representatives in a rather embarrassing position, although this was no doubt alleviated by their subsequent invitation to Yarrows to work with that company in engining two destroyers, the first with Fairfield gears and the second with Maag, the latter design having gears with hardened and ground teeth.

It almost follows that the Admiralty, as it then was, were never really enthusiastic about the whole arrangement. They felt that a design organization could not hope to develop an adequate link with widely spread manufacturing facilities, either to control their practical functions or indeed to learn from their mistakes. There was much truth in this viewpoint, but opportunities were on occasion taken to exacerbate weaknesses that could have been overcome had different personalities sometimes been involved.

In actual fact, while the Admiralty placed a lot of full-scale testing and research work with Pametrada, their turbine machinery design commitments were limited to six of the eight Daring class destroyers, and even one of these had an H.P. turbine designed by BTH. All later steam-propelled ships had turbines designed by English Electric or AEI with gears by David Brown or AEI. Many member firms of Pametrada took out licence agreements with these other manufacturers. Had the Admiralty's approach been different, Pametrada, apart from the contribution it could have made, might have been encouraged to become an even more effective instrument and could perhaps have weathered the storm in which it ultimately foundered. On the other hand, while it is the author's opinion that the Admiralty could have received steam turbines equally as good as those they actually obtained, the doors would not have been opened to them to make the delicate change from steam to gas turbine propulsion and, from this vital aspect, the country, and indeed the Western world, would have been the worse off today.

However, it is not the purpose of this lecture to dwell on such difficulties. Rather it is the intention to show the background against which a rather cumbersome organization operated very successfully for the first fifteen years of its existence. There were significant changes in organization as the years passed but, in the author's experience, it was a unique example of earnest, hardworking co-operative effort between competitors. Within a year or two of the Association's formation, turbine designs of an entirely different calibre were coming forward, and these were continually improved upon. Although their first designs were of reaction type, at an early stage they produced H.P. turbines of an impulse type and later L.P. turbines of a disc and diaphragm type with reaction stages towards the exhaust end; these changes being sequentially in order of design importance. In the research station which was built, a lot of development was carried out on components and a full-scale test bed was in use for much of the time, very often testing turbine and gear units of advanced design built and/or designed by land turbine and other interests. Extensive gear trials were run and much valuable information was thus accumulated.

Looking back on the early days with the advantage of hindsight, one feels it is perhaps a pity that a great proportion of available effort was put into the design and testing of a gas turbine with its gears, most of which was manufactured by member firms. The effort was really before its time and lacked the vast background of unified experience necessary for embarking on a project that, 30 years later, can still not be regarded as a commercial success, apart altogther from its very practical success in the Navy.

A difficulty that became apparent as the years passed was not foreseen at the outset. This was that if designs were to be standard in any way, they had to be suited to the member manufacturer least well equipped with machine tools. This also tended to preclude construction that could only be effected with special equipment and, as larger units developed and the quest for higher efficiencies went on, this became a significant handicap. To some extent it was minimized by individual firms equipping themselves for particular processes based on a subcontracting potential, but this was never very popular because of the fear of delays in delivery from overwhelmed units. Difficulties arising from any poorly supervised work by member firms were later mitigated by Pametrada employing their own adviser who would visit the members regularly, discuss their problems and make recommendations as to procedure and equipment.

In selecting diagrams that would show typical Pametrada turbines, the author has been under some difficulty, because the turbines he considers to be the most practical are those produced some years before the Association's dissolution, and yet to choose earlier drawings might indicate personal bias. The problem is overcome by showing, in FIGS. 5 and 6, a special design of 1960 that would not otherwise ever have been published. These are the turbines designed for the 20 000 s.h.p. single-screw nuclear-propelled tanker which the Ministry of Transport contemplated building. The H.P. turbine takes steam at 465 lbf/in^2 and 510°F exhausting at 90 lbf/in^2 6·8 per cent. wet to a steam reheater from which it passes to the L.P. turbine at 60 lbf/in^2 and 460°F, exhausting to the condenser at 28·5 in. vacuum 10 per cent. wet.

Unhappily there were members who after some years felt that they then knew enough about modern turbines to carry on without reference to Pametrada (except to their earlier drawings). It was only fitting that they should have themselves suffered for any mistakes so made, but it became hard on other members when later these drawings might be circulated to meet the needs of an owner extending a class of ships building. It was such an instance in 1959 that led to at least one of two member firms deciding that the time had arrived for another string to be provided for the bow.

