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PROGRESS IN MARINE ENGINEERING.

" *The following article formed the subject of a lecture before the Institution of Mechanical Engineers by the Engineer-in-Chief of the Fleet.*"

The bewildering variety of marine engine types and designs now available springs from the same motives that have always existed during the application of mechanical power to the propulsion of ships. It will, I think, be of interest therefore to trace in broad outline the principal developments since early days. A consideration of the reasons leading to changes from time to time, of the successes and above all of the failures, particularly those failures which later " came back," may indeed assist us to view in a better perspective the significance and promise of the modern advances and trends. In any case, and apart from the technical issues, the high endeavour of our predecessors affords an example whose study can hardly fail to stimulate our efforts at the present stage when further very substantial advances in progress are resisted by what appear to be great difficulties.

The motives to which I have referred are, broadly : the generation and application of power in the most economical way with the means available ; the design and production of machinery making a minimum demand on ship space and displacement ; and, paramount in the case of marine installations dependent for long periods on their own internal resources, the attainment of a design promising a proper standard of reliability and durability. These essentials are common to all marine installations whether mercantile or naval, although individual considerations modify the relative significance mainly of the two first-named, premising that the word " economical" implies capital cost no less than running costs.

My remarks will deal in the main with naval installations, but, while I am conscious that the history of the Mercantile Marine has been ably reviewed from time to time before the Institution, I purpose taking the liberty of referring from time to time to developments in that service when it appears likely to give a clearer view of the general marine situation.

The principal changes in the development of naval propelling installations are the substitution of the direct-action engine for the beam-engine, the tubular boiler for the flue boiler, the screw for the paddle, the quick-working engine for the slow-running geared engine, the surface condenser for the jet condenser, the multi-stage expansion engine for the simple engine, the cylindrical boiler for the box-shaped boiler, the water-tube boiler for the cylindrical boiler, the turbine for the reciprocating engine, oil fuel for coal, and the geared turbine for the direct-drive turbine.

Interwoven with most of the changes of type in engines and boilers have been the gradual improvements in materials and manufacturing methods. These improvements in many cases, indeed, alone rendered the use of new types practicable ; further, by permitting increases in pressure and speed of operation, they contributed no less to improved performance and demand for reduced weight and space than did the changes in the power plant itself. The application of scientific method, accurate observation, systematic research, and thorough analysis have also played an increasingly vital part in marine propulsion developments, and in no direction has this been more pronounced or yielded a more profitable return than in the development of the vessels themselves.

Attending these changes of type, too, has been the development of suitable auxiliaries and accessories to serve their growing needs and the gradually increasing replacement of man-power by mechanical power for the services connected with the operation, handling, maintenance, and fighting of the vessels.

The later history is known to all interested in such matters, but I think the early events have not been so widely recorded, and I will therefore dwell on the opening developments.

Although an engine had been ordered by the Admiralty from Boulton and Watt for the sloop " Congo " in 1815 (subsequently found to be too heavy and in consequence removed and fitted up on shore instead), and a number of small auxiliary vessels in the Admiralty service had used steam-engines primarily at the instigation of Brunel from 1816, it was not until March, 1828, that the name of a steam-vessel appeared in the Navy List. This was the " Lightning," of 100 nominal horse-power, which was built at Deptford and completed in December, 1823. My interest in her is on this particular occasion quickened by the fact that one of her Chief Engineers, John Dinnen, was the first naval engineer who contributed to engineering literature. His Paper on " Marine Boilers " appeared in 1838.

The decision to build a steam fighting ship resulted in the laying down of H.M.S. " Dee " of 200 nominal h.p. at Woolwich in 1829. From then on the use of steam slowly extended. The advantage of steam for a fighting service was made reasonably obvious during the Syrian Campaign in 1840, and by the time the Crimean War finished it was a somewhat grudgingly accepted means of auxiliary propulsion even for the ponderous line of battleships. It may be of interest here to recall that for some years before and after the Crimean War the fleets were accustomed to operating the purely sailing battleships in association with an attendant steam-frigate, the vessels towing each other alternately as the weather served better for steam or sail.

As might be expected, the early days of the transplanting of the steam-engine and boiler to service afloat were filled with difficulties, disappointments, and failures. A very early example is related by the Polar explorer, Captain Sir John Ross, who sailed north in the little ship " Victory " in 1829. His journal records with bitter satisfaction the landing on the ice in lat. 69° long. 92° of the Ericsson engine on which, earlier, the brightest hopes of furthering his expedition had been built. Ross had certainly the courage of his convictions, for he was an early advocate of the use of steam as an auxiliary in the Navy, and his book on "Steam Navigation," published in 1828, envisaged a system of naval tactics peculiar to this development.

In the Naval Service difficulties were experienced in respect of personnel as well as material, and considering the rigidity of naval discipline at that time the reason can well be appreciated : those unwelcomed interlopers, the enginemen, were recruited direct from the benches and forges of the engine shops and, undisciplined, came and went as they pleased. The organization of the engineering branch with continuous service in 1837 was the first of many changes to come.

The earliest engines were of the side-lever type, variations of the contemporary land beam-engine adapted to driving the paddle-wheels. The designs were cumbrous and heavy. Rennie refers to the great weight of the machinery of the " Great Western," built in 1836 with side-lever engines, which was about 1 ton per nominal horse-power, and left so little space for cargo-carrying that demands for reduced machinery space and weight became imperative and resulted in a reduction by no less than one-half by the year 1846.

The boilers were box-shaped and of the flue-type, designed to conform to and to fit neatly the ship space that chanced to be available for them, rather than to resist steam pressure which ranged from 5 to 7 lb. per sq. in. at that time. They were, in fact rarely tight, but water losses were of no great account as there was ample make-up feed available via the jet condensers then used. Safety valves were of the weighted type, and the weakness of the design to resist external pressure which might arise due to a vacuum when fires died down had also to be safeguarded by so-called " return valves " which in such an event admitted air to the boiler.

The Direct-Action Engine.—The first change of importance was the fitting of a direct-action type engine in H.M.S. " Gorgon " of 320 nominal h.p. in 1837, the Seaward " Gorgon " type so-called which was the forerunner of a number of direct-action designs, so described because the crank-centre was directly in line with the cylinder axis. In 1846, the " Gorgon " type engine for the Packet " Caradoc," also designed by Seaward, was arranged with a crosshead guide in place of the parallel motion hitherto fitted in the " Gorgon " type. Thus appears the marine reciprocating engine sensibly in its modern form. The side-lever engine was finally abandoned in the Naval Service in 1849, although it remained a favourite in the Merchant Service for many years afterwards. Some Atlantic liners were so fitted up till about 1860.

The " Driver," a sloop of 280 nominal h.p. which had a " Gorgon " engine, was the first steam-vessel to circumnavigate the globe (1842), although most of her work was done under sail ; she is of further interest as her boilers were fitted with mechanical stoking apparatus when she left England. They proved unreliable and were landed at the Cape.

Tubular Boilers.—Tubular boilers, retaining of course the old box form, were first fitted in H.M.S. " Penelope," a sailing frigate converted, lengthened and engined in 1843, and this type replaced the flue boiler in the Navy in 1844. This change was to prove of great importance. Apart from the reduced weight and space, it later permitted the necessary increase of pressure required to bring the fuel economy within reasonable bounds and to reduce engine size. The flue boiler remained in the Mercantile Marine, however, in improved forms for some years later. An interesting contemporary objection to the use of tubular boilers was the possibility of setting fire, through flaming at the funnels, to masted vessels when being towed alongside, the early type having no combustion chamber between the grate and the tubes. The " Penelope " was also fitted with surface condensers on the lines developed and patented by Hall in 1834 ; they had already been fitted in H.M.S. " Megaera " in 1836.

Sailing and Steaming Qualities in Paddle Steamers.—The difficulties of satisfactorily combining in the same vessel good qualities for both sailing and steaming became quickly evident. In the relatively small vessels concerned in these developments the heavy machinery and large space it occupied, coupled with the heavy fuel consumption, made disproportionate demands on the displacement, while the disposition of the machinery also prevented the sails being arranged to the best advantage. Consequently, the ship could never sail well and could only steam continuously for a relatively short time. The fuel consumption of the engine was indeed excessive, ranging from about 4 to 5 lb. per i.h.p.-hour at full power, and showed so little prospect of reduction that the question of dispensing with sails, upon which reliance had perforce to be placed to permit the vessels to keep the seas, did not come within the range of practical discussion.

In 1844 the official monopoly in the design of Admiralty steamers existing hitherto had been broken by the Earl of Dundonald, who submitted a design embodied in the " Janus " of 760 tons, having rotary engines and boilers of novel design (which, however, proved unsuitable and were replaced by ordinary designs), whilst a design by Lang resulted in the "Terrible," a highly successful paddle steam-frigate.

By greater co-operation with outside designers, advantageous changes in warship form were made, as well as improvements in the reduction of weight and space of machinery consistent with the low boiler pressures, for which, even as late as 1849, general opinion regarded 10 lb. per sq. in. as a safe and proper limit. But even with the increase in size of ships, which reduced many of the difficulties met with in reconciling the conflicting requirements, the steam-paddle war vessel could not be regarded as satisfactory.

The Screw.—The inherent disadvantages of the paddle from the naval aspect were appreciated quite early. They were, briefly, the vulnerability of the paddles and machinery, the occupation of space wanted for broadside armament and the unsuitability for cruising under sail.

Accordingly, the Admiralty had, since 1825, been seeking some alternative to paddle-wheels but without practical success, for they had, in common with contemporary professional opinion, dismissed the propeller as impracticable, notwithstanding a satisfactory demonstration before the authorities by Ericsson of his screw steamer in the Thames in 1837. The demonstration was literally before them, for his steamer towed the Admiralty barge at 10 knots from Somerset House to Limehouse and back. However, when in 1840, in the face of some opposition and great difficulty in getting a suitable engine made, a Rennie engine was fitted in association with a Pettit Smith's propeller in the "Archimedes," the Admiralty representatives watched the trials against the Dover Packet, "Widgeon," very closely. While the trials did not permit of precise comparison of the two systems, they showed the desirability of testing the screw in a more thorough manner, having in view its peculiar fitness for the Naval Service. Hence, the screw steamer "Rattler" was ordered to be built, and, to ensure a precise trial, it was constructed on the same lines as the paddle steamer "Alecto" and with engines of the same power; but the ship was adapted by an additional length aft for the reception of a propeller.

After preliminary trials commencing in October, 1843, which successfully determined the superiority of two short sections of helicoids as compared with the two half-convolutions fitted in "Archimedes," the series of trials culminated in April, 1845, in the historic tug-of-war where, lashed stern to stern, the "Rattler" steamed ahead with the "Alecto" at a speed of 2½ knots. Later in the year and before proceeding on service, the Rattler" towed the "Erebus" and "Terror," then on their way north under Sir John Franklin, as far as the Orkneys.

Generally the series of trials, considered as a whole, was held to show that the screw was not inferior to the paddle-wheel in fine weather, but some doubt continued as to whether it would prove equally efficient against wind and sea in heavy weather.

The fast-running engine was not then available, and, as in the case of most of the early naval screw ships, the " Rattler's " engine drove the propeller through four-to-one gearing in the words of the contemporary textbooks " to increase the number of revolutions of the shaft and thus enable the screw to make revolutions enough without giving undue velocity of the piston." The reintroduction of gearing to the Navy, over sixty years later, in this case to reduce the speed of the propeller shafts, will be related in its turn. It should be mentioned that the " Rattler's " engines, which ran at 26 r.p.m. and developed 428 i.h.p., were first fitted with a belt drive to increase the speed of the propeller shaft, but gearing was finally substituted. The gears of later designs were stepped, constituting a rough approximation to the helical teeth now used, and the wheels were fitted with teeth of gunmetal or hornbeam in association with wrought-iron pinions. A chain drive was fitted in the " Great Britain " and adhesion wheels were tried by Rennie, but do not appear to have been used afloat.

There was a general reluctance to apply the screw to merchant vessels before satisfactory results were reported in " Rattler." A notable exception, however, was the Atlantic liner " Great Britain," the first large iron ship, then under construction in which in 1840, as a result of the trials in " Archimedes," the decision was made to change from the paddle-wheel to the screw, with, as events proved, great success. The Admiralty experiments in " Rattler" were set on foot before the " Great Britain " was proved, but there seems little doubt that Brunel's courageous example was not without its influence.

The " Dwarf," formerly the " Mermaid," an iron steam-vessel purchased by the Admiralty from Rennie in July 1843, was actually the first screw vessel commissioned, and her special interest lies in the full-scale Admiralty experiments carried out at the suggestion of Thomas Lloyd, then Chief Engineer at Woolwich and later the first Engineer-in-Chief, to ascertain the influence of underwater form on the propellers. As Fincham has pointed out, " the striking and peculiar merit of Pettit Smith's plan consisted chiefly in his choosing the proper position for the screw to work in," but the need for considering the form of the ship was not appreciated until Lloyd instigated the trials. They showed the great influence of the form of the underwater body ahead of the screw on the screw efficiency and the need for giving this feature special study in the development of the faster screw ships. As it happened, the " Rattler's " lines and form were quite favourable for the screw, and the screw aperture had been made particularly long to suit the Smith screw in its full-threaded form as was first intended to be used.

The results of the contemporary experience afloat in the use of the screw and particularly the favourable reports of Naval Officers on the performance of " Rattler " on service, decided the Admiralty to adopt the use of the screw in 1845, when, as a result of the developments mooted in the French Navy, it was determined to increase considerably the steam navy. At the same time it was decided to construct the engines so that every part of the machinery would be below the water-line, and to arrange the screw and its fittings to be both readily unshipped and shipped in any weather, and thus to render the vessels perfect sailing ships as far as practicable whenever the occasion for using steam ceased.

After 1846, when the paddle ship "Basilisk" was ordered for trials against the screw ship "Niger," no further important war vessels were ordered with paddle wheels. The use of the paddle steamer continued, however, in various vessels and liners of the Mercantile Marine for many years, and as late as 1865 the relative merits of the paddle wheel and the screw for particular commercial services were still being discussed. In the Peninsular and Oriental Line at that time the paddle steamers were preferred by many passengers.

There was at the time of the adoption of the screw no type of engine available which would meet effectively the requirements of the screw under those conditions peculiar to the Naval Service, and all the prominent marine engineers of the country were therefore invited to submit designs, whilst being given quite a free hand subject to the conditions before mentioned and to a stipulated speed of revolution and diameter of the propeller. Tenders were accepted in this year for fifteen sets of screw engines for vessels of various dimensions and distributed amongst eight prominent makers, of whom none was allotted more than two.

Developments between 1845 *and* 1860.—The decade following the introduction of the screw is particularly marked by the variety of engine designs which were developed to meet the new conditions of higher engine speed and accommodation below the water-line, and, as may be expected at such times of transition when aspirations march ahead of practical fulfilment, the cases of removal of unsuitable engines were by no means rare. The use of mechanical gearing for screw ships was accepted perforce, for a time, but the specifications early expressed a preference for a direct drive. By 1850 it was found possible to get designs avoiding the use of gearing, after which it was abandoned in new construction thereby simplifying the machinery, reducing bulk and space, and obviating the noise which was objectionable in the early designs.

Gradually the weak engine designs were weeded out, complication, and unnecessary moving parts were eliminated, and by 1858 the relatively simple type with guided piston rod had emerged as most suitable in three forms, namely, the Humphrys Tennant direct connecting-rod engine, the Maudslay two piston-rod design with return connecting-rod, and the Penn trunk type (earlier used by Hall of Dartford for vertical marine engines), all being arranged horizontally.

