MARINE ENGINEERING IN THE RN 1860–1905

PART I. INTRODUCTION OF COMPOUND ENGINES

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This authoritative history of the development of marine engineering, from the Royal Navy's first armoured battleship, Warrior, *to the steam turbine, will be published as four self-contained parts in successive issues of the* Journal of Naval Engineering. *These parts deal respectively with the introduction of compound engines, development of the triple expansion engine, boiler development and condenser problems, and the introduction of turbines.*

ABSTRACT

The *Warrior*'s machinery installation was 'State of the Art' in 1860 with low pressure box boilers, little more than kettles, filled with sea water, supplying steam to Penn trunk engines. The advantages of higher pressures and two-stage expansion were recognized but there were many problems in designing and building a complete system to withstand these pressures. Machinery only slowly became economical enough to dispense with sail for long voyages.

Introduction

During this period, from *Warrior* to *Dreadnought*, steam was generated at ever higher pressures and used more efficiently in compound engines, made possible by closed feed systems using fresh water, recovered in surface condensers. In principle, the advantages of all these features had been recognized at least thirty years earlier and many had even been tried. However, the successful use of Scotch boilers and later of watertube boilers, of triple expansion engines, etc., was dependent on many detailed improvements, mainly in materials, such as the use of steel for boilers, reliable joint and packing materials, effective feed water treatment, better lubrication and precise balancing, many of these in turn depending on improvements in machine tools and metrology. TABLE I shows the magnitude of some of these changes.

TABLE I—*Machinery changes 1860–1905 (typical battleship)*

	1860	*1905*
Indicated Horse Power	5900	24,700
Pressure, lb/in^2	20	250
Piston speed, ft/min	430	1000
Revolutions/min	54	125 (turbine 328)

Twin screws had originally been seen as a handicap to sailing qualities but, with improved economy and reliability, twin screw ships could dispense with sails. At the end of the era, turbines had been accepted for the largest ships and oil firing had been proven in prototype installations.