One of these member firms took out a licence with Westinghouse. The other took a licence with Stal-Laval who at that time were breaking into the world market with a very successful drive. It has been pointed out how little marked by dramatic incidents has been the steady development of this latter firm, but perhaps just at this stage they made their sharpest departure from convention by the adoption of primary epicyclic gears of the Allen-Stoeckicht type in conjunction with orthodox secondary gears. In certain instances these have been followed by triple-reduction gears for the H.P. turbine, the first two

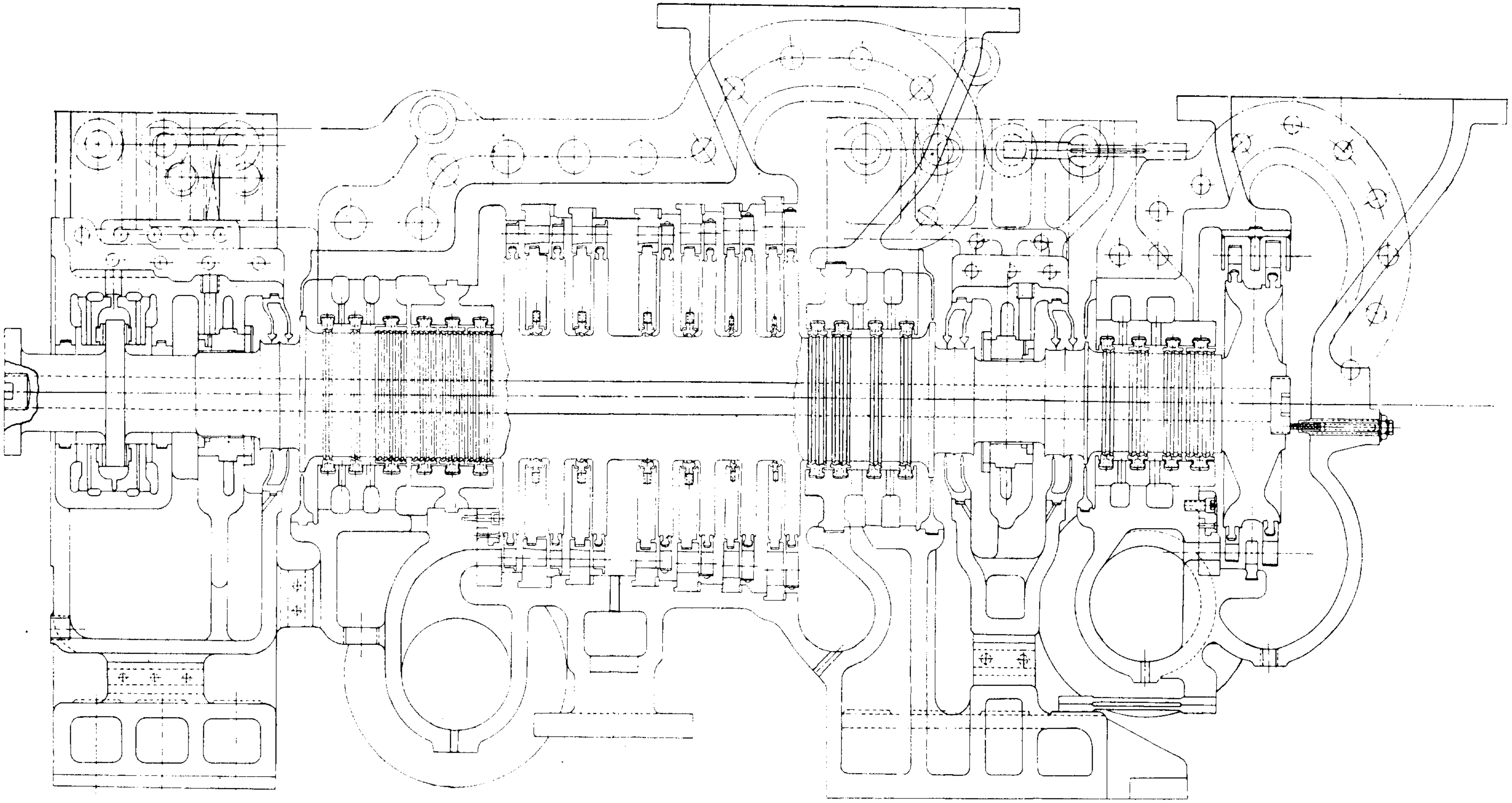

FIG. 5—H.P. TURBINE

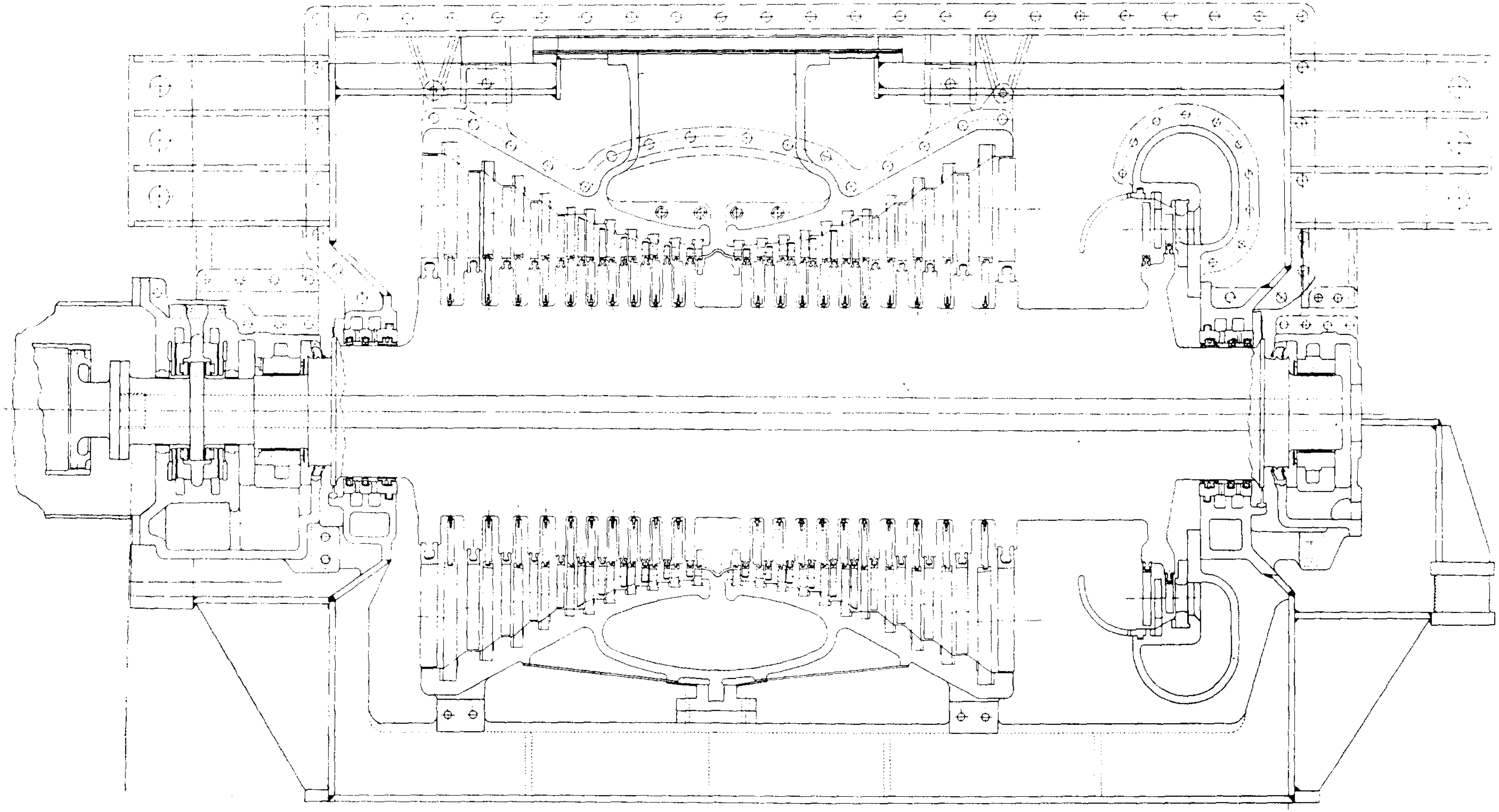

FIG. 6—L.P. TURBINE

reductions being epicyclic. In this regard Stoeckicht ranks as a basic inventor and, in recognition of this, his name is so indicated in FIG. 1.

In 1958 there was a growing concern among the Pametrada membership for the need to be able to market geared turbines of higher efficiency in an attempt to offset the increasing seriousness of diesel competition, although it was thought by some at the time that the designs were becoming over-complicated while still lacking the ruggedness that could only come with more general adoption of specialized manufacturing facilities. However, at the end of that year, member firms became almost united in their desire that a large capacity, high pressure, variable high temperature boiler be installed at the Research Station for testing turbines that would be of super advanced character. There followed the need to design such turbines but by the time manufacture had commenced financial difficulties were already looming ahead. Although the turbines were duly tested, they were never sold as a high-pressure installation and the sought-for boost to sales did not materialize. In 1967, the organization was dissolved, leaving the country largely uncompetitive in the boom for turbines