Boiler pressures, which had been increased generally to about 14 lb. per sq. in. by 1847, had reached 20 lb. per sq. in. by 1851, and remained generally at that figure for the next ten years. There were occasional designs with higher pressures, a particular exception being represented by the Crimean gunboats, of which over 200 were built for the war in 1854–5. Supply being urgently required and with rapid production in view, the engines were made non-condensing, which, with the light design required, led to the boiler pressure being increased to 60 lb. per sq. in. The boilers were cylindrical with straight-through tubes, and were tested to 180 lb. per sq. in. The engines ran at the then high speed of 220 r.p.m. The building of these gunboats affords an early example of what could be done by mass-production, Penn having completed eighty sets of machinery in three months by duplicating patterns and distributing sub-contracts throughout the country.

The sloop " Malacca," of 200 nominal h.p. with machinery supplied by Penn in 1854, was also a high-pressure non-condensing design, and is of interest as being the first case in which boilers of cylindrical design with cylindrical furnaces were fitted.

Superheat was generally used in all designs, and this continued as standard practice until, with the general use of compound engines in 1870, pressures advanced generally to 60 lb. per sq. in., when difficulties with engine packings, etc., led to its disuse. Importance was attached to the use of superheat on the grounds of improved economy, which was reckoned to be about 20 per cent. In experiments carried out in 1859 in the paddle steamer " Dee " the fuel consumption of the old Maudslay beam-engine installation was found to be 3·9 lb. per i.h.p.-hour at full power when using saturated steam. When using the superheaters, arranged to pass the steam through the jackets on its way to the cylinder, the fuel consumption was 2·97 lb. per i.h.p.-hour. The steam was at a temperature of 377°F. corresponding to a superheat of 137° for the boiler pressure of 10 lb. per sq. in., and on entry to the cylinder was superheated to the extent of 26°F. An early device for superheating, first suggested in 1827, consisted in the steam being arranged to pass through an annular space around the lower part of the funnel, but later designs were generally of tubular form fitted in the smoke-box. The use of a separate high-pressure boiler to provide steam for superheating the low-pressure engine steam was under consideration in 1848.

Until 1858, the demands for engine power in the Navy continued to be strictly moderate. At this time, all sea-going steamers for war or commerce were furnished with full sail equipment, and steam power was still regarded as auxiliary to sails. There appeared, indeed, no desire to make the fullest possible use of steam in the Navy, and although its application as an auxiliary proceeded, the period was one of indecision. The opposition to the use of steam, or it may be the reluctance to abandon the line of battleships in its long-established form, is indicated by the fact that numbers were laid down between 1847 and 1859 as purely sailing ships: these were, however, converted to use steam at the cost of extensive structural changes, or were abandoned.

The "Victoria," designed in 1856 and launched in 1859, was an example of a screw three-decker of the period, the last word in what could be accomplished using wood as the principal material of construction, and embodying over forty years' experience of marine engineering practice. Her displacement was 7,000 tons, and under steam she made 12½ knots for an indicated horse-power of 4,400. The jet condensing engines were horizontal and of Maudslay's double piston-rod type, with return connecting-rod and two cylinders of 92 inches diameter and 4 feet stroke, the engines running at 58 r.p.m. The steam pressure was 20 lb. per sq. in. and the total heating surface of the eight box-shaped tubular boilers was 18,000 sq. ft. The funnel was telescopic, and the propeller could be hoisted.

Brunel's advanced ideas embodied in the "Great Eastern" of 8,000 i.h.p., designed as early as 1853, are, of course, hardly a typical example of the Mercantile Marine in which the peak of general practice in 1859 is better indicated by the "Persia" of the Cunard Line, an iron paddle-wheel steamer of 4,000 h.p., giving a speed of nearly 13 knots.

The design of the "Warrior," our first ironclad, laid down in 1859, marked a distinct change both as regards the outlook on the value of speed and the possibilities of getting higher speeds.

The change from wood to iron for warships was as much due to the influence of Scott Russell backed by the technical success of the "Great Eastern" as to the envisaged shortage of suitable wood for shipbuilding should large demands arise. The use of iron at once rendered possible larger ship dimensions, and hence not only provided the space and weight for greater power, but ensured a proportionately greater return in the form of speed from the increased power than if it had been applied to smaller vessels. The favourable influence of the size of the ship on her performance was then only dimly realized. Writing as late as 1876, Lindsay, in the "History of Merchant Shipping," said: "It may be a hundred or fifty years hence, the maritime commerce of the world may have grown to an extent sufficient to justify with reasonable prospect of profit another ship of the dimensions of the 'Great Eastern.'" But within twenty-five years the White Star Company's "Oceanic," of greater displacement than the "Great Eastern," was running at sea.

The "Warrior" was of 9,000 tons displacement, and made a speed of 14·4 knots on trial for an indicated horse-power of 5,500. She was fitted with a single screw driven by a Penn two-cylinder trunk engine running at 54 r.p.m. The boilers were of the box, tubular form, designed for 20 lbs. per sq. in. pressure, and were of iron throughout except for the brass tubes. Ample sail power was provided : she could lower her funnel and hoist her propeller, and she proved as successful under sail as under steam.

Surface Condensers and Increase of Boiler Pressure.—The general opinion in 1860 was that pressures much in excess of 20 lbs. per sq. in. were not advisable, and this limit appears, notwithstanding the availability of the surface condenser, then temporarily abandoned, to have been grounded upon the fears of priming and overheating of boilers due to the use of salt-water feed. The naval experience with the 60-lb. gunboat boilers was far from satisfactory. Thus engine economy remained almost at a standstill. Sir Frederick Bramwell, in his Paper read before the Institution of Mechanical Engineers in 1872, called attention to the very slow improvement in the economy in terms of fuel per indicated horse-power hour during the two preceding decades, and maintained that the sensible improvements in economy in ocean transport which had been achieved rested in the improved forms of ships, the use of iron in shipbuilding and the replacement of the paddle-wheel by the screw, rather than in any radical improvement in engine economy.

The growing military need of increased endurance in the Navy, however, together with the call for lighter machinery, led to sources of improved economy being exploited. The surface condenser was reintroduced first in " Octavia " and " Constance " in 1860, and was, in association with pressures varying from 25 to 30 lbs. per sq. in., and an increased ratio of expansion, generally specified from 1863 onward. For a few years the requirement was qualified by the condition that the condenser was also to be capable of being worked as a common jet condenser.

The change in design was, like most other changes, not without its difficulties and troubles, which took the form in this case of corrosion in the boiler and tubes, threatening to shorten their lives appreciably. Numbers of cases are on record where boiler tubes lasted only six months. The only effective remedy then known was the protective scale obtained by purposely using salt feed-water for the early service of the boilers, and this was the usual practice. Doubts as to the benefit of surface condensers continued for some years, and it was stated in public as late as 1865 that in the Mercantile Marine the gain in economy promised by the surface condenser had not materialized ; but in the naval installations there was a consistent improvement attending the use of the surface condensers, higher pressures and increased expansion. I may say here that the " Megaera," which it will be recalled was fitted with Hall's condensers in 1836, showed a fuel economy improvement of 20 per cent. above her sister vessel " Volcano " during four years' service, most of which was attributed to the surface condensers. The vacuum recorded on the trial was 27½ in., with the barometer at 30 in. and a sea-water temperature of 60°F. The centrifugal pump had not then been developed, and one of the reasons why the use of surface condensers was not extended earlier in the

Naval Service appears to have been the difficulties apprehended in providing circulating pumps of sufficient capacity to attain a proper vacuum under high sea-water temperature conditions.

Multi-Stage Expansion Engines.—In 1859 Rankine and others had indicated on theoretical grounds the economies to be anticipated by higher pressures, but in the decade 1860–70 considerable controversy raged as to the practical advantages of the advance. As mentioned, the first appreciable advance in pressure was effected in conjunction with the reintroduction of surface condensers, and, notwithstanding the serious effect on the durability of the boilers and doubts as to machinery reliability with higher pressures, the deeper thinkers pressed for still further advance. Scott Russell, speaking in 1865, on a Paper revealing a somewhat gloomy view of the situation said, " I myself continue to hope that the engines of the future are to be high-pressure expansive engines working with surface condenser and fresh water in the boilers."

The use of the compound engine marks the first considerable advance of economy since pressures of 20 lb. per sq. in. became general. Compound engines on the Woolf principle, and to the designs of Randolph, Elder, were first used afloat in British ships, in association with a pressure of 30 lbs. per sq. in., by the Pacific Steam Navigation Company. This company was, in 1856, in difficulties owing to the high cost of sending coal to the Pacific Coast, and the greatly improved economy in the first installations so fitted, the paddle steamers " Valparaiso " and " Inca," led to their modifying all their fleet before 1872. Compound expansion quickly extended generally, but checks were experienced mainly in some of the engines of the tandem arrangement, where difficulty arose in the gland common to the two cylinders.

By 1872, although the compound engine was used considerably in the Mercantile Marine, its advantage was still an open question there, but general opinion inclined to favour it on grounds of the superior economy. It was definitely advocated for general use in the Royal Navy by the committee appointed in 1871 to report on the suitability of various designs of ships for their intended purposes, who found that the fulfilment of the advancing demands for heavier guns and armour was being retarded by the heavy requirements in respect of fuel stowage to meet the desired endurance with the existing type of engine. In fairness to the authorities who had already had practical experience of the designs from 1860 (generally in association with 30 lbs. per sq. in. steam pressure), even to the point of having to remove several as unsatisfactory, it must be said that they were fully alive to the advantages and receptive to the suggestion.

After 1871 compound engines were generally specified and fitted in naval ships, in association with steam pressures up to 60 lbs.per sq. in., which led to a 5 to 10 per cent. increase in machinery weight, but to an increased fuel economy of at least 30 per cent., which on balance led to the desired end. In several vessels, however, the design of Penn was fitted, comprising three cylinders of equal diameter which could be worked simple at full power and compound at half power, an attempt to compromise between the conflicting requirements of weight and economy. Incidentally, the expression " nominal horse-power," which had been in use since boiler pressures were such as to make it a reasonable basis of comparison—it assumed the effective cylinder pressure was 7 lb. per sq. in.—was at this time abandoned, having long ceased to serve a useful purpose.

In the case of H.M.S. " Briton," fitted with compound engines by Rennie in 1869, the fuel economy reached a very high order. With a boiler pressure of 60 lb. per sq. in. and engines running at 95 r.p.m., the indicated horse-power was 2,000 and the fuel consumption on a six hours' trial was 1·98 lb. per i.h.p.-hour, while at 600 h.p., with a ratio of expansion of 15, the recorded consumption on a four hours' trial was 1·3 lb. per i.h.p.-hour. This is believed to be the greatest economy attained by any steam-engine up to that date. The engine design, of the two-crank receiver type, was by Edward A. Cowper, President of the Institution of Mechanical Engineers in 1881, and, further, is of special interest as being an early attempt to reheat the steam between expansions; this was effected by means of superheated boiler steam flowing through an annular chamber disposed around the reservoir, while the exhaust steam passed through an adjacent annulus disposed on the interior of the reservoir. The device was popularly known as " Cowper's Hot Pot." From the trial reports it appears that the fears of difficulty with packing led to the superheaters not being fully used at full power. Humphrys had used a reheater in the P. & O. ship " Rangoon " in 1862 without success.

With the higher pressures the use of the trunk-piston engine designs has been abandoned for evident reasons. The advent of the twin-screw arrangement in 1860, and its general use beginning in 1868, removed the outstanding objection to the direct working connecting-rod type of engine, namely, the shortness of the rod in relation to the crank-throw due to the short length available between the centre-line shaft and the cylinders ; the direct-acting engine accordingly became the standard naval type. It continued to be arranged horizontally, a somewhat expensive arrangement in respect of floor space, but necessary in the unarmoured vessels of the time to provide the required protection. The vertical engine was at this time fairly general in the Mercantile Marine and came into the Navy in 1872 with the armoured ships, the need for the underwater arrangement then expiring. The horizontal engine continued to be fitted in cruisers until 1887.

After the establishment of the compound engine, pressures continued to increase steadily with improving manufacturing methods and the demands for better economy and reduced weight and space of machinery. The question of reduced weight came into particular prominence in 1875, when Kirk of the firm of Elder designed the vertical compound engines for H.M.S. "Nelson." These had, in place of the heavy cast-iron bedplates and columns generally used, a braced structure, comprising wrought-iron columns and bedplates, somewhat on the lines of the contemporary torpedo-boat designs of Thornycroft. The condenser shells were of plate brass and the end doors were of wrought iron. By these means the main engine weight was reduced by about 10 per cent.

While the vertical engines permitted of higher piston speeds and led gradually to reduced engine weight on this account alone, it was in the direction of increased pressures that still further reductions were sought, and pressures rose by 1884 to 130 lb. per sq. in. These pressures, however, brought the compound engine to the same condition in respect of temperature range as the simple engine which it had replaced. Kirk had already designed a triple-expansion engine for s.s. "Propontis" in 1874, with a pressure of 150 lb. per sq. in., but it was not at first a great success owing to the type of boiler. It was considered impracticable at that time to build an iron cylindrical boiler to withstand a pressure of 150 lb. per sq. in. and it was necessary to use the Rowen and Horton's water-tube boiler, which was later replaced by a cylindrical boiler designed for 90 lb. per sq. in. pressure. In 1880 Kirk, who had meantime joined the firm of Napier, designed triple-expansion engines for the s.s. "Aberdeen" which with steel cylindrical boilers then possible, pressed to 150 lb. per sq. in., proved a great success. Thereafter the use of triple-expansion engines quickly extended in the Mercantile Marine.

The first triple-expansion engines fitted in the Navy were in the "Sans Pareil" class in 1885 with a pressure of 135 lb. per sq. in. and thereafter the type was employed for all new construction. The triple-expansion engines of the "Magicienne" class cruisers (1887) of 9,000 i.h.p. were the last horizontal engines of any great size.

Twin Screws and Elimination of Sails.—Twin screws were first used in armoured gunboats and in the light-draught ironclad "Penelope" in 1865, but the extension of duplicate engines was not favoured while sail power continued to be regarded as of great value, since the twin screws were prejudicial to good sailing, while the sails themselves provided a standby to the single engine. They were, however, fitted in the "Captain" in 1866 and in 1867 in the "Invincible" class, as well as in the coast defence vessels of the "Glatton" class which, in view of the small requirements for endurance, were not provided with sails.

By 1869, with the rapid increase in the power of artillery and the need for countering it by the provision of heavy armour, it was found impossible to combine all the desired features required in the first-line heavy ships. Hence came the abandonment of the ability to move under sail in the "Devastation" class of 1869. Sails continued for a few years in some of the heavier ships designed for services complementary to those for which the first-line ships were intended, but this did not continue beyond 1874 when the last rigged ships, the " Alexandra " and " Temeraire," were laid down. The use of sails as an auxiliary continued in certain smaller vessels for some years and were last used in the sloops designed in 1903.

With the increasing engine powers due to the higher ship speeds the propeller-hoisting apparatus began to be abandoned from 1867, but as long as the use of sails continued it was usual to provide some form of disconnecting gear for the propeller shafts, with a view to allowing the propeller to trail when under sail. The use of the main engines, running at their slowest possible speed, was, however, often necessary to assure steerage way, and with a view to reducing the fuel consumption under such conditions, the question of providing a separate small engine of sufficient power to drive the propeller at 4 knots received a good deal of consideration. Such engines were fitted in " Alexandra " in 1874; they were provided with separate condensers and auxiliaries and were geared to the propeller shafts and gave a speed of 5 knots.

With the disuse of sails the adoption of twin screws became necessary to provide against the possibility of entire breakdown, and they were also of advantage in warships on account of the improved manœuvrability and improved watertight subdivision which they permitted. There was considerable controversy regarding their efficiency from the propulsive aspect, and they were not greatly employed in the Mercantile Marine until with the increase of speed to 20 knots in Atlantic liners about 1886 their use came in for these high-power liners where the desirability of dividing the large power became evident on grounds both of reliability and of manufacturing considerations.