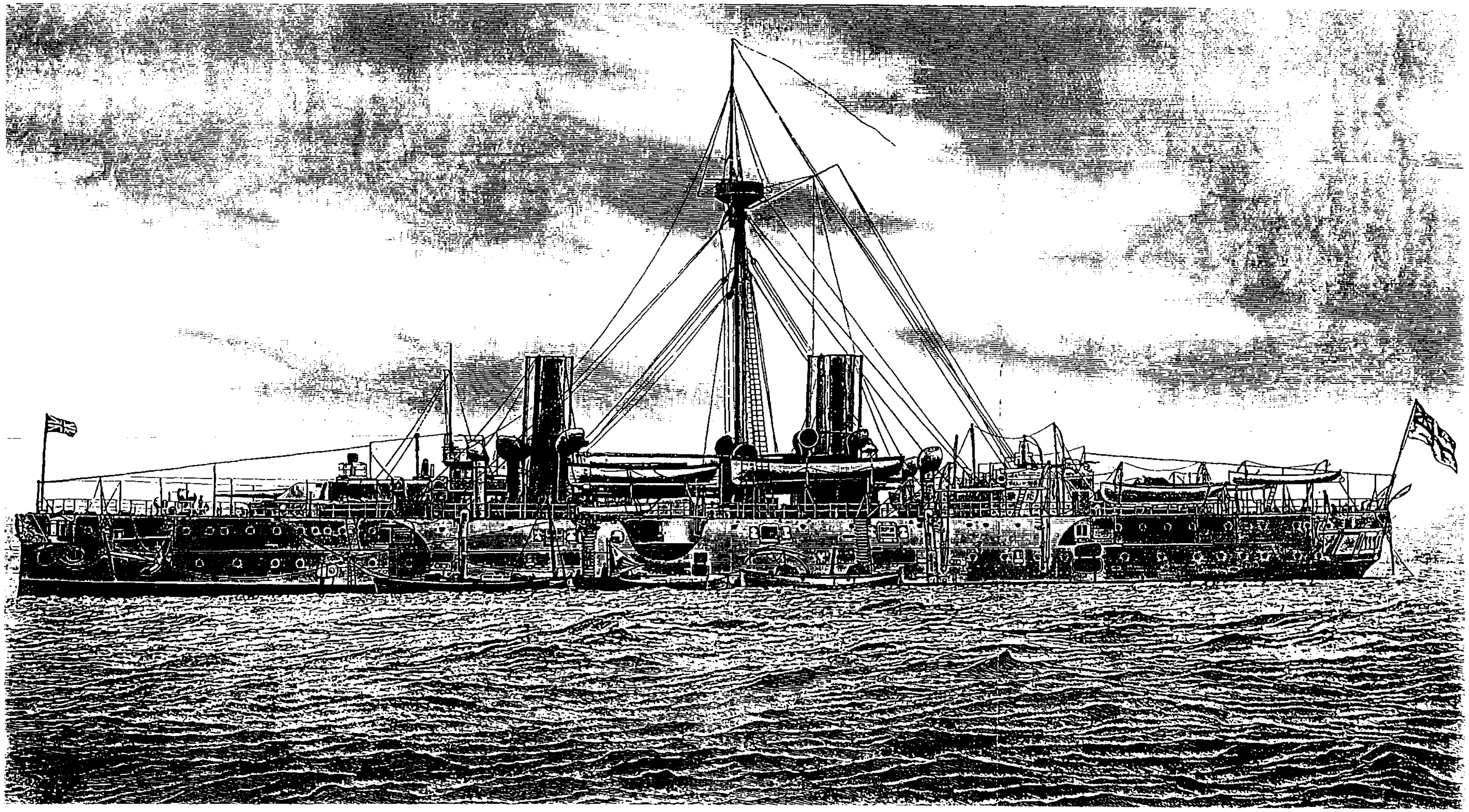

FIG. 1—HMS 'IMPERIEUSE', LAUNCHED 1883. SHIPS CHANGED GREATLY IN THE 45 YEARS COVERED IN THESE ARTICLES AND THERE CAN BE NO TYPICAL SHIP. HOWEVER, THE 'IMPERIEUSE' COMES ABOUT THE MIDDLE, HAS COMPOUND ENGINES AND CYLINDRICAL BOILERS, AND MAY AT LEAST BE SEEN AS THE 'MODE'.