for VLCCs which followed so shortly afterwards, and for all of which the operational steam conditions have been conservative. This was the final and saddest chapter in the story in which so much had been achieved, often in conditions of turmoil of one kind or another. If one were asked to point to the fundamental cause of defeat it surely would be fair to say that it was a failure on the part of Parsons Marine to recognize that, while the all-reaction turbine was supreme in the conditions existing at the time of its invention, in marine propulsion the impulse turbine was by its nature bound to win over for at least most of the cycle as the more sophisticated techniques it required became available, as knowledge of vibration and fatigue developed and as steam conditions were hence capable of being advanced, subject to the availability of gears of superior design and manufacture. Some acceptance of this situation should have been demonstrated in designing the machinery for H.M.S. *Acheron*, after which the whole future might have been different. Blindness was worsened by the double-reduction gear failures which occurred at a period which should only have been an interlude in success between the marine turbine's first quarter century and the era that was cut short by reluctance for further research. But as the 1920 gear trouble was countered by retreat, one is left wondering whether Parsons himself was lulled into a false sense of security, perhaps by thinking that his masterly creep invention had made possible the production of adequate gears. Certainly his company did not take any action in advising their licensees of the real situation but perhaps they lived in ignorance of it. It is, however, right to interject here that when the finishing process of shaving came to be adopted in the late 1940's, the finest results were achieved when the teeth had been cut on high quality hobbing machines incorporating Parsons creep drive.