Cylindrical Boilers.—The box-shape boiler, whether of the tubular or flue type, was unsuited to pressures much higher than 30 lb. per sq. in., and with the increase of pressure beyond this figure the cylindrical boiler took its place. Considerations of space, however, for some years entailed in certain classes a compromise represented by the flat-sided cylindrical type, generally called the oval boiler. The double-ended cylindrical boiler was first fitted in the Navy in 1874 in " Inflexible."

The corrosion which occurred in naval boilers following the general adoption of surface condensers continued to be serious, and accordingly the Admiralty appointed a committee in 1874 to inquire into its causes, and to propose measures to improve the durability. The original committee was dissolved in 1877 and was replaced in 1878 by a limited committee composed of Naval Engineer Officers, and the Admiralty Chemist. The committees conducted an extensive research, including experiments on the behaviour of metals in the boilers of numerous sea-going ships, embracing those of all the principal shipping companies. The early views were that the corrosion was due to fatty acids formed by the partial decomposition of the grease carried by the feed-water from the condensers to the boilers, but the committee's final view was that it was due mainly to air entering with the feed when under steam.

As a result of the committee's work, the regulations were extensively revised, and embodied in the first Steam Manual issued in 1879. The principal changes made were the indication of the measures to be taken for the exclusion of air as far as possible, including an increase in the permissible density of the water in the boilers from two to four times that of sea-water (it must be remembered that the main source of make-up feed was the sea and that at that time it was considered impracticable to avoid salt-water leakage into the feed system), the need for good metallic contact of the zinc slabs with the boiler parts (zincs had been introduced earlier but they were merely hung in the boilers), and the stiffening up of the regulations regarding the logging of the treatment and operation of the boilers. The desirability of working the boiler surfaces with a thin protective scale was emphasized and the use of soda to keep the water alkaline was recommended, although it was only to be added if the litmus test indicated acidity.

It is a sufficient commentary on the thorough investigation carried out by this committee to say that their recommendations, excepting for the matter of density and protective scale, remain in essentials in the regulations to this day.

The committee considered fully the available water-tube boilers and recommended in 1874 and again in 1877 a trial in a naval ship of boilers of the Perkins high-pressure water-tube type with a view to "gaining a practical acquaintance with their capabilities and developing the new conditions of working that would be entailed by their use." They expressed the opinion that such a system of boiler construction combined with the exclusive use of fresh water and tight condensers would lead to good results as regards endurance, safety from explosion and probably economy.

The demands for lighter and less bulky machinery grew from 1874 with increasing urgency, in view of the need for higher ship speeds and more powerful armament and armour. While considerable success was achieved in this direction in the engines themselves, the attempts to increase the output of the boilers led to important boiler defects, such as leaky tubes and seams, cracks and distortion of furnaces.

Forced draught, first used by Hawthorn for large ships in 1881, was introduced for large naval ships in 1882. This, in combination with particular features in naval boiler designs which space and weight considerations demanded, such as the narrow tube spacing which restricted the circulation, and common combustion chambers with relatively small heat-absorbing surfaces which led to high combustion-chamber temperatures, reacted unfavourably on the tightness of the tubes, particularly under naval service conditions which called for sudden and wide variations of output.

The "Sans Pareil" Class in 1885, incidentally representing the only order where a bonus was offered for surplus power, namely £6 per horse-power, is an outstanding example of the degree of forcing attempted. The machinery never attained on service the power developed during the contract trials and its rating was considerably reduced. It attained over 14,000 i.h.p. on trial, 4,000 in excess of the specified power, and burned coal at the rate of 45 lb. per sq. ft. of grate per hour.

Matters were improved somewhat in designs subsequent to 1889 by the increased employment of separate combustion chambers. The tube leakage trouble was further mitigated to a certain extent by the use of tube ferrules which were introduced in 1892, but nevertheless the development of full power under forced draught in all the larger vessels fitted with return-tube boilers was generally attended with anxiety, and full power, even where attainable, could not be maintained for any length of time.

Doubts as to reliability of the boilers of the more modern warships were so prevalent that in 1892 a design committee was appointed to consider whether, in view of the reports from afloat indicating that the increased pressures were leading to difficulties and increased troubles from boilers, together with difficulty in maintaining the required fresh water for boilers, a reduction of pressure was desirable.

This committee, when reporting in 1892, emphasized the gain in fuel economy attending the use of higher pressures and triple-expansion engines. Comprehensive inquiry in the Mercantile Marine showed this to be 25 per cent. above the compound engine using 60 lb. per sq. in. steam pressure, which was confirmed by the performance of naval ships showing 21 per cent. gain at full power and 18 per cent. gain at one-tenth full power. The committee produced estimates showing the serious effect on the general design of typical modern naval vessels if compound engines at 60 lb. per sq. in. pressure had been fitted to attain the same endurance as with the triple-expansion engine at 155 lb. per sq. in. Considering also the improved smoothness of running and reduced vibration attending the three-crank triple-expansion designs they recommended no reduction in pressure, but directed attention to various changes in practice and additions to existing equipment which promised, in the light of mercantile experience, to improve the durability. Briefly, they recommended an increase in heating surface, a reduction in the margin between natural and forced draught, reduction in grate length, separate combustion chambers in single-ended boilers, a general reconsideration of the tube spacing, and provision for circulating the water by external means. Increased distilling apparatus and the provision of grease extactors were also suggested.

With these changes it was considered that the boilers would be suitable for the Naval Service, but it may be inferred that the committee appreciated that the advances looming on the naval horizon could not be met by the cylindrical boiler, for their report concluded with the recommendation to fit two ships with tubulous boilers for experimental purposes without delay, and that a new cruiser should be arranged to receive tubulous boilers should the experiments be satisfactory.

As further illustrating the conditions of the period, Admiral Fitzgerald, speaking in 1897, said: "There was never a period during the development of boilers for warships when their general behaviour has been so unsatisfactory and when they have given so much trouble and been the cause of so much anxiety as during the past ten or twelve years. The cylindrical and marine type locomotive boilers have proved themselves unequal to the demands made on them. Anything like rough usage, corresponding to war requirements, has caused them to fail."

This marks the genesis of the use of the water-tube boiler for our large warships, and it will be convenient at this point to trace the sequence of later events.

Water-Tube Boilers.—It was lack of flexibility referred to in the last sentence of Admiral Fitzgerald's remarks which was the underlying reason for the change, although tubulous boilers promised also to prove a source of saving in weight and space. This consideration, paramount in the Naval Service, proved difficult for outside critics to appreciate if one can judge from the depth of feeling revealed in the subsequent "Battle of the Boilers."

An early example of the use of water-tube boilers afloat was s.s. "Thetis," built by Scott of Greenock in 1857 for experimental purposes. The machinery which comprised compound engines, and water-tube boilers with a working pressure of 120 lb. per sq. in., was by Rowan of Glasgow. The first design of compound engines failed, but after replacement the vessel ran in service for about a year, when the boilers failed from internal corrosion; they were also unsatisfactory in respect of accessibility for cleaning and repairs and of circulation.

Between 1859 and 1862, the desire to employ much higher steam pressures in the Mercantile Marine necessitated the use of a water-tube type of boiler and quite a number of vessels were fitted with designs by Rowan and by Howden; some gave fairly long service, but they were all difficult to maintain, and in the long run were judged unsatisfactory and were sooner or later removed. In 1860, Randolph, Elder fitted in s.s. "Murillo" a water-tube design by Williamson for 90 lbs. per sq. in. pressure, but this gave but short service under sea-going conditions and failed through salting up and tube trouble. The types of boiler were in fact ahead of the facilities available for providing pure feed-water. As a result of these difficulties Elder decided in 1862 to reduce the steam pressure to 50 lbs. per sq. in. and to fit cylindrical boilers in the "Murillo": these were the first cylindrical boilers fitted in the Mercantile Marine.

The water-tube boiler designed by Captain Cochrane, a development of the design installed by his father in the "Janus" in 1844, was fitted in 1865–70 in H.M.S. "Chanticleer," "Oberon," "Audacious," and "Penelope." Boilers of this design were subjected to evaporation trials on shore at Woolwich Dockyard in comparison with the Service boilers and showed an improved efficiency of some 18 per cent. One feature of the design was the direct admission of air to the combustion chamber, induced by a steam jet. It appears that the low steam pressures then in use were unsuited to a boiler of the tubulous type, in so far as the tendency to prime was unduly provoked by the high specific volume of the steam. These boilers were, in fact, abandoned finally, due to troubles from priming and difficulties in cleaning. The Perkins high-pressure type was also approved for H.M.S. "Pelican" in 1875, but was not completed owing to the withdrawal of the contractors. At this time other types of water-tube boilers were being successfully taken up by the French.

The first successful water-tube boilers in the Royal Navy were those fitted in the 2nd Class torpedo boats by the Thames shipbuilders, commencing in 1885 by an installation by Thornycroft in Torpedo Boat No. 100. It was these craft and the torpedo-boat destroyers developed to counter them which pointed the way to higher ship speeds, and with the help of the water-tube boiler very substantial advances were made.

The "Speedy," a torpedo gunboat of 4,500 h.p., was ordered in 1891 with Thornycroft boilers and carried out entirely satisfactory trials, including a series of long sea-going trials, during which the greatly improved flexibility of the machinery was amply demonstrated. The advantages realized in this vessel turned attention to the extended French experience with water-tube boilers, and investigation was made into the Belleville boiler, a type with which the most experience had been gained, especially in the long ocean-going voyages of the Messagerie mail steamers. It may be remarked here that the Belleville boiler is a very good example of persistent effort, having, I believe, been invented as far back as 1850.

As a result of the investigations made, it was decided in 1892 to replace for purposes of trial the unsatisfactory locomotive boilers in H.M.S. "Sharpshooter" by Belleville boilers, designed for a working pressure of 245 lb. per sq. in. The trials were carried out in 1894, and as in the case of the "Speedy" they comprised flexibility trials and a series of continuous trials at various speeds, including a series of runs of 1,000 miles each. These trials were regarded as entirely successful in respect both of economy and reliability. Above all, the ability to maintain high power continuously was demonstrated, a striking contrast to the performance earlier with the locomotive boilers.

In this year the decision was taken to fit the Belleville boiler in the cruisers "Powerful" and "Terrible," and meanwhile the use of the small-tube boilers of the Thornycroft, Yarrow, and Norman type was being extended in the case of torpedo craft.

To appreciate the situation at the time of the introduction of the Belleville boiler, it should be realized that the contract trials then usual for cylindrical boiler ships consisted of a four hours' maximum power trial at forced draught (1 in. air pressure), followed by an eight hours' trial at natural draught power (½-in. air pressure), which was 80 per cent. of the maximum power, and a thirty-hour trial at 50 per cent. of the maximum power. The last-named was called the continuous sea-going power. On service the periodical passage trials comprised a four-hour trial at natural-draught power and a twenty-hour trial at continuous sea-going power. Maximum power was only expected to be attained on service under favourable conditions, and then only for short periods.

The " Powerful " was designed to attain a maximum power of 25,000 h.p. for short periods and a continuous sea-going power of 18,000 h.p. for as long a period as the coal lasted, a definite advance on previous practice. Experience shows that when later the boiler was understood by naval personnel these design expectations were fulfilled, and for the first time since pressures began to rise appreciably our war vessels were able to develop their trial full power on service as and when required. The capacity to develop full power in the machinery was now only limited by the endurance of the personnel and not as hitherto by the endurance of the material.

As is generally known, the greater part of the steaming of warships in times of peace is done at relatively low speeds. As ship speeds increased the proportion of cruising power to maximum power decreased considerably, dropping in the case of " Powerful " to only 8½ per cent. It has been necessary to hold this condition in view to an increasing extent in the design of machinery for warships, and to compromise as between fuel economy and economy in weight and space. With this in view, a fuel consumption trial of thirty hours at 20 per cent. of full power was introduced in " Powerful," to test the economy of the installation in the neighbourhood of cruising speeds, and such trials have been continued in all subsequent designs. Taking advantage of the suitability of the boiler to withstand higher pressures and with the object of reducing the size of the engine and obtaining economy, the engine pressure was advanced to 210 lbs. per sq. in. for a boiler pressure of 260 lbs. per sq. in.

The trials were carried out satisfactorily in 1896. Generally the expectations of the design were realized, and the fuel consumption, namely, 2·06 lbs. per i.h.p.-hour for all purposes at 20 per cent. of full power and 1·83 lb. at 72 per cent. of full power, compared favourably with the preceding designs. There was a substantial saving in weight of machinery, due, in part, to the use of higher pressures, but, taking the boilers only, the increase in the power, weight factor at maximum sea-going power was more than 20 per cent. above the earlier designs of large high-speed cruisers.

The Belleville boiler was adopted for new construction cruisers and battleships, but trials of other large-tube types were arranged in smaller vessels, *e.g.*, the Niclausse boiler in " Seagull " and the Babcock and Wilcox boiler in " Sheldrake." The last-named boiler had already been in use in the Mercantile Marine, the first important installation being in s.s. " Nero " in 1892. Similarly in the torpedo-boat destroyers use was made of all the suitable small-tube types available for comparative trial.

Later Belleville-boilered ships were fitted with the economizer type of boiler, the generating surface in these cases being reduced accordingly. A noticeable improvement in economy resulted at the higher powers and a slight further saving in weight also accrued. The fuel consumption of " Diadem," the first economizer design, ranged from 1·59 lb. per i.h.p.-hour for all purposes at 75 per cent. of full power to 1·76 lb. at full power and 2·25 at 20 per cent. of full power.

It should be mentioned finally that the full power trials were carried out with open stokeholds in the Belleville-boilered ships, and that the large grate surface afforded by the design facilitated the continuous development of high power.

The Navy passed through difficult times during the next few years. So much has been written and said on the subject of this change in boiler design that it is hardly necessary here to do more than state the leading facts. The performance of the majority of the early Belleville-boilered ships on service fell far short of the promise given by the trials, and the mobility of these new naval units was, in fact, in some cases reduced to nil. Some of the trouble may be ascribed to the unfamiliarity of the Naval personnel with the new conditions arising from the greatly increased steam pressures, no less than to material unsuited to meet adequately those conditions. The advance in pressure was, in fact, ahead of its time.

An Admiralty committee was appointed in September, 1900, to ascertain the relative advantages and disadvantages of the Belleville boiler for naval purposes, to investigate the causes of the defects and how far they were remediable and to report on alternative types of water-tube boilers which might be suitable for trial.

The committee reported in May, 1902, after carrying out a great amount of investigation and full-scale comparative trials. They considered no less than thirty-six different types of water-tube boiler. They reported in the sense that the advantages of water-tube boilers for naval purposes were so great, chiefly from a military point of view, that providing a satisfactory type be adopted it would be more suitable for use in H.M. Navy than the cylindrical type ; they considered the Belleville boiler had no such advantage over other types as to lead them to recommend it as the best type. They thought that four different types of large straight-tube boilers were sufficiently promising for use in large vessels in H.M. Navy, namely, the Babcock and Wilcox, the Niclausse, the Dürr, and the Yarrow large-tube boiler. Their advantages over the Belleville were " drowned " tubes, a definite water-level reading, and the fact that no surplus boiler pressure or delicate automatic-feed regulators were required and a fairly well-defined circulation was obtained. Some of these boilers were already on trial, and further trials were arranged with the Niclausse in " Fantôme," the Dürr in " Medusa " and the Yarrow large-tube boiler in " Medea."

The committee formed the opinion that no type of water-tube boiler then in use was, on general service, as economical as the cylindrical boiler, and, having also in view that a large proportion of the coal used was expended in harbour, they recommended that cylindrical boilers of sufficient power to work the auxiliary machinery and drive the ship at her ordinary cruising speed should be fitted until such time as a thoroughly satisfactory type of water-tube boiler was obtained. The boiler pressure was recommended to be 210 lb. per sq. in.