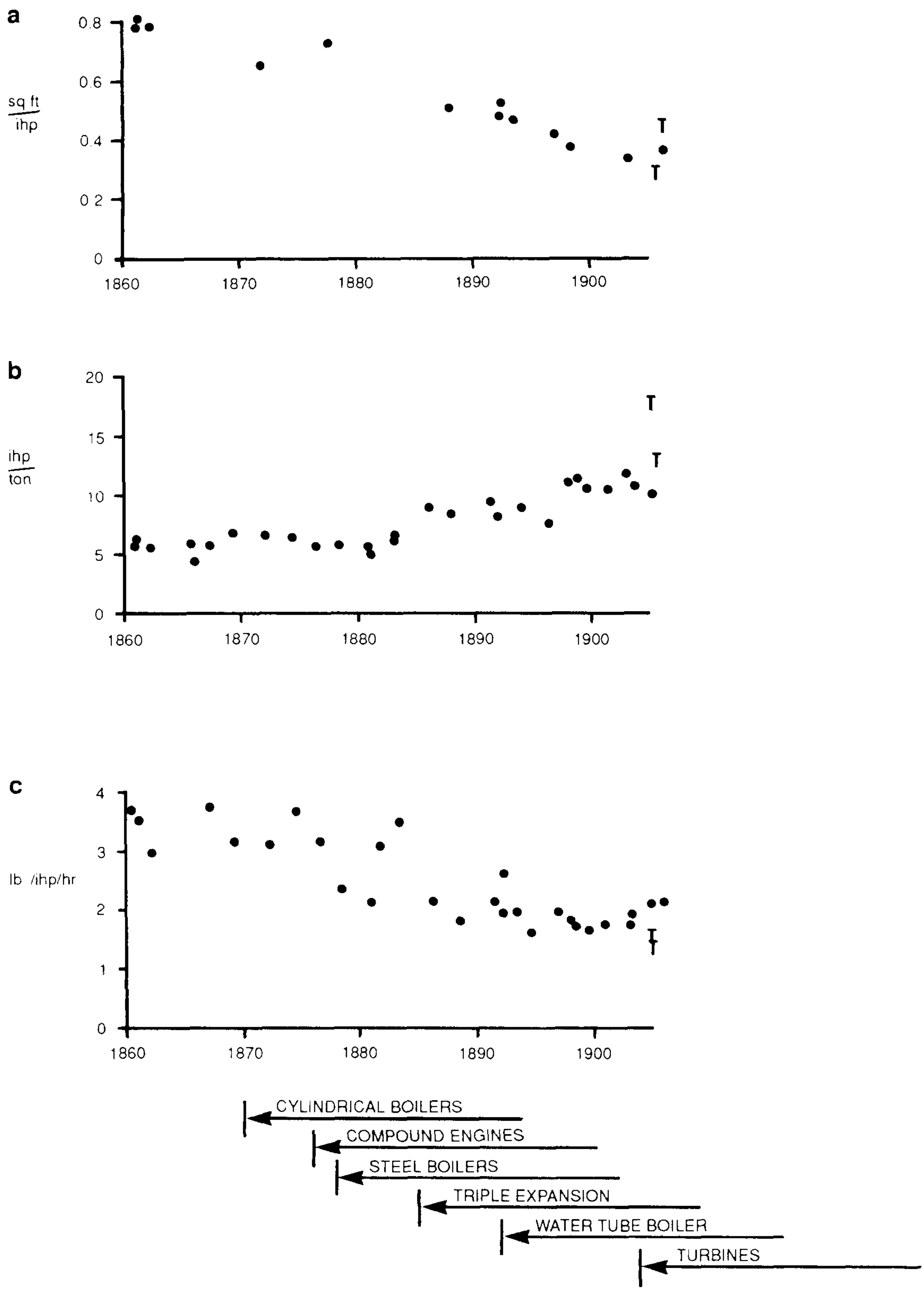

FIG. 2—THESE GRAPHS SHOW THE TRENDS WITH DATE OF:
a. MACHINERY SPACE FLOOR AREA WITH POWER
b. INDICATED HORSEPOWER PER TON (WET)
c. COAL CONSUMPTION PER IHP PER HOUR
KEY DATES ARE SHOWN FOR MAJOR MACHINERY DEVELOPMENTS WHICH INDICATE THAT IMPROVEMENTS WERE NOT CONTINUOUS BUT DEPENDED, TO A LARGE EXTENT, ON DESIGN CHANGES. T DENOTES TURBINE SHIPS

These developments led to a reduction in the weight and space needed for machinery and fuel (FIG. 2); the savings going into heavier armament and protection. Only brief mention is made here of the engineering of weapon systems or of electrical engineering. The Admiralty under Thomas Lloyd and subsequent Engineers-in-Chief (E-in-C) were active in encouraging manufacturers to try and use new ideas and were amongst the leaders in accepting new technology into general service, once proven.

Chronology

Though a few notable trials are shown, the intention is to show when introduction became general rather than to produce a list of 'firsts'.

Lloyd	1860	Institution of Naval Architects founded
(E-in-C)	1861	*Warrior*
	1864	Royal School opened
	1865	*Constance* trials of compound engine
	1867	*Cerberus*, no sails
Wright	1869	*Devastation*, first battleship without sails
(E-in-C)		Lloyd retires; Wright E-in-C
	1870	Cylindrical boilers
	1872	Committee on Designs
		Torquay model tank opens
	1874	*Inflexible*, electricity, auxiliary machines increase
	1873–77	Compound engines, *Alexandra, Dreadnought*
	1875	*Iris* steel hull and boilers, corrugated flue
		Trials, propeller design, etc.
	1876	TB *Lightning*
	1877	*Marlborough* for training
	1879	Steam Manual published
		Keyham opens
	1880	Forced draught
	1885	Triple expansion, *Victoria*—turbo generator
	1887	Wright to Sennett as E-in-C
	1889	Sennett to Durston as E-in-C
		Institute of Marine Engineers founded
	1892	Boiler committee
		Belleville boilers, *Powerful*
		Destroyers
	1896	*Turbinia* trials
	1898	*Viper* ordered with turbines
		Trials of oil fuel
	1900	Boiler Committee, alleged failure of Bellevilles
	1904	*Dreadnought*