The last machinery designed by Pametrada was that for the Cunarder *QE2*. An early fault is referred to in a paper by Fleeting and Coats, but the proved relability in this Queen of the Seas will provide a memorial for Pametrada for as long as she sails. It is fitting that in the context of the complex history of the marine turbine the builder should have been John Brown.

Marine Steam Turbine Manufacture Today

In the form of a postscript, it is interesting to study the development of relationships between turbine-building firms shown on FIG. 1 and to find that a link between Parsons and current marine production still remains.

Several references have been made to the fundamental influence of Parsons in helping Westinghouse into the turbine business and to contributions that

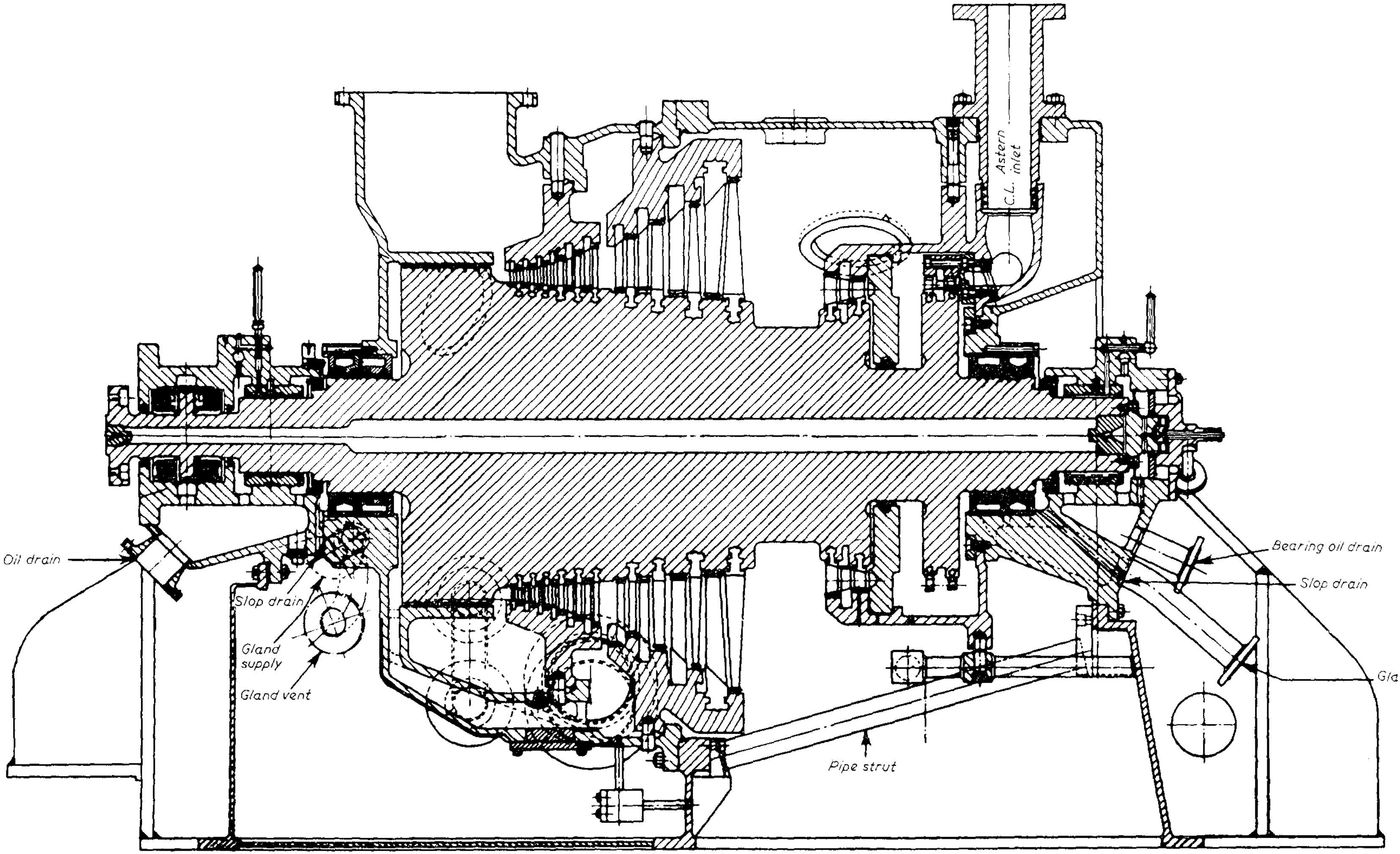

FIG. 7—SECTION OF L.P. TURBINE AND ASTERN ELEMENT

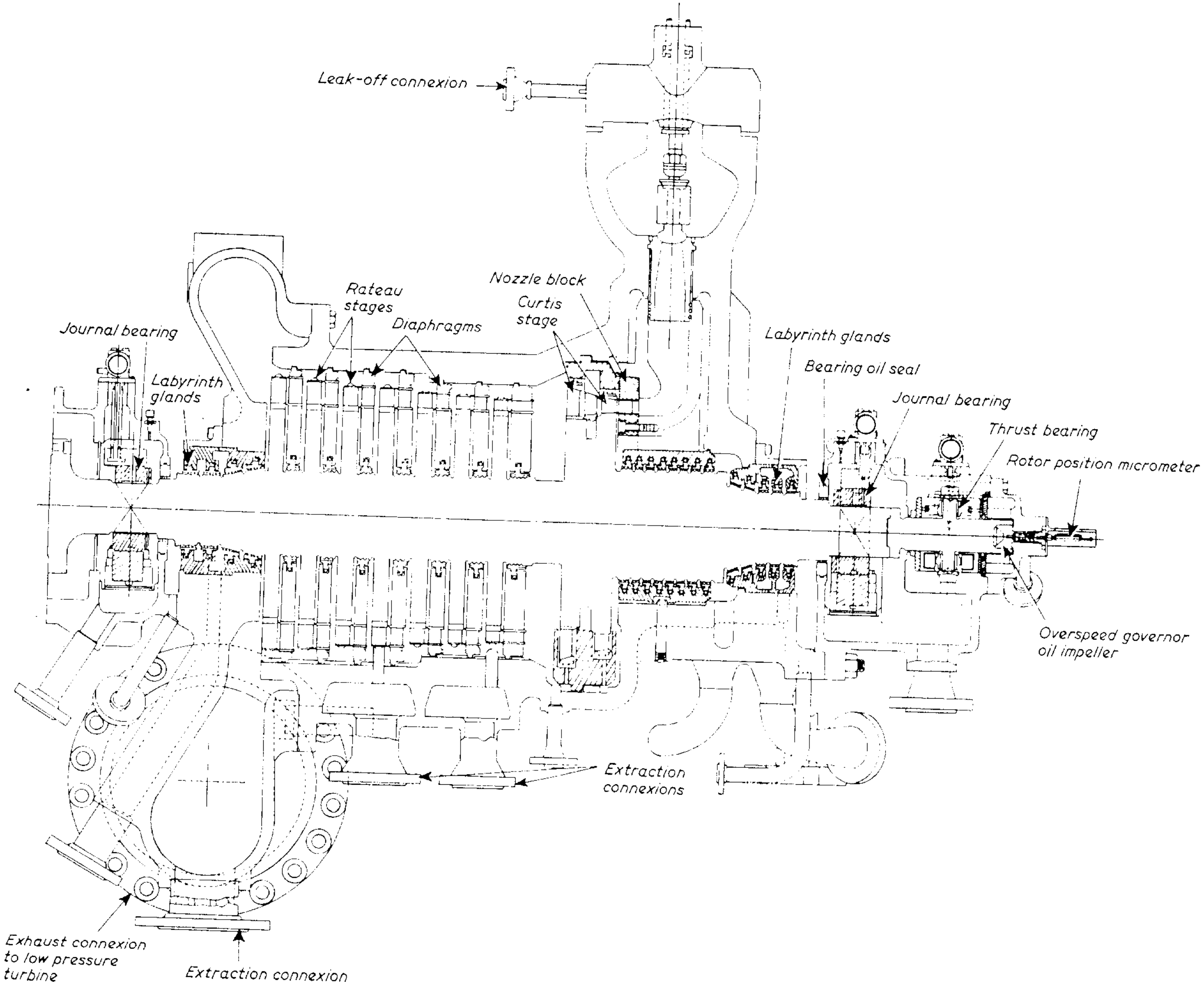
Leak-off connexion
Nozzle block
Curtis stage
Rateau stages
Diaphragms
Journal bearing
Labyrinth glands
Labyrinth glands
Bearing oil seal
Journal bearing
Thrust bearing
Rotor position micrometer
Overspeed governor oil impeller
Extraction connexions
Exhaust connexion to low pressure turbine
Extraction connexion