The recommendations were accepted and no Belleville boilers were fitted after the designs then in course of construction were completed, one of the later designs to be so fitted being H.M. Yacht, " Victoria and Albert," built in 1897, which continues in service to this day with her original boilers.

Meantime, the engineering personnel of the Navy faced the difficult situation, and little by little overcame the crushing difficulties, finally perfecting the appliances and the operating, maintenance, and repair processes to such a degree as to convert an apparent failure into a definite success. The remarks of Admiral Domvile may fittingly be quoted here. He was the Chairman of the 1900 Boiler Committee, and became Commander-in-Chief in the Mediterranean before the final report was signed. When forwarding the report he was constrained by his recent experience to qualify it by reporting that the Mediterranean Fleet, constituted of Belleville-boilered ships, had reached a high and satisfying standard of performance.

Viewing the matter at this date in long perspective, it is perhaps not too much to say that the successful outcome of the European War, which, when all is said, turned ultimately on the endurance of the British Navy, was due to a considerable extent to the high degree of perfection of the engineering machinery of the Fleet developed and operated by the personnel who were intensively trained and tried both in design and operation in the troublous times of the Belleville boiler.

The succeeding designs of cruisers and battleships were provided for a time with dual boilers at the expense of increased machinery weight and space, until, from the various types of water-tube boilers suggested by the committee for trial and fitted in the naval programmes of 1902-4, the Babcock and Wilcox and Yarrow large-tube type boilers soon emerged as suitable types in respect of economy and durability for complete boiler installations in large vessels. Meantime, in the light cruisers and torpedo-boat destroyer classes, the three-drum small-tube boilers of the Yarrow and the White-Forster types also proved their suitability for future needs, and were after 1906 generally adopted in new construction.

Boiler pressures advanced to 300 lb. per sq. in. during the Belleville boiler stage, but were subsequently reduced to 210 lb. per sq. in. as mentioned before, and shortly afterwards were increased again to 250 lb. per sq. in. which remains the general practice to-day.

The cylindrical boilers in some of the ships fitted with the combination boiler system were provided with Howden's system of preheating.

Oil Fuel.—It is believed that the earliest successful experiments to burn oil fuel in connexion with marine boilers were those carried out by Captain Selwyn at Woolwich Dockyard in 1867–70, using the steam-spraying system designed by Aydon. The fuel used was creosote, at that time a waste product from the distillation of tar for chemical purposes, and it was steam-sprayed with very simple appliances over the bricked-over grate of a coal-burning furnace. In a launch boiler an evaporation of 12·3 lb. from and at 212°F., per lb. of fuel was obtained, and later in a tubular marine boiler from H.M.S. " Oberon " set up on shore an evaporation of no less than 15·6 lb. was reported, nearly double that attainable in this boiler with coal. The trials were carried on up to the closing of Woolwich Dockyard in 1870. The many advantages of oil fuel for naval purposes were then clearly appreciated, but special emphasis was laid on the necessity for a fuel heavier than water which would sink clear of the vessel in the event of tanks being damaged in action, and it appears that the limited supplies of such fuels possessing this quality was the reason why the matter was allowed to lapse. The recent successful use of pulverized fuel brings to mind in this connexion another instance of the resuscitation of a successful idea, in this case in a double sense. T. R. Crampton had also, according to a contemporary discussion on Captain Selwyn's experiments, burnt oil successfully at this time, but in view of the difficulties of supply he had devoted his attention to pulverized fuel. He had brought his devices to a fairly high degree of perfection, injecting the powdered fuel in quantities proportionately to the air stream in the belief that the ideas were original, only to find that his methods had been discussed some fifty years earlier. It appears that difficulties with the refractories for furnace linings led to the abandonment of Crampton's system.

As is well known, liquid fuel was used in the locomotive boilers of the great Eastern Railway in 1886, but the earliest marine installation of which I am aware is that fitted in s.s. " Gretzia," by the Wallsend Slipway Company, in 1881. So far as the Navy is concerned, the question of the use of oil fuel remained more or less in abeyance until 1898 when experimental work was commenced in earnest at Haslar. Ranging through methods of atomization by steam and air, this culminated about 1902 in the development of devices for pressure spraying, otherwise called mechanical atomization. This has remained in essence the system used by the Navy to this day. The effects of the characteristics of the various available fuels were fully studied, and the appliances necessary for the passage and mixing of the air for combustion and other purposes were simultaneously developed. By the time the Admiralty were satisfied that supplies of suitable fuel in the desired quantities would be forthcoming the devices began to be applied to new construction.

The Coastal Torpedo Boats Nos. 1 to 32, and the fast torpedo-boat destroyers of the " Tribal " class, ordered in 1905, were equipped to burn oil fuel exclusively, and from 1903 all the large vessels of the new construction programmes were equipped to carry and burn a certain amount of oil as well as coal. The boilers in these large ships were designed to develop the full power on coal alone, and oil was adopted as a means of enhancing the endurance both of fuel and of personnel. This policy heralded the almost entire extinction of the art of coal-firing which had been brought to a high standard by the water-tube boiler, and it also led finally to the passing of the superb specimens of physical manhood developed by work in the coal-fired stokeholds, of which the engineer officers of the period were so proud. The lowering of the physical standard really began with the supersession of the cylindrical boilers when the requirements for firing the high wing furnaces were such as to require a standard of height of 5 ft. 9 in.

Subsequent to 1912 all new-construction battleships and cruisers were designed or modified to burn oil fuel exclusively, and at the present time the only important survivors of the coal-burning vessels in service are the battleships of the " Iron Duke " class.

The many advantages of oil fuel for the Naval Service are well known and need not be mentioned in detail. The military advantages of speedier fuelling and increased endurance, and the operating advantages of steadier steaming and improved flexibility are, however, deserving of emphasis, together with the favourable reaction on the design of the ship as a whole, and the number of men required to operate the machinery. In the design of torpedo-boat destroyers following the " Tribal " class, namely, the " Beagle " class, the position as regards fuel supply was considered to entail a reversion, which proved temporary, to coal. The effect of the change is revealed by a comparison of the " Beagles " with the next following class, the " Acorns," both classes having been designed for the same speed and endurance. With a superior armament, the " Acorns " required 20 per cent. less displacement, they cost 16 per cent. less and attained on average a higher speed to the extent of 1½ knots. The effect on engine-room complements is even more marked. As an example, the " Lion " of 70,000 s.h.p.

burning coal, required an engine-room complement of 608, whereas, in the oil-fired " Hood " of 144,000 s.h.p., the ship is operated with a complement of 306.

Main Engines.—During the twenty years which elapsed between the introduction of the triple-expansion engine and the general adoption of the turbine, important design advances were made and the performance and reliability greatly improved. As a result of the increase of pressure from 135 lbs. to 210 lbs. per sq. in, and the increase in speeds of revolution from 100 to 140 per minute in the case of the higher-power engines, sensible reductions in engine weight were achieved. A fuller appreciation of the principles of engine balancing and the development of a system of forced lubrication for large engines permitted advances in speed of revolution and yielded a noteworthy return in smoothness of running, reliability, and durability. Piston speeds advanced from 700 to 1,000 ft. per min. in the large engines, while speeds up to 1,300 ft. per min. were attained in the torpedo-boat destroyer type. An interesting example of the early stages was the " Blenheim," a cruiser of 20,000 h.p. designed in 1890, in which an earlier Admiralty idea for attaining economy at cruising speed was revived. Two sets of triple-expansion engines coupled together by a disconnecting coupling were fitted on each of the two propeller shafts, the intention being to use the two after engines alone for cruising. The system was, however, not used to any great extent on service, in view of the difficulty experienced or feared in reconnecting should uneven wear of the bearings occur. Many similar ideas involving the cutting out of one or more cylinders were evolved from time to time with the same object in view, but except for making arrangements to design the valve-gear and propellers to suit the natural-draught power rather than the full power in some later classes, nothing was done in the direction of altering the engine system for a particular range of speed until the coming of the turbine, when, of course, the principle operated in the reverse sense, the cruising turbines being cut out at the higher speeds.

Quadruple expansion was not employed in the Navy. In the Mercantile Marine, however, the s.s. " Jumna," of 3.500 i.h.p. with quadruple-expansion engines by Denny, was running in 1886 at a working pressure of 160 lbs. per sq. in., and by 1900 a number of high-power merchant ships were using quadruple expansion with boiler pressures in some cases up to 267 lbs. per sq. in.

The high-pressure installations attending the use of the water-tube boiler were provided generally in the high-power naval ships with a four-cylinder design, comprising two low-pressure cylinders. An example of this type is the twin-screw design of the " Drake " class (1898), which developed 30,000 i.h.p. at 120 r.p.m.; this is the highest power reciprocating-engine installation ever fitted in the Naval Service.

In the " Britannia " (1903) of 18,000 i.h.p., one group of Babcock and Wilcox boilers was arranged with superheaters designed to give a superheat of about 50°F.

The designs from 1903 were fitted with forced lubrication, and, while the numerous reciprocating-engine ships that served during the war period did yeoman service, the greatly improved reliability attending the change to forced lubrication was then abundantly demonstrated. The engines of the " Agamemnon " class of 16,500 i.h.p. which, with forced lubrication and the manifold improvements suggested by long experience, had attained to a stage which designers were legitimately entitled to regard as a near approach to perfection, proved to be the last of their type for large ships in the Navy, the turbine having in the meantime shown in other applications its fitness to replace them.

With the introduction of the water-tube boiler the practice of carrying out efficiency trials of boilers ashore was revived, and in 1897 the practice was instituted of carrying out water-measurement tests of the main and auxiliary engines during the sea trials, which has been continued, except for the war period, in typical new designs ever since. It may be recalled that the Marine Engine Trials Research Committee of the Institution of Mechanical Engineers had conducted main engine water-measuring trials on mercantile ships at sea between 1889 and 1892. Such trials have proved of the greatest value for later design work, particularly in pointing the way to improved overall economy by using the exhaust steam from the extensive chain of auxiliary engines to better advantage. The first series conducted in the " Argonaut," which included separate measurement of the main and auxiliary steam, was primarily arranged to ascertain the main engine consumption under various conditions as regards jacketing, steam pressure and rates of expansion. The utility of jackets had been a long-disputed question and the trials showed that the use of the jackets was attended in this design by an increase in the steam consumption for powers above 20 per cent. of full power.

As a result of trials of this nature, arrangements were made later to utilize the exhaust from the auxiliaries in the main engines, thus in effect compounding these expensive steam users which were in general necessarily of the simple type. Also the evaporators were arranged to use auxiliary exhaust as an alternative to boiler steam. Later the exhaust steam was also employed for feed-heating. By these means a considerable improvement in economy was attained, particularly under harbour and cruising conditions.

At the other end of the scale of size and power, the machinery of the torpedo-boat destroyers, a class of vessel first introduced in 1892, had reached the last reciprocating-engine design in the " River " class, and with a dependable water-tube boiler had attained a high order of reliability considering the narrow margins entailed by weight reduction. These designs developed about

7,000 h.p. on two shafts when running at about 340 r.p.m. The designed speed was 25 knots, and the vessels were therefore, judged on trial results, relatively slow in comparison with their immediate predecessors which attained trial speeds from 30 to 31½ knots. But as these higher speeds were attained at the expense of reliability and could not be realized in all weathers, it was necessary to compromise to ensure that the vessels would serve their intended purposes in the scheme of naval operations. The early high-speed designs, while generally insufficiently robust to stand up to continuous service in modern warefare as then envisaged, served, however, a necessary and useful purpose in the development of naval material and influenced the designs of all classes of war vessels.

Enclosed forced-lubrication engines were fitted in the torpedo-boat destroyer "Syren" by Palmers, in 1899, and its use was afterwards extended to some of the later torpedo-boat destroyers.

Turbines.—Sir Charles Parsons has stated that the marine application of turbines was mooted as early as 1884, but it was not seriously considered until 1892 when the economy of the turbo-generator ashore had proved it superior to the compound engine. Its application is one of the few important marine changes which were made without any set-back and the initial success and the rapid extension of the system is undoubtedly attributable to the experience gained in its long and gradual development under proper conditions on shore, no less than to the soundness of the conceptions of the inventor and his thorough exploratory work in connexion with the marine application.

The turbine was evidently particularly suited to the needs of fast vessels, and it was accordingly first fitted by Sir Charles Parsons in the "Turbinia" of 42 tons in 1896, where a speed of 34½ knots was obtained.

The "Viper," of the same size as the contemporary 30-knot torpedo-boat destroyers, was ordered by the Admiralty in 1899, and while 31 knots had been guaranteed by the builders, the Parsons Marine Steam Turbine Company, she reached a speed of 33·38 knots under contract load conditions and 36·5 knots under light load. The installation was quite successful, but the trials revealed a low economy at cruising speed, and in 1901 the Parsons Company laid down as a speculation the "Velox," a torpedo-boat destroyer similar to the "Viper" but arranged with two reciprocating engines, each of 150 i.h.p. coupled to the low-pressure turbine shafts, through clutch couplings. These engines exhausted to the high-pressure turbines when in use at low speeds and were disconnected at speeds above 13 knots. This vessel was acquired by the Admiralty in 1903, and in the same year the "Eden," a similar design arranged with cruising turbines, was laid down. "Eden," "Velox," and a reciprocating-engine torpedo-boat destroyer ran a series of comparative trials which definitely demonstrated the superiority of the turbines for high speeds and confirmed the necessity for cruising turbines to assure a suitable economy at cruising speeds.

The cruiser "Amethyst" with Parsons turbines was ordered in 1902 and carried out comparative trials in due course with sister vessels equipped with reciprocating engines, which again showed the superior economy of the turbine at higher speeds, in this case 15 knots and above, the full speed being 23·6 against 22·3 for the sister vessels on the same fuel consumption.

As a result of these trials, although the experience of the turbine afloat was then very limited, the important decision was taken in 1905, after experimental investigations regarding such aspects as astern power capacity, manœuvrability etc., to equip the battleship "Dreadnought" with turbines of 23,000 s.h.p. using a boiler pressure of 235 lbs. per sq. in.; the order for the machinery was placed in June, 1905. A little later turbines were ordered for the "Invincible" class of battle cruisers of 41,000 s.h.p. The design expectations as regards saving in machinery weight, economy at full power, and reduced complements, on which so much depended to assure the success of these highly developed fighting units, were fully realized, besides, as time has shown, marked advances in reliability no less than durability. It may be mentioned, as an example of rapid production, that the "Dreadnought," notwithstanding her novelty as regards ship, armament and engines, proceeded on trial within 366 days of being laid down.

The Cunard Company had ordered early in 1904 a Parsons turbine installation for the "Carmania' of 20,000 s.h.p., from Brown of Clydebank, and this vessel was completed in November, 1905. A still more striking decision was taken by them a little later when it was decided to equip similarly the "Lusitania" and "Mauretania," in which vessels they had contracted with the Government to attain a speed of not less than 24½ knots in moderate weather. The decision, which turned upon doubts as to whether such a high speed was attainable by the use of reciprocating engines, was, as is well known, fully justified. The vessels were ordered about the middle of 1905, and were completed in 1907: the machinery of the "Lusitania" being by Brown of Clydebank, and that of the "Mauretania" by the Wallsend Slipway and Engineering Company. The soundness of the design and its execution has been abundantly demonstrated by the service performance of these vessels, of which the survivor, the "Mauretania," held until last year pride of place for speed in the Atlantic service.

From 1905 war vessels of all classes were equipped with turbines.