The Committee on Marine Engines, 1860

The work of the Engineer-in-Chief's Department was reviewed by a committee in 1860[1,2] whose rather muddled report endorsed the procedures of Thomas Lloyd and his staff in both technical and contractual aspects. The committee recognized that the requirements for warship machinery were different from those of merchant ships and set out the following essential features:

- The machinery should be arranged entirely below the waterline.
- Engines should be simple in construction as far as is consistent with efficiency.
- All parts of the engine must be readily and easily accessible so as to be easily removed and replaced when required.

Though they fully recognized the value of higher steam conditions, they accepted that there was, in 1860, no way of using such conditions reliably and recommended the continued use of box, tubular boilers. For higher powers, they recommended the Penn trunk engine, while for lower powers the single piston rod engine, introduced by Humphrys, Tennant and Dyke and also built by Penn and Maudslay, was superior to all others.

The Admiralty's practice of inviting tenders from only a limited number of firms, mainly on the Thames, had been sharply criticized but evidence to the committee by Baldwin Walker (Controller) and Lloyd showing that contractors were judged on their record of cost and reliability, together with the skill and experience of their current technical staff, was seen as justifying this procedure.

In 1860, the Navy had 132 steam ships of 400 NHP or more and 367 smaller steamships, with a total of 116,540 NHP installed, equivalent to about 540,000 ihp[3].

Warrior—The State of the Art

The machinery of HMS *Warrior* (FIG. 3.) was typical of the best engineering practice of the day[4]. She had ten smoke tube, box boilers built of wrought iron with brass tubes, experience having shown that problems from galvanic action were less than those due to corrosion of iron tubes. The boilers (FIG. 4) were water tested to 40 lb/in^2 and the safety valves were set at 22 lb/in^2 though, in service, they were usually operated at 15 lb/in^2. Each boiler contained 17 tons of sea water at working level.