Fig. 8

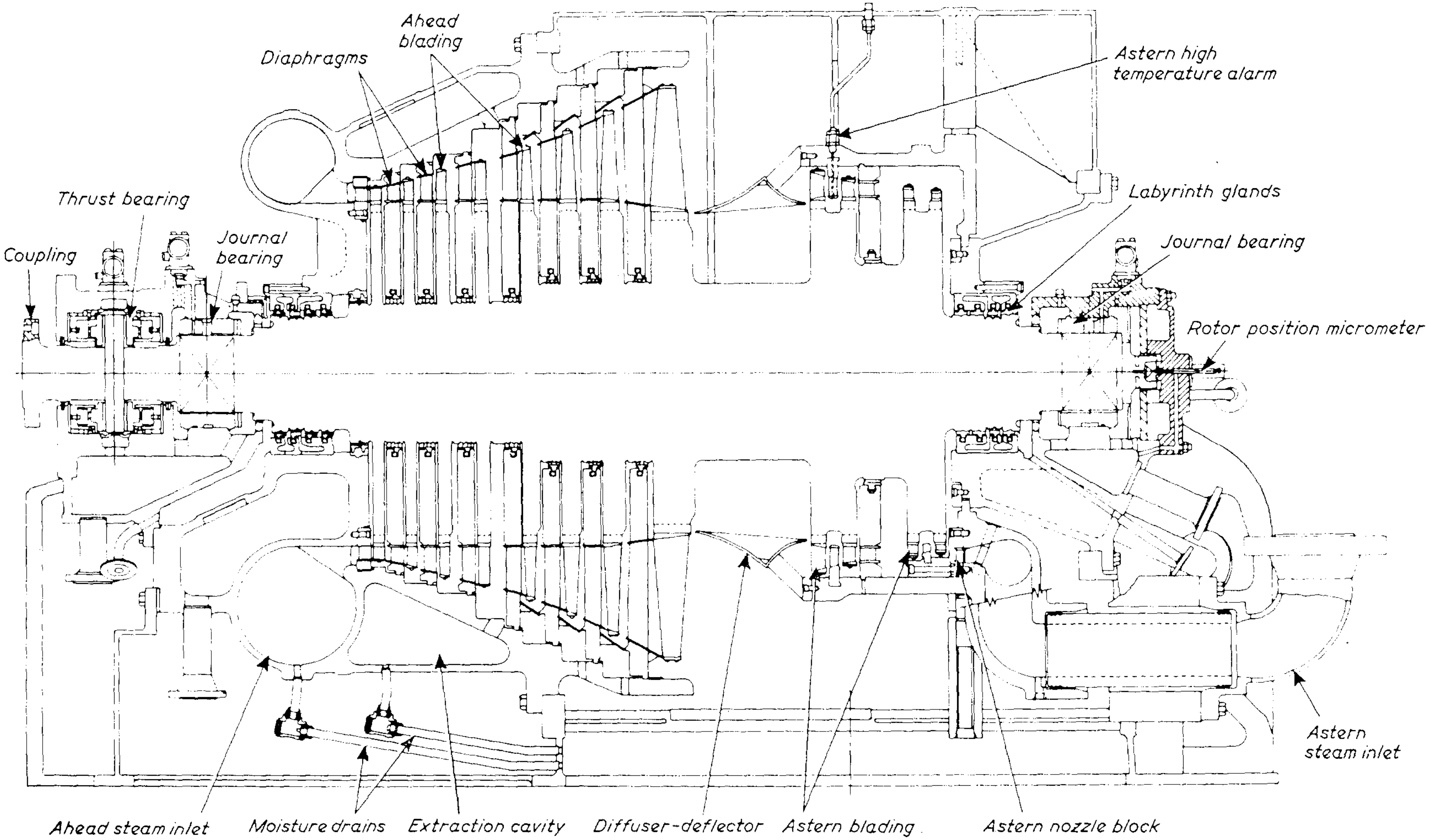
Ahead blading
Diaphragms
Astern high temperature alarm
Thrust bearing
Labyrinth glands
Journal bearing
Coupling
Journal bearing
Rotor position micrometer
Astern steam inlet
Ahead steam inlet
Moisture drains
Extraction cavity
Diffuser-deflector
Astern blading
Astern nozzle block

FIG. 9

that firm in its turn made to this country. They saw for themselves the need to develop a higher pressure drop over each stage and, while still being wedded to the reaction principle, they did this in a very effective way by using massive plant to produce forged blades suited for higher speeds and which varied in profile from stage to stage and radially as required. However, for naval construction, the advent of the locked-train gear, with its capacity to allow turbines to run faster, eventually broke down this last bastion, and they switched to impulse design, first for the H.P. turbines and then for the L.P., although to this day the rotor blades in the last few stages are of a form that creates a partial reaction effect to significant advantage.

After the Second World War, reaction L.P. turbines were once more used for merchant construction, and one of the last of these, built in the mid 50's, is shown by FIG. 7, which represents the ultimate in marine reaction turbine design. But heat inertia made even these turbines sensitive to rubs unless handled with special care, and they were finally dropped so that the maker's reputation might not suffer—the reaction turbine had a long following of admirers. Lest this be thought to represent modern design, FIGS. 8 and 9 show contemporary designs of H.P. and L.P. turbines for 40 000 s.h.p.

Referring back to FIG. 1, it will be seen that Westinghouse and their licensees today represent the closest link with Parsons.

It would be unreasonable to comment on the whole diagram in any detail but one cannot help being struck, and even surprised, by its complication. An odd sequel was earlier hinted at in making minimal reference to Rateau but, now looking to the similarity between the original patent and current designs, it is not inappropriate that this should be the inventor most closely linked by licenseeship and successive ownership with the only firm producing marine turbines in this country (except under foreign licence), namely GEC Turbine Generators Limited, Manchester, whose premises were built by George Westinghouse and are identical with a building in East Pittsburgh where heavy electrical rotating machinery is still built. The interlocking of turbine manufacturing interests makes a fascinating study.