The higher speed of shaft revolution necessary to permit the application of Parsons direct-driven turbines of acceptable weights and dimensions led to the use of multiple-shaft arrangements. This facilitated the attainment of economy by permitting the turbines, without exceeding desirable lengths, to operate conveniently in series. The larger vessels usually had a four-shaft arrangement, comprising two independent systems. The smaller vessels had a three-shaft arrangement with low-pressure turbines on the wing shafts running in series with a high-pressure turbine on the centre shaft, but arranged so that the wing shafts could be operated independently ahead and astern as required.

The Brown-Curtis turbine, developed by Brown of Clydebank, was first fitted in the torpedo-boat destroyer " Brisk " in 1909, and in the cruiser " Bristol " in 1910, in association with superheated steam (50° F.), and this design of turbine was thereafter employed as an alternative to Parsons turbines in all classes of war vessels, in general with saturated steam. The special torpedo-boat destroyers by Yarrow from 1910 onward were fitted with Brown-Curtis turbines in association with a superheat of 100° F.

The Brown-Curtis turbines had a two-shaft arrangement in the smaller ships, as had also the Parsons impulse reaction turbine which came into use in 1910. In the four-shaft battle cruisers and battleships fitted with Brown-Curtis turbines, the turbines were in three stages—high pressure, intermediate pressure, and low pressure, arranged with the high pressure and low pressure on the centre shafts and the intermediate pressure on the wing shafts.

The capabilities of turbines of reasonable sizes to utilize steam at low pressure economically led to greater attention being given to the design of the marine surface condenser which had remained for many years without appreciable change in type or proportions. In addition to alterations of form and proportions of the cooling surface the ordered evacuation of air was provided for and special auxiliaries and accessories were developed for the purpose, with the result that the more exacting demands of the turbine were met by a much smaller cooling surface than had been usual in reciprocating practice. As an example, the " Agamemnon " (1904) had a cooling surface of 1·2 sq. ft. per i.h.p., while the " Hercules " (1908) had a cooling surface of 0·8 sq. ft. per s.h.p.; the vacuum at full power was 25·4 in. and 28·0 in. respectively.

In the Mercantile Marine, as an alternative to the complete turbine drive, the combination system covered by the Parsons inventions in the form of a three-shaft arrangement with a reciprocating engine on each wing shaft and a turbine on the centre shaft, which utilised the best features of the old and new, was favoured by some companies, notably the White Star Company in their large liners. These designs proved to be highly economical and reliable. The more recent combination of reciprocating engines in association with fast-running turbines for low-power ships seems likely to be no less successful.

Geared Turbines.—Notwithstanding the success of the direct acting turbines, it was realized from the first that the best performance of the propeller or of the turbine was not in general attained in the direct-drive installations, to such an extent indeed that, in the case of slow ships of low power, the application of turbines was quite out of the question. These considerations led to the design and development of suitable high-power reduction gearing by Sir Charles Parsons, and following trials and service in s.s. " Vespasian," so fitted in 1909, reduction gearing began to come into use in the Mercantile Marine, commencing in 1911 in the London and South Western Railway steamers " Normannia " and " Hantonia " of 5,000 s.h.p., built by Fairfield.

The geared turbine entailed a reversion to the use of the thrust-block in its independent form. There appears little doubt that the availability of the Michell thrust-bearing—a development based upon Osborne Reynold's investigation into the problem of lubrication in 1886—facilitated the application of the all-geared turbine, if indeed it did not alone render its use practicable in installations of considerable power.

The first application in the Naval Service was in the torpedo-boat destroyers " Badger " and " Beaver " with machinery by Parsons, ordered in 1911, where the high-pressure turbines only were geared, the low-pressure turbines remaining directly connected to the propeller shafts. They were followed by the all-geared torpedo-boat destroyers " Leonidas " and " Lucifer " also by Parsons and ordered in 1912, which were completed by the outbreak of war in 1914; they went directly into war service, and served throughout the War. The cruisers " Champion " and " Calliope " of 40,000 s.h.p. were ordered in 1913. So the wheel again ran full circle, and after a lapse of sixty-four years, gearing reappeared in connexion with the main engines of war vessels.

The all-geared torpedo-boat destroyer designs showed a marked improvement in economy at all speeds over the contemporary vessels, then generally fitted with a two-shaft design with a single turbine of the impulse reaction or impulse type, and this permitted of a reduction in boiler power. The weight of the gearing and heavier shaft lines practically discounted the saving in weight of boilers and turbines, and the advantages attending the change in this class of vessel rested in the better fuel economy and in the greatly improved propulsive efficiency arising from the slower running propellers, as was shown by the attainment of a higher speed with less power than was required in contemporary similar vessels. The earlier designs of turbines of torpedo-boat destroyers with fast-running propellers has been lacking in this respect in various degrees depending upon the particular speed of revolution, and on an average a gain of about 20 per cent in propulsive efficiency resulted from the change from direct drive to gearing.

Generally the turbine has proved a reliable and durable prime-mover. Cases of blade stripping of cruising turbines occurred in a relatively large number of the earlier designs which were trailed with the main engines, due to the absorption of blade clearances following casing distortion under variation of temperature. But with proper attention to design and operation this trouble has been practically eliminated, and the number of blading failures is small considered in relation to the number of installations fitted. There are turbines running on service which have never been examined over a lifetime of fifteen years, but experience has shown the desirability of opening up turbines for examination at intervals of five or six years, in order that the policy of the " stitch in time " may be applied to defects such as broken binding, eroded blades, loose and eroded nozzle-plates, etc., which, although small in themselves, may lead to a major defect if left uncorrected.

With the improved materials now available, both in respect of strength and resistance to erosion and corrosion, and a wider knowledge of the dynamical problems involved, it is reasonable to expect an even higher standard of reliability and durability from the turbine in the future, notwithstanding the increasing speeds and temperatures to which the desire for improved economy leads.

In reliability and durability, the single reduction gear has proved satisfactory. Of some 720 sets fitted transmitting powers ranging up to 36,000 s.h.p., there are on record only five cases of failure on service which have entailed renewal.

Auxiliaries.—In early days the few auxiliaries were those required in connexion with the main engines, and they were operated directly by them, except for the auxiliary feed-pump which was fitted with an independent engine. There was a time, indeed, when no auxiliary feed-pump was provided, the alternative to the main-engine driven feed-pump being a cistern arranged high up in the ship from which water could be passed by gravity to the boiler. The main feed, air, and bilge pumps were main-engine operated, as were later the condenser circulating pumps, while they continued to be of the direct-acting type. The last-named was retained for a time and it afforded a convenient means of augmenting the air pumps in the event of the alternative jet arrangement then specified being used. An Appold's centrifugal pump, specified to be driven by " an independent pair of small cylinders," was fitted in H.M.S. " Enterprise " in 1862, and a few years later the Gwynne pump came into general use.

The other auxiliaries became independent by degrees as powers and speeds increased and the need for greater flexibility arose, the last survivor being the main air-pump, which remained main-engine driven in some cases until 1903. A second auxiliary feed-pump, capable of being used for bilge and fire purposes, was fitted in 1866, and the separately driven main boiler feed-pump of Admiralty type was first fitted in 1875. The Weir feed-pump was first fitted in " Magnificent " in 1884.

The separate steam-pump for fire purposes was first fitted in " Black Prince " in 1862, this being also used to operate the capstan hitherto hand driven, and in 1866 an additional pump of the same design was fitted in the engine-room of " Hercules " ; these were the well-known " Forty Horse " pumps which endured until the " Eighties," generally in the non-condensing form. The fire pump was adapted in " Hercules " to drive blowing fans by means of pulleys and belts in order to supply additional air to the stokeholds. With the advent of the steam-boats the steam-hoist was fitted in " Hercules " in 1866.

The steering engine was the means of replacing man-power to an important degree when under way. With the increase in size and speed of ships the need for mechanical power in this connexion became acute, notably in the " Great Eastern " which was steered by hand until 1867 ; it was replaced with marked success by the steam steering-gear designed by McFarlane Gray. The steam valve-gear of this design endures in much the same form to this day. Similarly the need arose in the Navy, and it is recorded that the vessels of the " Black Prince " class required the assistance of not less than forty men to put the helm over at full speed. It was first fitted to H.M.S. " Northumberland " in 1870, while the " Warrior " was fitted at the same time with a hydraulic system, deriving power at source from a steam-engine.

Engines for starting and turning the main engines became necessary as powers increased. In the early armoured ships the difficulties of getting a free supply of air to the boiler fires were first met by the use of a steam blast, first fitted in " Monarch " in 1869. In 1870 separately driven fan blowers were fitted to augment the air supply, and in 1882, when forced draught began to come into use, larger fans capable of dealing with the whole of the air supply were provided. The Belleville-boilered ships were similarly fitted : the full power was, however, usually attainable without their full use, but furnace air-pumps were fitted to facilitate the combustion by supplying air above the fires. Steam ash-hoist engines were fitted in 1872, to be replaced in the course of time by ash ejectors in various forms.

The electric generating engine began to be fitted in 1875 for searchlight purposes, subsequently extended to internal lighting, and its course has been one of continuous development from the open type, Willians type (1885), compound open type (1891), to the enclosed forced-lubrication double-acting type (1898). A Parsons turbo-generator was supplied for H.M.S. " Victoria " in 1885, and similar installations were also used in " Cobra " and " Viper." Steam turbo-generators began to be fitted generally in the larger ships in 1912, and the types fitted included the De Laval geared design. The heavy-oil engine for electric generating was first fitted in 1904 and has been fitted subsequently in almost all new battleships and battle cruisers in addition to steam generators, where it has proved a profitable source of fuel economy, particularly under harbour conditions.

Steam-engines were first used for operating gun turrets in the " Glatton " in 1868, and steam driven hydraulic machinery for heavy gun working in the " Temeraire " in 1874. The latter application, which was due to Rendel and developed by the firm of Armstrong, was to prove the means of greatly reducing the gun's crews while also increasing speeds of operation. Air-compressors for torpedo work were employed with the introduction of the automobile torpedo in the " Admiral " class in 1880.

A distilling apparatus in one form or another appears to have been fitted ever since steam was used. Its use was considered before that date, and there is on record a letter dated 1684 from Pepys, Secretary of the Admiralty, to the Captain of H.M.S. " Mermaid " instructing him to test and report on " an engine for making salt water fresh."

In the early days of steam the distiller took the form of an iron box fixed in the paddle boxes, to which steam from the boilers was led, and from which the condensate was returned by pipes to the stokehold. In the screw ships the condensate drawn from the steam-jackets was frequently used to eke out the supply of fresh water, and the practice permitted a reduced stowage. The inventions comprised in Hall's surface-condensing scheme included an evaporator arranged in the boiler to distil *in vacuo* to the condenser—an ingenious device ; this was fitted in " Megaera " with the surface condenser and is reported to have worked successfully when properly operated.

Distillers supplied with steam from a main or auxiliary boiler began to be generally fitted in 1867, but were of very limited capacity. So-called double distillers were first fitted in 1884 ; these were the first evaporators but were still of relatively small capacity. They were arranged high up in the engine-room to permit the brine to be blown direct to the sea, no brine pumps being fitted. This practice continued until 1890 when, as already mentioned, the need for increased supplies to ensure that the boilers could be supplied with fresh water was about to be emphasized by the Admiralty Committee. Evaporators of practically the modern type with brine pumps were then introduced both for new construction and existing ships.

The need for further increase became evident after experience with the Belleville boilers, and in 1899 appreciable increases in evaporator capacity were made.

It has been said that the steam-boat was the direct lineal forbear of the torpedo craft, and considering the incidence of the torpedo craft on large ship design, to which I have already referred, their development is deserving of a little more detailed description. The use of fast, light steam-boats began in the " Fifties," this type of craft being then unknown in British harbours. The first really satisfactory design for the Naval Service appears to have been that supplied by Messrs. J. Samuel White in 1861 for H.M.S. " Sylvia," employed on surveying work. This was a 27-ft. boat with a speed of 9 knots. In 1864 the same boat designers, in collaboration with Bellis, began to develop the high-speed engine. This early work on the fast-running engine led in the course of time to the evolution of the Bellis and Morcom double-acting enclosed forced-lubrication engine which, as a type, finally took the place of the Willan's single-acting engine for such high-speed services as electricity generation.

A 36-ft. design was produced in 1867, which compared most favourably with the heavy 40-ft. steam-launch then being carried by the larger warships in respect of engine weight and fuel economy. These 40-ft. launches were twin-screw designs with vertical simple non-condensing engines, supplied by steam from a locomotive boiler; the machinery weighed 4 tons and required about 6 lb. of coal per i.h.p.-hour. Developments in the production of light fast-running engines and extremely handy boats proceeded, and by the " Seventies " the steam-launches had developed into what can now be recognized as the early form of the torpedo boat. Some of these carried the original spar torpedo and others the automobile torpedo in outboard dropping gear, both of which it may be remembered were aimed with the boat's head. Thornycroft and Yarrow had by this time, working independently along similar lines from the fast steam-boat, already reached the same end and were producing fast torpedo boats for naval use.

A 42-ft. pinnace of more advanced type, known as the " turnabout boat "—a tribute to her handiness—was purchased from White for H.M.S. " Inflexible " in 1881, and this became the pattern for naval steam-launches, from which was evolved the 56-ft. boat with a speed of 15 knots for an indicated horse-power of 150 and a machinery weight of 6½ tons. The steam-boat machinery developed as time went on through the same stages but was generally ahead of the contemporary main propelling machinery in respect of forced draught, water-tube boilers and forced-lubricated engines.

It may be mentioned that several geared-turbine driven pinnaces have been constructed, but they compared unfavourably with the reciprocating-engine designs in engine weight and economy, and the design was not repeated. This is the exception which proves the rule. For the very small engine powers required in a boat of this size the turbine is, of course, severely handicapped, particularly in a design requiring a comparatively slow-running propeller.

The steam-engine is still considerably used for the boats of capital ships, in some cases with oil-fired boilers, but it has been largely replaced by the internal-combustion engine for all lighter types of war vessels.

Submarines.—At the time of the introduction of the submarine in 1902 the employment of the petrol-engine was necessary, the heavy-oil engine not being then sufficiently developed to meet the special needs. Horizontal petrol-engines of up to 600 b.h.p. were fitted in the single-screw Holland type and in the " A," " B " and " C " class, and some of the last-named class served in the War; the last orders for petrol-engines were placed in 1909. The shortcomings of petrol as fuel for this particular service were well appreciated, and in 1903 a heavy-oil engine design of 500 b.h.p., intended for use in one of the " A " class submarines, was ordered from Hornsby, a leading firm in the production of heavy-oil engines for shore purposes. The engine did not develop the desired power and was judged to be insufficiently advanced for service in a submarine. Vickers had been experimenting in the same direction, and in 1905 an order was placed with them for an engine of 500 b.h.p. with air injection. This engine was the subject of a good deal of experimental work, and in 1907 was sufficiently developed to warrant its fitting in submarine " A.13," and while the design still left a good deal to be desired in respect of reliability and durability —the compressors were particularly liable to defects—it marked a definite advance over the contemporary petrol-engine.

The twin-screw " D " class of 1,200 b.h.p., ordered in 1907, was first fitted with a new engine design by Vickers based on the experience with the " A.13 " engine, and this design, so far at least as the cylinder unit is concerned, was the basis of all subsequent engine designs up to and including the war period. Difficulties and delays were again experienced, but these were surmounted by the end of 1910, when the vessel carried out satisfactory trials. The compressors, however, continued to prove a source of difficulty on service, and as a result of the work of Vickers and the Submarine Service a system of solid injection was evolved with a view to eliminating this troublesome feature. This was first fitted for trial in " D.6 " and by the beginning of 1913 all the " D " Class were similarly altered, the air-compressors being removed.

The design thus modified, with various improvements suggested by experience on service, became the standard construction for most of the later submarine programmes, including those of the war period. Of a specially light construction, with fabricated steel columns and bearers, the engine developed 100 b.h.p. per cylinder at speeds of revolution up to 360 r.p.m. In the " E " class, designed in 1910, the power was increased to 1,600, using an eight-cylinder design of the same standard construction as in the " D " class.