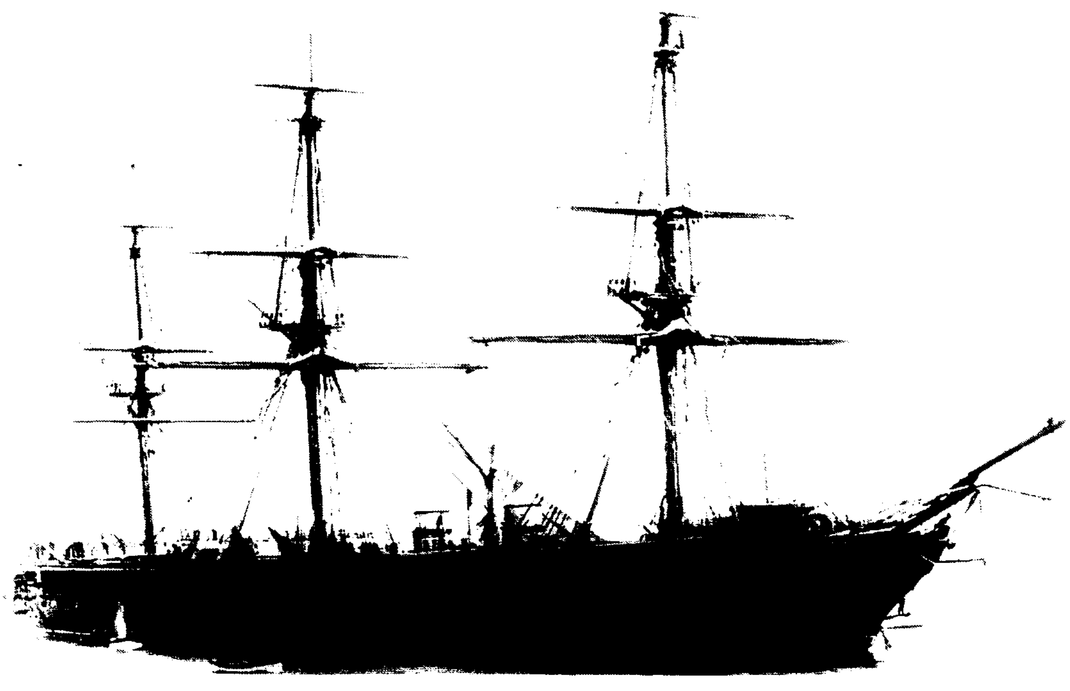

FIG. 3—'WARRIOR', THE IRON-HULLED, ARMOURED SCREW 'BATTLESHIP' WHICH OPENED THE ERA. LAUNCHED 1860

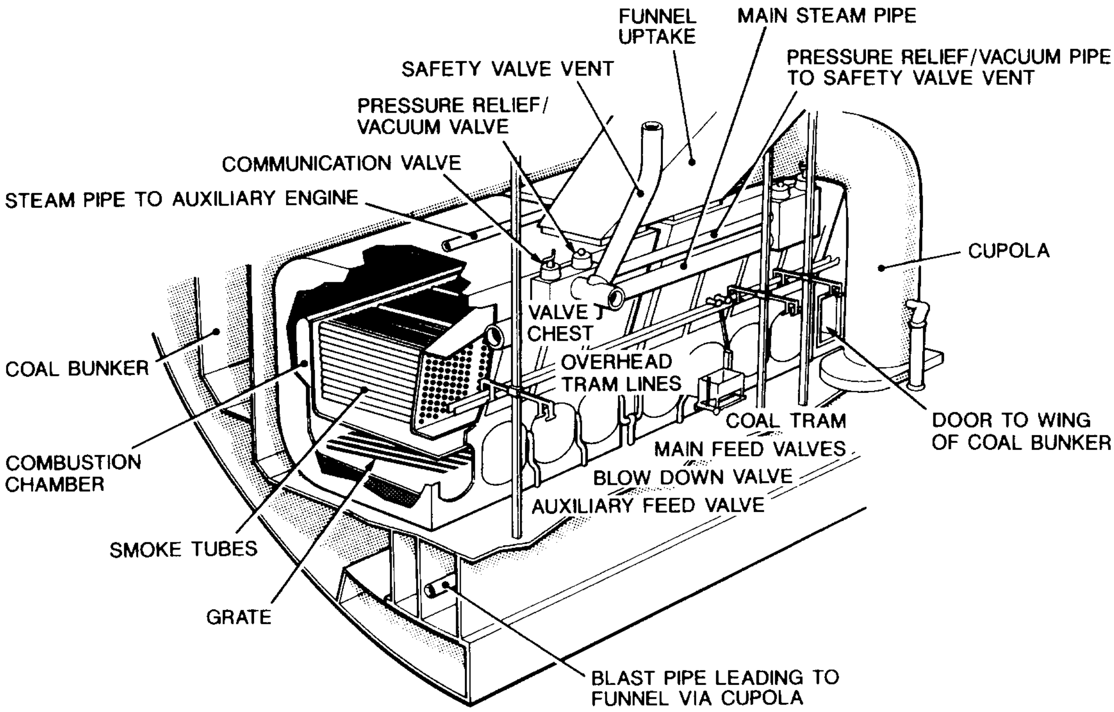

FIG. 4—A SKETCH OF WARRIOR'S BOILERS

Steam was delivered to the twin cylinder, double acting, single expansion, trunk engine through a condensate separator. Particulars of this and other machinery plants are given in Appendices I and II (pp. 406–407). Steam cut-off to the cylinder could be varied considerably by a link mechanism on the valve gear. All valves needed for the operation of an engine and its condenser could be worked from a starting platform over the condenser.

There was a small 'donkey engine' which could work a bilge pump, fire main, the ventilation fans for the gun deck and to hoist full ash buckets to the upper deck for disposal. *Warrior*'s engine room complement was 95 officers and stokers.