In a concluding glance at FIG. 1 it will be seen that the line representing the Parsons Marine Steam Turbine Company carries on downwards beyond the point where the Company entered membership of Pametrada, and this reflects the fact that for some time they retained their own design potential. The last set of turbines manufactured to Pametrada design were completed in 1962, these being for the Shaw Savill liner *Northern Star* of 22 000 s.h.p. total on twin screws, with boiler steam at 600 lbf/in^2 and 900°F. The last installation was completed in 1964 and was for H.M.S. *Glamorgan*, having turbines of AEI design.

Acknowledgements

Many people in different parts of the world have been most helpful in the author's quest for information and although it is impossible to mention all these by name, he would particularly like to refer to Mr. E. P. Crowdy, Mr. Williams and his staff of the Institute's library and to Mr. W. McLaughlin, formerly Chief Engine Designer with the old John Brown Company, who gave valuable information regarding the significant role played by that company in the events described. The author also wishes to thank Reyrolle-Parsons Ltd. for providing the photograph of Sir Charles Parsons and the Society of Naval Architects and Marine Engineers, New York, for permission to reproduce FIG. 7 of this lecture from the 1954 Transactions of that Society.

Bibliography:

'Some Notes on Steam Turbines'. Warburton, F. J. *Trans.N.E.C.I.E.S.*, 1901–2.
'The Curtis Steam Turbine'. Emmet, W. L. R. *Proc.I.Mech.E.*, 1904.
'Marine Application of the Curtis Steam Turbine'. Curtis, C. G. *Trans.S.N.A.M.E.*, 1905.
'Design and Progress of the Floating Frame Reduction Gear'. Macalpine, J. H. *Trans.I.E.S.S.*, 1918.
'Progress in Turbine Ship Propulsion'. Hodgkinson, F. *Trans.S.N.A.M.E.*, 1918.
'Experience and Practice in Mechanical Reduction Gears in Warships'. Tostevin, H. B. *Trans.I.N.A.*, 1920.
Janes Fighting Ships. 1921.
'High Pressure Geared Turbine Steamer *King George V*'. *The Shipbuilder*, Oct. 1926.
'The Steam Turbine in the United States'. *Trans.A.S.M.E.*, 1936:
  i. Developments by the Westinghouse Machine Co. Keller, E. E. and Hodgkinson, F.
  ii. Developments by the General Electric Co. Robinson, E. L.
'Sir Charles Parsons and Marine Propulsion'. Cook, S. S. *Proc.I.Mech.E.*, 1938.
'A Short History of Naval Marine Engineering'. Smith, E. C. Cambridge University Press, 1938.
'Modern Marine Steam Turbine Design'. Cook, S. S. *Trans.I.Mar.E.*, 1938–39.
'The Engineering of High Speed Ships'. Pigott, Sir Stephen. *Trans.N.E.C.I.E.S.*, 1940.
'Reduction Gearing for Marine Steam Turbines'. Dorey, S. F. 1942.
'The Development of Marine Engineering'. *Trans.S.N.A.M.E.* (Historical), 1893–1943.
'Parsons—The Man and His Work'. Gibb, C. *Proc.I.Mech.E.* 1947.
'Progress in Marine Propulsion 1910–1950'. Barnaby, K. C. *Trans.I.N.A.*, 1949.
'Some Operating Experiences with Westinghouse Marine Turbines'. Anderson, H. *Trans.S.N.A.M.E.*, 1954.
'Birger and Fredrik Ljungstrom'. Publ. A. B. International Stal Co. 1955.
'A Review of Naval Propulsion Engineering Progress in the Last Ten Years'. Mason, Sir Frank. *Trans.N.E.C.I.E.S.*, 1956.
'A Marine Engineering Review—Past, Present and Future'. Brown, T. W. F., *Trans.R.I.N.A.*, 1960.
'British Destroyers'. March, E. J. *Seeley Service*, 1967.
'De Laval Memorial Lecture'. Jung, J. J. and Sonderberg, C. R. R. Swed. Acad. Sci. 1968.
'Anatomy of a Merger'. Jones, R. and Marriott, D. Publ. J. Cape. 1970.
'Blade Failures in the H.P. Turbines of the RMS *Queen Elizabeth 2* and their Rectification'. Fleeting, R. and Coats, R. *Trans.I.Mar.E.*, 1970.
'Design, Operating Experience and Development Potential of Marine Propulsion Epicyclic Gears'. Jones, T. P. *Trans.I.Mar.E.*, 1972.