A number of smaller submarine designs with relatively low-power heavy-oil engines by Vickers and other makers were evolved between 1912 and 1914, while a twin-screw two-cycle design of 1,600 b.h.p. intended for " E.3 " was ordered for trial in 1914. Reversible engines were first fitted in the " G.13 " designed in 1912.

An attempt was made in 1912 in the " Nautilus " to increase considerably the engine power on the basis of experimental work carried out by Vickers. The design was intended to develop 3,700 b.h.p. on two shafts, and, although the vessel was never used as a submarine, the work of development was of considerable value in determining advanced problems of design. Similarly, in 1913 a steam-propelled submarine, the " Swordfish," of 7,500 s.h.p.

on two shafts, with geared turbines, was designed by Scott of Greenock, which, while also not used as a submarine, paved the way to the later successful developments in this direction.

Of the ninety-four submarines in construction prior to the War, seventy-eight were built by Vickers, the pioneers of this development in this country.

Materials.—Cast iron and wrought iron were the materials principally used in the early days together with a small amount of copper, gunmetal, and brass. Soft metal was also used for bearings to a limited extent. The increasing use of wrought iron in place of cast iron for such items as engine frames, etc., led to important savings in weight up to 1845. Steel was used to a very limited extent for piston-rods and valve-rods as early as 1845, but as these fittings became larger they were replaced by wrought iron, which was also used, of course, for the larger forgings such as shafts. Boilers were of iron, and the early tubular boilers had iron tubes, but they were soon replaced by brass tubes ; seamless brass tubes were available from 1838.

Lignum vitæ for outboard shaft bearings was first used about 1855. This material was introduced by Penn in 1854. His work in this connexion is an early example of the value of carefully considered experimental work.

Steel had been used by Adamson for boilers for service on shore in 1860, by Ramsbottom for locomotive boilers in 1873, and by Hawthorn for all parts of marine boilers from 1877. Its use for naval boilers began in 1870 and was confined at first to the boiler shells, but it had replaced Lowmoor and Bowling iron for combustion chambers, furnaces and tube-plates by 1883.

The change from iron to steel for boiler pressure parts led to a reduction of weight by 10 per cent. It may be mentioned here that the Admiralty cylindrical boilers were later on generally of lighter scantlings than those permitted in the Mercantile Marine, the thinner plates leading to a reduced weight of about 18 per cent., but the test pressure was only 90 lb. per sq. in. in excess of the working pressure instead of double the working pressure as required by the Board of Trade and the Registration Societies.

The use of steel facilitated the application of the corrugated furnace, introduced by Fox about 1874, and made in the first place of iron. It began to come into general use in 1881, replacing the Adamson ring which was first fitted in naval boilers in 1870.

So called " homogeneous metal " tubes were under trial by the Admiralty in 1858. The boiler tubes continued, however, to be of brass until 1882 when they were replaced by iron and subsequently by lap-welded steel. Lap-welded steel tubes were employed for the first Belleville boilers, but subsequently to 1894 seamless tubes were used for the large-tube water-tube boilers. Seamless steel tubes were used on the small-tube water-tube boilers from the early days of their employment in the Navy. The seamless steel pipe was first made by the Weldless Steel Company in 1872 and some samples by this process of Bessemer and Siemens steel were tried during the 1872 Boiler Committee's later investigations, but this source was not available for supplies until some years later.

The bicycle boom of 1884 appears to have been the means of developing the commercial production of seamless steel tubes when the processes of the Credenda Tube Works, Birmingham, under the 1883 patents of Stiff and Bennett were being used; the Mannesmann patents covering the rotary piercer and the pilger rolls followed in 1886 and 1891 respectively.

Copper boilers and copper tubes were fitted in isolated cases, both before and after the introduction of steel, but in general proved unsuitable.

Up till 1876 wrought iron was generally used for propeller shafts, crank-shafts, piston- and connecting-rods. The experience in the Navy was generally satisfactory, but in the Merchant Service it was recognized that the life of iron propellers and crank-shafts left something to be desired, and in some cases it appears to have been as little as five to ten years. The failures were attributed to fatigue, and in the light of our present knowledge it seems probable that this trouble was due at its root to torsional vibration. Propeller- and thrust-shafts of Whitworth steel and of hollow design were first fitted in "Iris" in 1878, and by 1880 all the larger forgings were specified to be of steel, at which time the crank-shafts also were made hollow. The "Rattlesnake," a torpedo-boat catcher of 1885, had hollow piston- and connecting-rods and steel propellers, a practice which was followed later for torpedo-boat destroyers. Cast steel began to come into use in the Navy about 1884, when the pistons and sole-plates of this material were used for "Archer." Vickers had made cast-steel propellers for merchant ships before this date. Its use gradually extended to engine columns and cylinder covers until, with the introduction of the Belleville boiler, it was used for all the larger and more important castings exposed to steam pressure.

Forged-steel cylinder liners were first fitted in 1880, and jacketed cylinder ends and covers were then generally given up.

Steam pipes were usually of copper, reinforced by wire in the case of the later cylindrical boiler designs with pressures up to 155 lb. per sq. in.; at these higher pressures there was a certain lack of faith in the durability of copper steam-pipes of large diameter under the effects of temperature or vibration. Seamless copper pipes of large diameter were not then commercially available, and the brazed seams were sources of trouble. With the introduction of the Belleville boiler and the higher boiler pressures the use of steel steam-pipes became general for all but the smaller sizes. It may be mentioned here that the "Great Eastern" (1846) had wrought-iron steam-pipes.

At the time of the introduction of the Belleville boiler seamless steel pipes were available commercially up to diameters of about 6 inches, and steam-pipes above this size were made lap-welded and reinforced by a butt strap. Since 1914, however, the naval needs for steel pipes, which extend up to pipes 14 inches in diameter, have been generally met by seamless pipes.

Gunmetal was the material generally used for naval propellers from the early days of the introduction of the screw, but with the introduction of fast-running propellers and higher blade pressures, high-tensile bronze began to be used for the blades in 1893 and was extended to bosses in 1896. Forged-steel propeller blades were commonly used for the early torpedo craft.

The shells of condensers were made of cast iron until 1874, when consideration of weight led to the use of cast brass or gunmetal. This remained the naval practice, except for the lighter vessels where brass plate was commonly employed, until the steel-plate construction was introduced generally with Weir's designs in 1908. The tube-plates have remained of brass.

The tubes were sometimes of copper in the early days, but 70/30 brass was in early use and was specified from 1870.

As may be inferred from my earlier remarks, leakage of condenser tubes appears to have been accepted as inevitable for a considerable time after the introduction of the surface condenser. The necessity, however, of providing for a pure feed supply with the increasing degree of forcing in naval boilers and the serious failures of condenser tubes in the Fleet in the preceding few years led in 1890 to the Admiralty policy of pressing for a higher standard from the manufacturers of condenser tubes which has remained in force to the present day. Till that date the manufacturers had been practically left to themselves. It must be recorded as an exception to the general rule that this interference was stoutly resisted by some of the tube makers who, with a long record of successfully meeting commercial requirements by the use of time-honoured father-and-son processes, claimed that they knew better than the Admiralty what was wanted. It took many years to break down the opposition, but in the end I think they were convinced that the radical changes enforced from time to time were beneficial to both parties. The subject is of sufficient importance to warrant the relation of the measures taken. The leakage had been due to failure at the gland, or to splitting, or to perforation of the tube by corrosion or erosion. The last-named defect, perforation, was never entirely eliminated with the brass tube, but it was definitely reduced from year to year by such steps as the addition of tin to the alloy, purer constituents of the alloy and refinements in the manufacturing processes, coupled with the provision of cast-iron water doors, steel protectors and increased care in design and operation. The first-named defects, gland leakage and splitting, were practically eliminated in the course of time by improvements in the accuracy of dimensions and in the manufacturing processes in association with design improvements in the condenser.

In 1890 the alloy was altered by adding 1 per cent. of tin, making the Admiralty mixture 70 per cent. copper, 29 per cent. zinc, an 1 per cent. tin. This was adopted as a result of the benefit proved to have been obtained by the same addition to naval brasses intended for exposure to sea-water, suggested by Farquharson in 1874. Greater accuracy in dimensions was called for, and heating and jarring tests were introduced to provide a check against a tendency to split. The purity of copper was specified to be 99 per cent. In 1894 the packing test was instituted to ensure that the tubes were sufficiently hard to stand up to the packing when holding a 30 lb. per sq. in. water-pressure test.

The trouble still continued to be serious, and between 1894 and 1900 provision was made for boring and turning the tubes before the final draws, this being introduced to ensure concentric tubes. In 1901 were introduced the following tests: (*a*) all tubes to pass without splitting an end-flattening test to half the original diameter (subsequently made less stringent); (*b*) sample tubes to stand heating to a dull red; (*c*) sample tubes to be cut up for examination for surface defects; and (*d*) all tubes to be drawn on a mandrel. The last stipulation was considered of great importance, as evidence showed that the failure of a great number of tubes on service was attributable to their having been drawn without a mandrel at the last draw. The flattening test also proved an effective means of detecting doubtful tubes.

In 1904 further measures were taken as a result of the continued complaints from afloat which, with the increasing use of the water-tube boiler, were to be regarded as even more serious than the earlier troubles, notwithstanding the great improvements made in the durability of the tubes. The principal changes were the increase of the water-test pressure (formerly 300) to 700 lb. per sq. in., sufficient metal to be turned and bored from the cast billets to remove all surface defects, and the tolerance on the external diameter to be 0·005 inch. As a result of further experience, a higher standard in the purity of components was called for, namely, copper 99·6 per cent. with a total impurity of the alloy not exceeding 0·625 per cent., together with a higher standard of accuracy of dimensions and concentricity and a limitation in the use of tube scrap to 20 per cent. With the addition of a provision for rigorous internal sighting of all tubes and an increase in the water-pressure test to 1,000 lb. per sq. in., the tests described represent the standard Admiralty practice up to 1914.

The requirements for steel for forgings generally kept pace with that of first-class commercial practice except that the requirements respecting ingot cropping were in general somewhat more severe. Acid hearth steel for forgings and boiler plates has consistently been used.

In the case of seamless boiler tubes it was the practice of manufacturers until 1912 to use Swedish steel, but in that year the necessity for independence of foreign supplies led to the Admiralty specifying the use of British produced steels for all purposes. Although naturally some difficulties were experienced, this requirement was met satisfactorily by the British steel makers, and in the first place by Messrs. Steel, Peech and Tozer of Sheffield, who supplied the steel for the tubes made by Messrs. Tubes for the battleship " Malaya," the first important installation.

In general, the steel requirements were met by the ordinary carbon steels, but the introduction of turbine gearing and impulse turbines led to the increasing use of nickel-steels for pinions and nozzle-plates.

War Period.—The further development of machinery was necessarily checked by the conditions imposed by war, but, nevertheless, the intensive experience gained on war service influenced design and hastened the application of some of the relatively untried innovations. Noticeably the all-geared turbine, the use of which was extended in turn to most of the torpedo-boat destroyers constructed from 1916, to all cruisers, and finally to the battle cruisers of the " Hood " class, of which only the " Hood " was completed. The use of separate cruising turbines, some of which had been of the geared type, was gradually dropped, alternative means being provided in the form of cruising stages in the main turbines to assure a proper standard of economy at low speeds.

The use of oil fuel was further extended to all classes of warships (excluding auxiliary vessels) built or completed during the War, including the battle cruisers, " Repulse " and " Renown " of 112,000 s.h.p., the highest-power units afloat during the war period.

The " Hood " was fitted with small-tube, three-drum, water-tube boilers, the performance of this type of boiler in the torpedo-boat destroyers and cruisers under the strenuous conditions of war having inspired confidence in its suitability for larger vessels. The degree of forcing permitted in the more important capital vessels and the size of the boiler units was in ordinary prudence less than in the torpedo-boat destroyer and cruiser classes, but nevertheless the reduction in machinery weight and space reacted noticeably on the design of the ships as a whole, and permitted of a higher speed than would otherwise have been possible. Thus the capital ship was finally placed in respect of main engines, boilers and fuel, on a footing with the torpedo-boat destroyer class which had led the way to these developments.

The small-tube boiler which had before the War developed in the torpedo-boat destroyer class into large units generating up to 115,000 lb. of steam per hour, increased during the War to larger units generating 140,000 lb. in the leaders of the " Shakespeare " class with an evaporation rate of 15·5 lb. per sq. ft. per hour. The availability of such accessories as the MacNicoll safety-valve by

Cockburn and the Antony feed regulator by Mumford played no small part in the development of the larger boilers.

The "Tribal" class (1905) had been designed to give a speed of 33 knots and the contracts provided for a bonus for speeds in excess. The contract speed was generally appreciably exceeded, and the "Tartar" by Thornycroft exceeded 35 knots. The "Swift," the first flotilla leader, by Cammell, Laird (1906), also exceeded 35 knots. Thereafter the design speeds were assessed on a more modest basis and ranged from 27 to 31 knots until Yarrow's 1911 special designs attained in the "Lurcher" a speed of over 35 knots.

The immediate pre-war designs by Yarrow and Thornycroft were capable of still higher speeds. The Admiralty pre-war designs similarly marked a considerable advance in speed, and all designs subsequent to 1915 were capable of a speed of 35 knots under trial conditions. Engine powers increased in special cases to 34,000 s.h.p. The "Tyrian" by Yarrow attained in 1918 a speed of 39·8 knots on the measured mile run during her official trials, and while the Thornycroft torpedo-boat destroyers were not run on the official mile, there is evidence that their contemporary vessels were capable of giving a speed of the same order.

Speeds exceeding 40 knots were attained in the coastal motor boats, a special development of the war period provided with fast-running petrol-engines developing up to 750 b.h.p. and hulls of specially light design.

A noteworthy design produced during the War was the "K" class submarine which continued the pre-war efforts already mentioned to produce a much faster vessel than was possible with the oil-engine then available. The surface running machinery was designed on torpedo-boat destroyer lines and developed 10,000 s.h.p.; the submerged running machinery followed the usual submarine practice, oil-engines being fitted for battery charging. The propelling machinery design was successful, and the many novel problems involved, including the rapid and effective closing of the funnel and other large hatches for submerged work, were solved satisfactorily. While not the first steam-propelled submarines, they were the only ones which have been used extensively in war. These steam-propelled vessels served their purpose, but have not been repeated, a particular disadvantage being the impracticability of providing an adequate fuel endurance.

The war period is particularly marked by the rapid production of monitors, submarines, torpedo-boat destroyers and the host of auxiliary vessels such as sloops, patrol boats, shallow-draught gunboats, mine-sweepers, trawlers, drifters, etc., which the needs of the War called into requisition. Their production affords a lasting example of the tremendous manufacturing capacity of the country and the adaptability of our marine engineering and allied manufacturers, many of whom had never before attempted the construction of oil-engines, turbines, gearing and water-tube boilers. The auxiliary vessels were in general reciprocating engine designs with coal-fired boilers which suited the needs of the case or the paramount consideration of rapid production. A reversion from Admiralty practice is to be noted in the numerous paddle minesweepers built during the war period which were used as a result of the satisfactory performance and general suitability of paddle steamers taken up for this work during the early stages of the War. The aggregate horse-power of the propelling machinery produced during the war period for naval service exceeded ten million.

At the outbreak of war, there were available very few designs of oil-engines suitable for use in submarines, and all but one, the Vickers solid-injection four-stroke design used in the pre-war designs of the " E " class, were comparatively untried in the Service. It was accordingly decided to adhere to this type for the large requirements in view. Jigs were made for the engines and orders placed throughout the country for some 200 components. The components were assembled by nineteen engine-makers who passed them on complete to the submarine builders. Engines of this type were fitted in the following classes, " L " 2,400 b.h.p., " J " 3,600 b.h.p., " M " 2,400 b.h.p. In the " H " class submarines built in this country, a smaller type, the four-cycle, blast-injection engines of 480 h.p. were of American design and the requirements for the engines were met by two British makers who concentrated largely on this work. A similar design was used in the " R " class..