Once a few teething troubles had been overcome, her machinery proved very reliable. During her service with the Channel Fleet she covered 51,000 miles and a further 36,000 while in First Reserve. While in the Channel Fleet she spent 36% of her time at sea under steam alone, 42% with steam and sail combined and only 22% under sail alone. During normal cruising she would run at 25–30 rev/min with either four or six boilers working, roughly half speed.

All fuel consumption figures (TABLE II) varied very considerably with the quality of coal, accuracy of measurement, fouling, sea state and the experience of the engineers. It should be appreciated that the cost of coal was not very important as the price was about £0.8 per ton in home waters and £1.5 in the Mediterranean. As Scott Russell said (of merchant ships) 'The fuel cost is so little that I do not care so long as the one man is enough to put it in. If I required two men to put it in, I should have to economise'[5].

TABLE II—*Warrior's coal consumption*

Boilers in use	*Speed* knots	*Coal* ton/hr
4	11	3.5
6	12	4.5
10	14.5	9.0

Several changes were made during her 1874 refit, as well as making good some defects. The valves were modified to give an earlier cut off, making more use of the expansion of the steam, and new boilers were installed with superheaters to reduce the carry-over of water. Such superheaters were in common use until about 1870, more to reduce the amount of solid water carried over, which could cause priming, than to improve steam conditions.

Similar changes, together with better thermal insulation and improved lubricants gave worthwhile improvements in fuel consumption and kept the box boiler and trunk engine as the main contender for the machinery of major warships (Appendix II). Surface condensers were coming into use but there were many problems with fouling, corrosion and failure of seals.

Professional Matters

1860 was the year of the Great Exhibition, seen by many as the apogee of British engineering and that year also saw the formation of the Institution of Naval Architects whose formation was largely due to Admiralty professional officers and which then saw marine engineering as coming within its scope[6]. The Institute of Marine Engineers was founded in 1889.

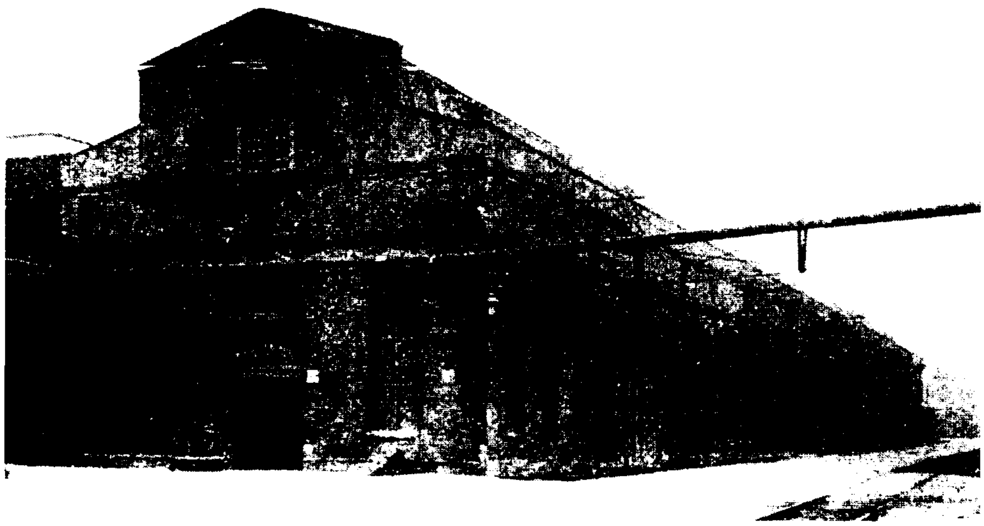

FIG. 5—THE WOOLWICH STEAM FACTORY. OPENED IN 1836 AND CLOSED WITH WOOLWICH DOCKYARD IN 1869, IT WAS THE CRADLE OF NAVAL ENGINEERING TRAINING FOR BOTH SEAGOING PERSONNEL AND FUTURE DESIGNERS AND BUILDERS

The spiritual home of naval engineering was the Woolwich Steam Factory (FIG. 5) which not only refitted engines but trained a large proportion of Admiralty civilian engineers and many seagoing naval engineers. Many of its brightest men left to form their own businesses, an important factor in the predominance of Thameside industry in naval work[7]. Thomas Lloyd, one of the greatest of Victorian engineers, had been Chief Engineer at Woolwich and had nearly another decade of service as Engineer-in-Chief to come.