APPENDIX

PREVIOUS PARSONS MEMORIAL LECTURES, 1936-1973

Year	*Title, Lecturer and Institution*
1936	'Sir Charles Parsons and Steam' by Sir Frank E. Smith, K.C.B., D.Sc., F.R.S. (North East Coast Institution of Engineers and Shipbuilders).
1937	'Scientific Activities of the late Hon. Sir Charles Parsons, O.M., K.C.B., F.R.S.' by G. Stoney, D.Sc., F.R.S. (Institution of Electrical Engineers).
1938	'Sir Charles Parsons and Marine Propulsion' by S. S. Cook, B.A., F.R.S. (Institution of Mechanical Engineers).
1939	'Some Researches on Steam Turbine Nozzle Efficiency' by Dr. H. L. Guy, F.R.S. (Institution of Civil Engineers).
1940	'The Engining of Highly Powered Ships' by Sir Stephen J. Pigott, D.Sc. (North East Coast Institution of Engineers and Shipbuilders).
1941	'Sir Charles Parsons and the Royal Navy' by Sir Stanley V. Goodall, K.C.B., O.B.E., R.C.N.C. (Institution of Naval Architects).
1942	'Reduction Gearing for Marine Steam Turbines' by S. F. Dorey, D.Sc., Wh.Ex. (Institute of Marine Engineers).
1943	'Optical Topics in part connected with Sir Charles Parsons' by Lord Rayleigh, F.R.S. (The Physical Society).
1944	'The Determination of Critical Speeds, Natural Frequencies and Modes of Vibration by Means of Basic Functions' by Professor C. E. Inglis, LL.D., F.R.S. (North East Coast Institution of Engineers and Shipbuilders).
1945	'High Voltage Research at the National Physical Laboratory' by R. Davis, M.Sc. (Institution of Electrical Engineers).
1946	'Recent Developments in Optical Glass Manufacture' by Sir Hugh Chance (Institution of Civil Engineers).

1947 'Parsons—The Man and His Work' by Sir Claude Gibb, C.B.E., M.E., F.R.S. (Institution of Mechanical Engineers).

1948 'British Marine Gas Turbines' by T. W. F. Brown, C.B.E., D.Sc., S.M., A.R.T.C. (North East Coast Institution of Engineers and Shipbuilders).

1949 'Progress in Marine Propulsion, 1910–1950' by K. C. Barnaby, O.B.E., B.Sc. (Institution of Naval Architects).

1950 'Sir Charles Parsons and Cavitation' by Professor L. C. Burrill, M.Sc., Ph.D. (Institute of Marine Engineers).

1951 'Sir Charles Parsons and Optical Engineering' by F. Twyman, F.R.S. (The Physical Society).

1952 'From Stodola to Modern Turbine Engineering' by C. Seippel (North East Coast Institution of Engineers and Shipbuilders).

1953 'Continuity of Electricity Supply' by H. Leyburn, B.Sc(Eng). (Institution of Electrical Engineers).

1954 'Factors Influencing the Continuing Development of the Steam Turbine' by F. Dollin, B.Sc.(Eng.) (Institution of Mechanical Engineers).

1955 'The Development of the Gas Turbine' by Sir Harold Roxbee Cox (Institution of Civil Engineers).

1956 'A Review of Naval Propulsion Engineering Progress in the Last Ten Years' by Vice-Admiral Sir Frank T. Mason, K.C.B. (North East Coast Institution of Engineers and Shipbuilders).

1957 'Aspects of Propellers for the Royal Navy' by R. W. L. Gawn, C.B.E., D.Sc., R.C.N.C. (Institution of Naval Architects).

1958 'Some Recent Progress in Nuclear Engineering' by Sir John Cockcroft, O.M., K.C.B., C.B.E., F.R.S. (Institute of Marine Engineers).

1959 'Atmospheric Imaging Systems' by Dr. C. R. Burch (The Physical Society).

1960 'Sir Claude D. Gibb—Engineer' by A. T. Bowden, B.Sc.(Eng.), Ph.D. (North East Coast Institution of Engineers and Shipbuilders).

1961 'Magnetohydrodynamics' by Professor M. W. Thring, M.A. (Institution of Electrical Engineers).

1962 'The Duty and Development of Modern Power Station Plant' by F. H. S. Brown, C.B.E., B.Sc. (Institution of Mechanical Engineers).

1963 'Spadeadam Rocket Establishment' by A. B. Mann (Institution of Civil Engineers).

1964 'The High-Speed Generator—Eighty Years of Progress' by W. D. Horsley (North East Coast Institution of Engineers and Shipbuilders).

1965 'Sir Charles Parsons and the Naval Architect' by Professor E. V. Telfer, Ph.D., D.Sc. (Royal Institution of Naval Architects).

1966 'The Prospect for Steam Propulsion' by Captain N. J. H. D'Arcy, R.N. (Institute of Marine Engineers).

1967 'The Measurement and Control of Small Displacements' by Professor R. V. Jones, C.B., C.B.E., F.R.S. (Institute of Physics and the Physical Society).

1968 'Sir Charles Parsons and Astronomy' by Mr. G. M. Sisson (North East Coast Institution of Engineers and Shipbuilders)

1969 'Large Turbine-Generators—A Survey of Progress' by Dr. A. Frankel (Institution of Electrical Engineers).

1970 'Designing Warships for Cost-Effective Life' by Vice-Admiral R. G. Raper, C.B. (Institution of Mechanical Engineers).

1971 'The Linear Motor and its Application to the Tracked Hovercraft' by Professor E. R. Laithwaite (Institution of Civil Engineers).

1972 'The Development of Large Wet Steam Turbines' by Mr. N. C. Parsons (North East Coast Institution of Engineers and Shipbuilders).

1973 'The Impact of the Gas Turbine on Warship Design' by S. J. Palmer, C.B., O.B.E. (Royal Institution of Naval Architects).