It is, I think, a matter of common knowledge that the propelling designs during the War did all and more than was expected of them. While I am mindful that the success was in no small measure due to the efforts of the personnel, I am no less conscious of the debt the personnel owe to the patient work and enterprise in design which have led step by step, as I have attempted to describe to the development of the machine by means of which the high degree of reliability and durability proved by the severe test of a protracted war, was alone attainable.

The period was not, however, entirely without anxiety. Notwithstanding the strict measures taken, as already described, to assure that the highest available product was used for condenser tubes, some of the more important Fleet units suffered early in the War from difficulties due to condenser leakage. The trouble was, however, got under control and so occasioned no serious embarrassment, but its liability, which existed in all classes of vessels, could only be regarded as a possible source of weakness which merited still closer attention.

The other important difficulty arose in the water drums of the three-drum water-tube boiler. These pockets had been designed almost since the inception of the type in the so-called " D form " comprising a thick tube-plate of relatively small curvature united by a riveted joint to a roughly semi-circular and thinner wrapper plate of larger curvature. It had been appreciated early that the design was liable to concentration of stress at the riveted joint, but it possessed important advantages in weight and space and had shown no weakness on service during pre-war years except in one instance just prior to the War. With war service, however, which exposed the boilers to conditions of working much more strenuous than those of peace, the tendency to develop defects in the form of wrapper-plate grooving and cracking increased, and in some cases prejudiced the expected durability of the pressure parts. Special measures were accordingly necessary to meet the situation, and took the form of renewing the wrapper plates as opportunities offered in cases where trépanning the plates—the only reliable means of ascertaining the precise condition—indicated that the strength was being seriously affected. Emergency repairs by strapping were carried out in some cases, but as this repair merely transferred the trouble to the tube-plate, it was only adopted where unavoidable.

This defect was more pronounced in the pre-war cruisers and torpedo-boat destroyers, most of which had to have the wrapper plates renewed, but it did not occasion any of the more important naval units being withdrawn from service. The opportunity afforded by the subsequent retubing of the boilers has been taken advantage of by replacing the pockets by circular pockets in cases where the ship was remaining on post-war service. In new designs subsequent to 1917 circular pockets have been provided.

Post-War Developments.—The increase of steam pressures and temperatures in land practice and the economies found possible by these means were naturally watched carefully. The need for rapid production during the war period prevented any changes in these directions being introduced, but the investigation made led to the decision that within the permissible limits of weight the use of higher temperatures showed the most profitable source of economy.

Accordingly, a superheater design of boiler was produced towards the end of the War, and having passed satisfactory shore trials, boilers of this type were later embodied in post-war new construction. It has been mentioned that superheated steam had been employed already to a limited extent in modern naval designs. These designs were satisfactory and gave increased economy, but only to a profitable extent at the higher powers. Accordingly, in preparing the new design the desirability of attaining also the maximum possible superheat at lower outputs and so augmenting the endurance at cruising speeds, was held well in view. It was found possible to get a considerable degree of superheat at low outputs, typical results for a boiler of the type being 200°F. superheat when running at full output of the boiler and 120° at three-tenths output. The designs have further proved on service that the durability has attained a satisfactory standard, although the objective of the new design necessarily led to the superheaters being placed nearer the furnace than is usual.

Greater attention has been given to the question of air supply for combustion, both in respect of the economical delivery of the air to the boilers, following up the pioneer work of Allen of Bedford in this direction, and of the proper distribution and utilization of the air in the burners. The use of preheated air has been introduced on a small scale in isolated cases. While it is appreciated that this device offers an important source of further fuel economy, the limits of weight and space make its application a matter of considerable difficulty in naval vessels.

The foregoing changes, together with detailed improvements in the components, especially condensing plant and auxiliaries, and the utmost possible use of the auxiliary exhaust in feed-heating, have led to a considerable improvement in fuel economy over the standard obtaining during the War.

A rough indication of the advances achieved, and in particular the advance in economy at cruising powers, is afforded by the fact that the battleship " Nelson," of 33,500 tons uses the same amount of fuel at 12 knots as a " D " class cruiser of 4,500 tons. I hasten to say that a comparison of this sort must not be pressed too far, as the proportion of full power for 12 knots is much greater in " Nelson " as a result of her lower full speed.

Considerable attention has also been given to auxiliaries both from the aspects of economy and durability. With improved economy, reduced maintenance and vibration, and suitability for superheated steam in view, the use of rotary engines has extended, and it appears likely that the reciprocating steam engine will soon be a thing of the past in at least the larger vessels of the Naval Service. The older generation, those with first-hand experience of the attention and upkeep required by the primitive auxiliaries of the " Nineties," can hardly fail to view with sentimental regret the passing of faithful servitors such as the Weir direct-acting pump and the forced-lubricated fast-running engine which were such tremendous advances over their predecessors; but, having served their purpose, they must now give way to successors more fully suited to modern needs.

Electrical power requirements have extended rapidly from year to year with the demand for increased amenities, elimination of man-power and higher speeds of operation, until to-day the electric motor has practically replaced the steam-engine for ship services outside the main machinery spaces. In particular, the steam steering engine has been generally replaced by the electro-hydraulic system, with advantage as regards economy and elimination of noise in addition to the avoidance of the vulnerable and noisy shafting leads between the engine-room and the rudder head.

In the main machinery spaces the electrical drive is provided for most of the auxiliaries not directly connected with the operation of the propelling machinery, and for certain main-engine standby auxiliaries as well as for cruising auxiliaries. As is well known, the turbine auxiliary falls off considerably in economy at reduced outputs. In the " Kent " class, for example, a cruising speed of 14 knots requires only 6 per cent. of the full power, and by means of electric motors driving smaller auxiliaries or as alternative drives to the turbine auxiliaries, the auxiliary consumption can be reduced and the endurance at cruising speed correspondingly enhanced.

The electric motor has a deservedly high reputation for reliability, durability and efficiency, and we are sure that even in the difficult engine-room environment to which it is being transplanted to bear its part in propelling the vessel, it will not suffer by comparison with its excellent predecessors, and in respect of maintenance at least will make definitely less demand on the personnel.

The closed-feed system which was fitted in several torpedo-boat destroyers ordered in 1917 has been provided in the post-war cruisers with the object of eliminating the ingress of air to the system. In conjunction with the use of deaerators for harbour use it is thereby anticipated that the durability of the boiler tubes will be increased. The life of boiler tubes averages about ten years, and while many vessels have completed their service life without renewal no reason is seen why this should not now be the general rule. It may be mentioned here that under naval conditions external corrosion of water-tube boiler tubes due to moisture is by no means uncommon, and close attention is required to ensure that serious tube deterioration from this source is avoided.

With the advancing standards of living, increased amenities have naturally been introduced in modern warships leading to greatly increased demands for auxiliary service. These tend to increase the fuel consumption somewhat, but with attention to waste-heat economy and improved design the effect need not be important. The recent designs of evaporator have been arranged on the compound principle to reduce the fuel expenditure for distilling, observing that the water requirements for domestic services exceed greatly that for boiler make-up feed which averages at full power a little under 1 ton per day per 1,000 h.p. in modern designs. In this connexion it may be mentioned that the use of expansion glands for steam-pipe systems has practically been abandoned for new construction; they have been replaced by bent pipes and in the larger sizes by the Aiton corrugated pipes. Similarly, the use of materials more highly resistant to erosion for steam-valves and fittings and of improved detailed design has been the means of further reducing leakage.

A very definite advance in the reliability and durability of condenser tubes appears to be possible by the use of cupro-nickel tubes. The experience with this material has so far been most encouraging. With greater knowledge of the source of the troubles, accruing from the work of the Tube Corrosion Committee and a better appreciation of the incidence of design on corrosion and erosion, there seems to be a good prospect of minimizing appreciably this vexatious and long-standing trouble.

I need hardly emphasize the importance of a pure water supply for water-tube boilers.

Noticeable advances remain to be recorded in the use of alloy steels and other materials for turbine blading and for such services where the high speeds call for resistance to erosion in addition to strength, also the use of special heat-resisting materials for such items as superheater supports and furnace fittings.

A measure of the progress from time to time in respect of machinery weight and space reduction and of fuel economy is afforded by the comparative table in the Appendix which gives the leading particulars of the steam machinery design of some typical large war vessels from 1846 to 1925.

As regards the heavy-oil engine, the requirements of post-war submarines have led to demands for an appreciable increase in the engine power per cylinder which has been met by the designs available as a result of the work carried out by the Admiralty Engineering Laboratory, instituted early in 1917. The designs so far used afloat in post-war construction employ the four-stroke cycle with air injection and develop mean indicated pressures up to 135 lb. per sq. in. at full power at a speed of about 400 r.p.m. It will be appreciated that the attainment of such high pressures in a high-speed engine calls for the closest attention to the details of design and a considerable amount of experimental work. The preliminary work has, in this instance, been well repaid, and except for some difficulty in obtaining the desired quality in the special materials entailed by the design requirements and the necessity in some cases for some adjustments and reinforcements to correct the effects of torsional vibration, the construction has proceeded on the lines developed in the single-cylinder experiments. These designs show every promise of giving the utmost reliability and durability consistent with that at present attainable in practice from such a type of engine. I may say here that the torsional vibration problem in a submarine engine design, in which the propeller shaft necessarily carries abaft the engine the relatively large electric motor for under-water propulsion, usually proves to be difficult of solution if the unrestricted use of the oil-engine at all speeds within its range is to be assured.

The highest-power submarine vessel at present on service is the "X.1," in which the heavy-oil engines develop at full power 6,000 b.h.p. on two shafts. The main engine weight is 68 tons, that is 51 lb. per b.h.p.

The heavy-oil engine has also been fitted in two surface vessels, the minelayer "Adventure" and the submarine depot ship "Medway." In the "Adventure" it takes the form of an oil-engine driven electric installation of 6,000 b.h.p. for use at cruising speeds. The two oil-engines are of Vickers design and operate on the four-stroke cycle with solid injection and develop an indicated mean pressure of 100 lb. per sq. in. at a speed of 390 r.p.m. The electric installations were to the designs of the General Electric

Company. The " Medway," like her tenders, is entirely dependent upon oil-engines for her propulsion. Her twin-screw engines, aggregating 8,000 b.h.p. at 115 r.p.m., are of the M.A.N. double-acting, two-stroke, air-injection type to the design of Vickers. The machinery in respect of speed and weight approximates to Mercantile Marine practice.

Conclusion.—My own service responsibilities have been mainly concerned with the operation and maintenance of the machinery afloat rather than with its design, and I shall not therefore be judged as being likely to have an undue bias toward the designers. I submit, however, that the foregoing record, wherein I have endeavoured, necessarily imperfectly from the very breadth of the subject, to co-ordinate the stages in the development of naval engineering material, reveals a high order of vision, courage, and enterprise on the part of those responsible for advising on engineering policy during the last few decades.

It may be said that they were not hampered by any commercial considerations which must operate inevitably against the general employment of new features until they are exhaustively tried out. That is true, but it must be remembered, on the other hand, that their trust was a weighty one, since upon the accuracy of their judgment depended the mobility and efficiency of the Fleet. Admittedly, too, the responsible authorities had afloat a body of men who could be relied upon to bring the designs to fruition if it was humanly possible to do so, but they were equally responsible for the initial engineering training and equipment which fitted the sea-going personnel to assume the heavy burdens imposed by the urgent need for progress in naval materiel.

The record brings out, too, and I hope no less prominently, the extent to which dependence has been placed on the efforts of the marine engineering designers and allied manufacturers throughout the country, to whose assistance the Navy has seldom looked in vain. I gladly acknowledge our obligations. I do not think it will be disputed that naval progress has reacted on commercial designs, and it is gratifying to feel that this continuous effort directed towards the development of weapons of war has not been without its influence toward the peaceful end of furthering economical ocean transport and free international intercourse.

The pendulum has swung so wide in this review of a century's progress that I am tempted to follow its swing into the uncharted regions ahead. The unsuccessful predictions of past engineering prophets and recorders of " finality in design " constrain me, however, to take a cautious course, and accordingly I will confine my further remarks to a brief consideration of the promise of some of the existing propelling systems.

In past discussions on progress are found recurring plaints directed against a tendency to follow the fashion in marine engineering design. I am inclined to think that this tendency is not entirely absent to-day. The varied design types now available for marine propulsion do not, however, arise fortuitously. They have all been designed and developed to meet some specific need. The nature of the considerations involved in making a choice of machinery type vary so widely from one service to another, from one shipping line to another, and possibly even from one ship of any one line to another, that it is clearly not possible to lay down any general rule and say that any one system is superior to or better fitted to marine use than another. Each party must accordingly judge for himself in the light of his particular needs, and the decision can only rest upon the balance of advantage shown for the service in view; further, in commercial work, as such fluctuating matters as fuel costs and changes in itinerary may be involved, the decision taken to-day will not necessarily be the proper decision for to-morrow.

From the naval aspect, the steam installation continues to give the best promise of meeting our needs for high-power surface vessels. While, however, the economy of steam-plants is steadily improving and converging towards the heavy oil-engine standards there is, and appears likely for some time to continue to be, a considerable disparity in the fuel economy of the two systems in favour of the oil-engine. This difference, which may be assessed at about 30 per cent. between reasonably attainable designs of either type, is attractive, as is also the somewhat readier availability for immediate use on service which the oil-engine offers. But serious consideration has to be given to the price that would have to be paid for the advantage in the form of increased machinery weight and space or in reduced reliability and durability. It is a far cry from the placid, slow-running heavy-oil engine, on which the reputation for performance of the oil-engine afloat largely rests, to the fast-running engine in a submarine in which our own experience of the heavy-oil engine has been gained. It is to this type that we would have to turn if the oil-engine in its existing form is to compete with the available steam designs as regards weight, space, and output of power on reasonably comparable terms for the fast warship. In these highly forced types the influence of the cyclic temperature and stress changes, inevitable in a reciprocating oil-engine, affects increasingly unfavourably the reliability and durability as speed is advanced. While, therefore, the ingenuity of the designers in attempting to circumvent these inherent disabilities can hardly fail to inspire admiration, I feel that at this stage of development the standard of durability and reliability is likely to prove so far below that desired and expected as to outweigh decidedly the advantages regarding economy and readier availability for use. Another aspect not without some importance is the question of fuel supply, which might prove more difficult to meet in the case of the oil-engine of this type than for steam-plants, which in this respect are not so exacting in their demands.

On the other hand, the possibility of furthering the economy of the steam-plant is by no means exhausted. The complications necessary to permit the exploitation of steam-plants to the limits now realised on shore do not adapt themselves so readily to the marine case but, nevertheless, appreciable advances beyond the general standard are attainable. I may mention here the Canadian Pacific Railway Company liners of the 1928 " Duchess " class, where the oil-fuel consumption of 0·62 lb. per s.h.p.-hour for all purposes shows to what we may at least aspire. The work, too, in connexion with materials suited to higher steam.temperatures is not without some promise of affording ultimately the means of still further advances in association with higher steam pressures up to profitable limits for the marine case.