One may also see Rankine's book *Steam Engines and other Prime Movers*, published in 1860 as a major step in professional matters, bringing together the theory of thermodynamics and practical engine design. The publication of steam tables showed the need for better use of the expansive power of steam in compound engines.

Compound Engines

The power available in the expansion of steam had been used for many years in single stage engines but there were limits to such use. As the pressure dropped in the cylinder, so did the temperature and this caused considerable heat losses from the alternate heating and cooling of the cylinder[8]. The changes in pressure during the stroke caused big fluctuations in the force on the crank which led to vibration and wear. As boiler pressure rose, the advantages of expanding the steam in two stages, two cylinders, became clearer, though there were fears of 'high' piston speeds[9].

Multi-stage expansion engines had been known since Woolf's patent of 1803; indeed, early compound engines were often known as Woolf engines even when not of his design. The advantage of compound engines over the 'simple' single expansion engine are not great at lower steam pressures and hence success depended on boilers and steam systems which could work reliably at 60–70 lb/in^2 which, in turn, implied surface condensers with closed feed using very pure water. All these aspects created new problems and though inventors could demonstrate the efficiency of the compound engine, their reliability was usually poor.

Elder's patent of 1853 may be seen as marking the first practical compound engine and this design was adopted by the Pacific Steam Navigation Co in 1855 for two new paddle steamers, as they were concerned by the high cost of coal on the Pacific coast of South America. These ships proved successful and the company re-engined three older ships shortly afterwards. Their fuel consumption was reduced by 50% but some of this improvement was thought to be due to more efficient steam jacketing. The P & O line adopted a Humphrys compound engine in 1861.

In discussion[9] Sir C. A. Hartley compared two small ships of 1000 tons deadweight, one with simple and one with compound engines (TABLE III). This showed a saving of £2112 over six years.

TABLE III—*Comparison of simple and compound engines*

Ship	*Engine*	*Coal per annum* tons
King Coal	simple	2376
Glenmanna	compound	1496

TABLE IV—*Trials comparing the economy of HMS 'Constance' (compound engine) with 'Arethusa' and 'Octavia' (simple engines). All three ran out of coal at varying distances before Madeira*

	Distance from Madeira miles	*Coal consumption* lb/ihp/hr
Arethusa	200	3.64
Octavia	160	3.17
Constance	30	2.51

The rise of British commercial steam shipping had been aided by the high charter rates paid to steamships during the Crimean War, by the collapse of US shipping during the Civil War (1861–65) and by the opening of the Suez Canal at the end of 1869 which gave steamships a great advantage over sail in the Far East trade. The very fast blockade runners built to supply the Confederacy during the Civil War helped to develop high power machinery. The operation of commercial shipping was greatly assisted by the extension of the cable network between 1860 and 1880.

In 1860 the Admiralty installed an Elder's engine in the wooden, screw frigate *Constance* (FIG. 6) which was tried against sister ships with simple engines, *Arethusa* with Penn and *Octavia* with Maudslay design, all three using steam at 25–30 lb/in^2. The three ships left Plymouth on 30 September 1865 heading for