Of the alternative steam systems available for high-power ships, the mechanically geared turbine largely predominates, but the electrical transmission system is finding increasing use in the Mercantile Marine. The latter is used exclusively in the United States Navy for ships of the battleship and battle cruiser classes, and it has been periodically considered for our naval use from 1906 onward. It has been judged less suitable for our service than the mechanical gearing on the score of increased machinery weight and space and lower economy at full power, and because it offers no sufficiently compensating advantages in other respects. It adds another link in the chain between the boiler and propeller, but it would be idle in the face of the proved durability of electrical designs to discredit the system with a disadvantage on that score. On the other hand, the merit of avoiding the use of an astern turbine is, in the face of the performance of geared turbine designs, equally no real advantage. On balance, the advantage of mechanical gearing for capital ships is somewhat narrow, but this advantage increases as the vessel becomes smaller and faster until in the limiting case of the torpedo-boat destroyers the system is, as I think will be generally agreed, definitely impracticable. The general advantage resting in uniformity of machinery type appears likely, therefore, to continue to impose the choice of mechanical gearing for the steam drive in all our naval vessels.

For mercantile installations of relatively low power the steam reciprocating engine appears to have gained a new lease of life by the use of more highly superheated steam, by the adoption of the turbine to utilize to fuller advantage the lower end of the pressure scale, and by the use of drop valves in place of the time-honoured slide-valve, the last-named in some cases in association with compound engines. Fuel economy has advanced as a result by leaps and bounds, and when the essential considerations, such as type of fuel, first cost, and running costs are taken into account, and remembering also that the steam designs have available an ample pool of well-experienced personnel, these developments appear likely to reduce the further encroachments of the heavy-oil engine on the small-power marine designs.

The actual advantage of oil fuel over coal for steam generation in naval designs is considerably more than is suggested by a comparison of the calorific values alone. The much greater power attainable for a given boiler weight and space attending the larger boiler units and improved combustion, the facility of ready stowage in small ship spaces unsuitable otherwise for profitable use, and the reduced engine-room complement, combine with the higher calorific value of oil fuel, weight for weight, to influence ship design in a far-reaching manner. Thus the theoretical advantage is in practice magnified out of all recognition. Apart, therefore, from the operational advantages, which are also of the utmost value for naval purposes, it will be appreciated that a reversion to the use of coal in fast warships would impose such a crippling handicap on the designer under the present competitive conditions as to require the very gravest reasons to warrant its consideration.

It need hardly be said, however, that the question of the use in suitable mercantile installations of powdered coal, which gives promise of affording a means of reducing running costs beside reducing to some extent this country's dependence on external supplies, is being watched with great interest, I think when the initial difficulties are solved this system will find increasing use. The question of home-produced oil fuels is a matter of still closer interest to the Navy. As is well known, the problem of producing liquid fuels from coal is receiving very close attention from a great number of workers, and while it is early yet to predict whether and to what extent it will be possible to look to this source to meet naval needs, our experiments show at least that fuels suitable in respect to quality can be produced in this way.

APPENDIX

Ship.	Year of Design.	Paddle or Screw.	No. of Shafts.	Engines.	
				Type.	I.H.P. (S.H.P. for Turbines).
"Terrible" ..	1842	Paddle	—	Simple; horizontal direct; jet condensing; 4 cyls. 72 in. × 96 in. stroke.	1,859
"Hannibal" ..	1845	Screw	1	Simple; horizontal geared; jet condensing; 2 cyls. 71¼ in. × 48 in. stroke.	1,071
"Nile"	1846	Screw	1	Simple; horizontal geared; jet condensing; 4 cyls. 62¼ in. × 42 in. stroke.	1,247
"Agamemnon" ..	1851	Screw	1	Simple; horizontal trunk; jet condensing; 2 cyls. 70¾ in. × 42 in. stroke.	2,268
"Cæsar" ..	1852	Screw	1	Simple; horizontal trunk; jet condensing; 2 cyls. 58⅛ in. × 39 in. stroke.	1,420
"Aurora" ..	1854	Screw	1	Simple; return connecting-rod; jet condensing; 2 cyls. 64 in. × 36 in. stroke.	1,698
"Biter" .. (Gunboat)	1854	Screw	1	Simple; horizontal trunk; non-condensing; 2 cyls. 17·9 in. × 12 in. stroke.	172
"Victoria" ..	1856	Screw	1	Simple; return connecting-rods; jet condensing; 2 cyls. 92 in. × 48 in. stroke.	4,403
"Warrior" ..	1859	Screw	1	Simple; horizontal trunk; jet condensing; 2 cyls. 104¼ in. × 48 in. stroke.	5,469
"Octavia" ..	1860	Screw	1	Simple; return connecting-rod; surface condensing; 3 cyls. 66 in. × 42 in. stroke.	2,265
"Constance" ..	1860	Screw	1	Compound (Woolf's principle); surface condensing; cyls.: $\left.\begin{matrix}(2)\ 60\text{ in.}\\(4)\ 78\text{ in.}\end{matrix}\right\}\times 39$ in. stroke.	2,301
"Devastation" ..	1869	Screw	2	Simple; horizontal trunk; surface condensing; 4 cyls. 80 in. × 39 in. stroke.	6,652
"Dreadnought" ..	1872	Screw	2	Vertical; compound; surface condensing; cyls.: $\left.\begin{matrix}(2)\ 66\text{ in.}\\(4)\ 90\text{ in.}\end{matrix}\right\}\times 54$ in. stroke.	8,207
"Inflexible" ..	1874	Screw	2	Vertical; compound; surface condensing; cyls.: $\left.\begin{matrix}(2)\ 70\text{ in.}\\(4)\ 90\text{ in.}\end{matrix}\right\}\times 48$ in. stroke.	8,483
"Nelson" ..	1875	Screw	2	Vertical; compound; surface condensing; cyls.: $\left.\begin{matrix}60\text{ in.}\\104\text{ in.}\end{matrix}\right\}\times 42$ in. stroke.	6,282

R.P.M.	Boilers.			Machinery Weight, lb. per h.p.	Machinery Floor Spaces, sq. ft. per h.p.	Machinery Cost, £ per h.p.	Fuel Consumption, lb. per h.p. hour.
	Type.	Design Pressure, lb. per sq. in.	Heating, Surface, sq. ft.				
13¾	Box-shaped, flue	7½	5,784	675	1·26	21·6	4·3
Engine 27·5 Screw 64·9	Box-shaped, tubular ..	12	7,022	646	1·7	21·8	4·4
Engine 30 Screw 60	Box-shaped, tubular ..	16	7,949	668	2·26	24·4	4·2
63	Box-shaped, tubular ..	20	10,200	320	0·85	15·9	5·0
60	Box-shaped, tubular ..	20	6,800	338	1·04	17·8	5·25
61	Box-shaped, tubular ..	20	7,200	437	0·97	15·0	5·0
220	Cylindrical (through tubes)	60	1,080	495	2·93	20·0	5·5
58	Box-shaped, tubular ..	20	18,000	385	0·5	14·4	5·1
54	Box-shaped, tubular ..	20	22,400	359	0·78	13·6	4·4
69	Box-shaped, tubular ..	20	6,500	368	0·8	14·7	3·48
54	Box-shaped, tubular ..	30	6,276	414	0·79	14·8	2·95
77	Box-shaped, tubular ..	30	17,154	327	0·65	9·1	3·18
67	Oval (return-tube) ..	60	22,460	390	0·626	13·0	2·32
73	Oval (return-tube) ..	60	21,200	361	0·725	14·2	2·5
79	Oval (return-tube) ..	60	17,630	363	0·65	12·9	2·14

Ship.	Year of Design.	Paddle or Screw.	No. of Shafts.	Engines.	
				Type.	I.H.P. (S.H.P. for Turbines).
"Sans Pareil" ..	1885	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}43\text{ in.}\\62\text{ in.}\\96\text{ in.}\end{array}\right\}\times 51$ in. stroke.	8,080 (N.D.) 14,483 (F.D.)
"Blenheim" ..	1888	Screw	2	Vertical; triple-expansion; surface condensing; cyls. (2 engines on each shaft): $\left.\begin{array}{r}36\text{ in.}\\52\text{ in.}\\80\text{ in.}\end{array}\right\}\times 48$ in. stroke.	13,000 (N.D.) 20,000 (F.D.)
POST-DEFENCE ACT VESSELS.					
Battleships.					
"Majestic" ..	1893	Screw	2	Vertical; triple expansion; surface condensing; cyls.: .. $\left.\begin{array}{r}40\text{ in.}\\59\text{ in.}\\88\text{ in.}\end{array}\right\}\times 51$ in. stroke.	10,000 (N.D.) 12,000 (F.D.)
"Venerable" ..	1898	Screw	2	Vertical; triple expansion; surface condensing; cyls.: $\left.\begin{array}{r}31\frac{1}{2}\text{ in.}\\51\frac{1}{2}\text{ in.}\\84\text{ in.}\end{array}\right\}\times 51$ in. stroke.	15,000
"Hibernia" ..	1903	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}38\text{ in.}\\60\text{ in.}\\(2)\ 67\text{ in.}\end{array}\right\}\times 48$ in. stroke	18,000
"Agamemnon" ..	1904	Screw	2	Vertical; triple-expansion; surface-condensing; cyls.: $\left.\begin{array}{r}32\frac{3}{4}\text{ in.}\\52\frac{3}{4}\text{ in.}\\(2)\ 60\text{ in.}\end{array}\right\}\times 48$ in. stroke.	16,750
"Dreadnought" ..	1905	Screw	4	Turbines; series; direct drive.	23,000
"Iron Duke" ..	1911	Screw	4	Turbine; series; direct drive	31,000
"Malaya" ..	1912	Screw	4	Turbines; series; direct drive.	75,000
"Nelson" ..	1922	Screw	2	Turbines; geared drive ..	45,000
"Royal Arthur"	1889	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}40\text{ in.}\\59\text{ in.}\\88\text{ in.}\end{array}\right\}\times 51$ in. stroke.	10,000 (N.D.) 12,000 (F.D.)
"Apollo" ..	1889	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}33\frac{1}{2}\text{ in.}\\49\text{ in.}\\74\text{ in.}\end{array}\right\}\times 39$ in. stroke.	7,000 (N.D.) 9,000 (F.D.)

R.P.M.	Boilers.			Machinery Weight, lb. per h.p.	Machinery Floor Spaces, sq. ft. per h.p.	Machinery Cost, £ per h.p.	Fuel Consumption, lb. per h.p. hour.
	Type.	Design Pressure, lb. per sq. in.	Heating, Surface, sq. ft.				
101	Cylindrical (return-tube)..	135	23,250	300 168	0·51 0·29	16·3 9·1	2·4 2·26
105	Cylindrical (return-tube)..	155	27,450	266 173	0·484 0·314	10·9 7·1	2·13 2·3
100	Cylindrical (return-tube)..	155	26,273	300 250	0·56 0·47	8·3 6·9	2·35 2·22
108	Belleville, with economisers	300	37,120	203	0·41	9·4	1·88
120	3 cylindrical .. 18 Babcock and Wilcox ..	210 210	8,144 40,068	224	0·42	12·8	1·92
120	Yarrow, large-tube ..	275	50,654	211	0·38	13·4	2·0
320	Babcock and Wilcox ..	250	55,400	184	0·45	13·9	1·52
300	Babcock and Wilcox ..	235	63,756	157	0·26	7·9	1·63
300	Babcock and Wilcox .. (Oil fuel).	235	98,160	108	0·18	6·5	1·26
160	Three-drum, small-tube with super-heaters (Oil fuel).	250	51,760	102	0·16	11·4	0·789
100	Cylindrical (return-tube)..	155	24,550	266 221	0·49 0·41	9·7 8·1	1·75 1·98
140	Cylindrical (return-tube)..	155	15,770	233 181	0·54 0·42	9·4 7·3	2·7 2·98

Ship.	Year of Design.	Paddle or Screw.	No. of Shafts.	Engines.	
				Type.	I.H.P. (S.H.P. for Turbines).
"Terrible" ..	1894	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}45\frac{3}{4}\text{ in.}\\ 70\text{ in.}\\ (2)\ 76\text{ in.}\end{array}\right\}\times 48$ in. stroke.	25,000
"Diadem" ..	1895	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}34\text{ in.}\\ 55\frac{1}{2}\text{ in.}\\ (2)\ 64\text{ in.}\end{array}\right\}\times 48$ in. stroke.	16,500
"Drake" ..	1898	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}43\frac{1}{2}\text{ in.}\\ 71\text{ in.}\\ (2)\ 81\frac{1}{2}\text{ in.}\end{array}\right\}\times 48$ in. stroke.	30,000
"Black Prince"	1902	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}43\frac{1}{2}\text{ in.}\\ 69\text{ in.}\\ (2)\ 77\text{ in.}\end{array}\right\}\times 42$ in. stroke.	23,500
"Amethyst" ..	1902	Screw	3	Turbines; series; direct drive.	10,000 (Est.)
"Shannon" ..	1904	Screw	2	Vertical; triple-expansion; surface condensing; cyls.: $\left.\begin{array}{r}40\frac{5}{8}\text{ in.}\\ 65\frac{1}{2}\text{ in.}\\ (2)\ 74\frac{5}{8}\text{ in.}\end{array}\right\}\times 48$ in. stroke.	27,000 27,000
"Invincible" ..	1905	Screw	4	Turbines; series; direct drive.	41,000
"Glasgow" ..	1908	Screw	4	Turbines, independent; direct drive.	22,000
"Lion"	1909	Screw	4	Turbines; series; direct drive.	70,000
"Cleopatra" ..	1913	Screw	4	Turbines; independent; direct drive.	40,000
"Repulse" ..	1914	Screw	4	Turbines; series; direct drive.	112,000
"Furious" ..	1915	Screw	4	Turbines; geared drive ..	90,000
"Hawkins" ..	1916	Screw	4	Turbines; geared drive ..	60,000
"Hood"	1916	Screw	4	Turbines; geared drive ..	144,000
"Delhi"	1917	Screw	2	Turbines; geared drive ..	40,000
"Enterprise" ..	1920	Screw	4	Turbines; geared drive ..	80,000
"Berwick" ..	1925	Screw	4	Turbines; geared drive ..	80,000

R.P.M.	Boilers.			Machinery Weight, lb. per h.p.	Machinery Floor Spaces, sq. ft. per h.p.	Machinery Cost, £ per h.p.	Fuel Consumption, lb. per h.p. hour.
	Type.	Design Pressure, lb. per sq. in.	Heating, Surface, sq. ft.				
110	Belleville	260	61,800	208	0·42	7·6	2·0
110	Belleville, with economisers	300	40,490	205	0·39	9·5	1·76
120	Belleville, with economisers	300	71,970	183	0·35	10·1	1·81
135	6 Cylindrical .. .. 20 Babcock and Wilcox ..	210 210	11,417 51,040	206	0·39	12·8	2·11
Wings 680 Centre 480	Yarrow, small-tube ..	300	25,968	121	0·31	10·4	1·45
125	Yarrow, large-tube ..	275	80,424	181	0·39	11·9	1·82
275	Yarrow, large-tube ..	250	103,881	166	0·3	12·6	1·83
470	Yarrow, small-tube ..	235	49,500	104	0·27	6·7	1·64
275	Yarrow, large-tube ..	235	155,022	154	0·25	6·6	1·67
590	Yarrow, small-tube (Oil fuel).	235	42,400	48·4	0·12	4·6	1·33
275	Babcock and Wilcox (Oil fuel).	235	157,206	113	0·166	8·6	1·28
320	Yarrow, small-tube (Oil fuel).	235	108,000	66·5	0·128	6·4	1·03
420	Yarrow, small-tube (8 Oil fuel) (4 Oil and coal).	235	79,900	71·2	0·158	8·1	1·26
210	Yarrow, small-tube (Oil fuel).	235	175,000	84·0	0·136	9·6	1·11
275	Yarrow, small-tube (Oil fuel).	235	40,050	53·5	0·132	6·3	1·15
350	Yarrow, small-tube (Oil fuel).	250	67,998	44·0	0·108	7·2	1·17
300	Three-drum, small-tube, with super-heaters (Oil fuel).	250	67,504	45·5	0·118	5·6	0·89

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