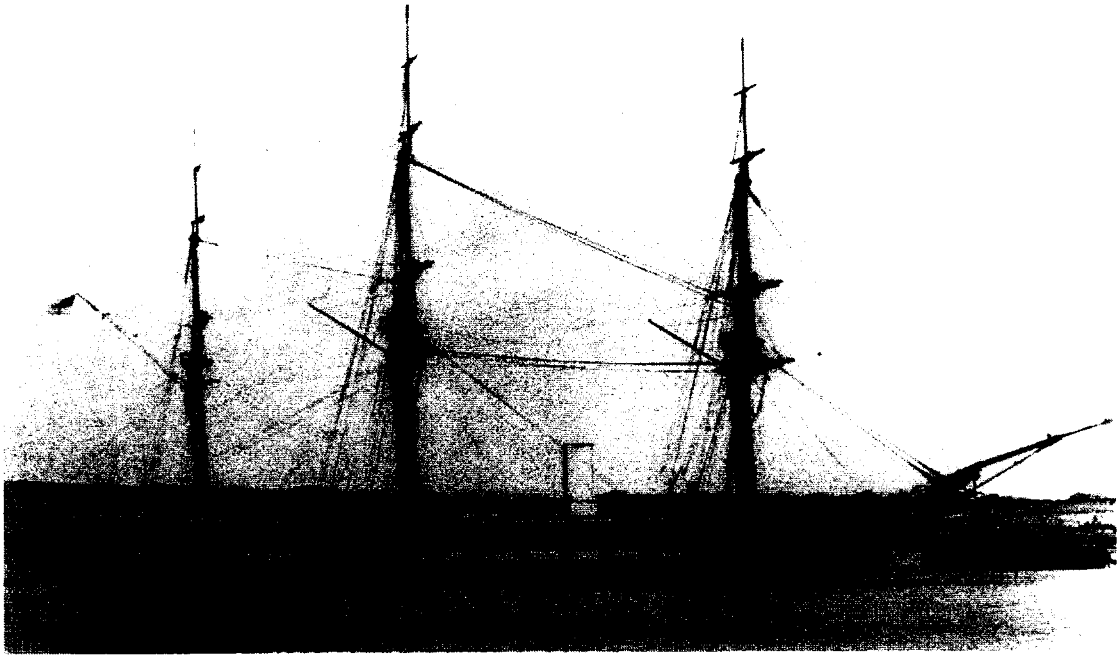

FIG. 6—'CONSTANCE', LAUNCHED (AS STEAMER) 1862. A HANDSOME WOODEN STEAM FRIGATE WHICH CARRIED OUT TRIALS WITH A COMPOUND ENGINE BY ELDER

Madeira, the 'race' ending on 6 October when all three ran out of coal. The distances from Madeira when this happened are shown in TABLE IV. Though *Constance*'s engines (FIG. 7) were fuel efficient, they were said to be complicated, difficult to handle and unreliable[10]. She, and *Octavia*, had surface condensers which corroded rapidly in fresh water, it being claimed that salt water formed a protective layer on the tubes. *Pallas* was laid down in 1863 with a Humphrys compound in which the two HP cylinders were rearward extensions of the LP cylinder. Once again, she was economical but, though there seems to have been no complaint of her reliability, she was not repeated. Engines of the same design were fitted in two Indian troopshops and suffered from rapid wear, being replaced by simple engines.

In the late 1860s corvettes were built with different designs of compound engines, all working at about 60 lb/in^2 and achieving just over 2,000 ihp. *Briton*'s Rennie engines used 1.3 lb/ihp/hr at full power and 1.98 at lower power on trial though she could not repeat these figures in service. *Thetis* managed 2.55 at full power and 2.4 at 8 knots, while in 1869 the new turret battleship *Monarch* recorded 2.79 lb/ihp/hr, helped by a steam blast in the uptake to increase the draught, all better than any simple engine. The corvette *Spartan* (Rennie) was said to be very unreliable due to the long steam pipe to the HP cylinder and the inexperience of her engineers, though when re-engined in 1875 with a nominally identical engine, she proved reliable.

The 1872 Committee on Designs[11], set up after the loss of the *Captain* to examine the design of ships under construction or planned, strongly recommended compound engines: '. . . the weight of evidence in favour of the large economy of fuel thereby gained is overwhelming and conclusive . . . economy of fuel may mean thicker armour, greater speed, a smaller and cheaper ship or the power of moving under steam alone for an extended period.' In general, compound engines were being introduced into larger ships but further trials were carried out in some gunboats before they were fitted generally in smaller ships.

Opinion was still divided; an anonymous writer in *Naval Science*, 1872[12], saw the adoption of compound engines as 'very doubtful' Other navies made the transition to compound engines at about the same time as the RN.

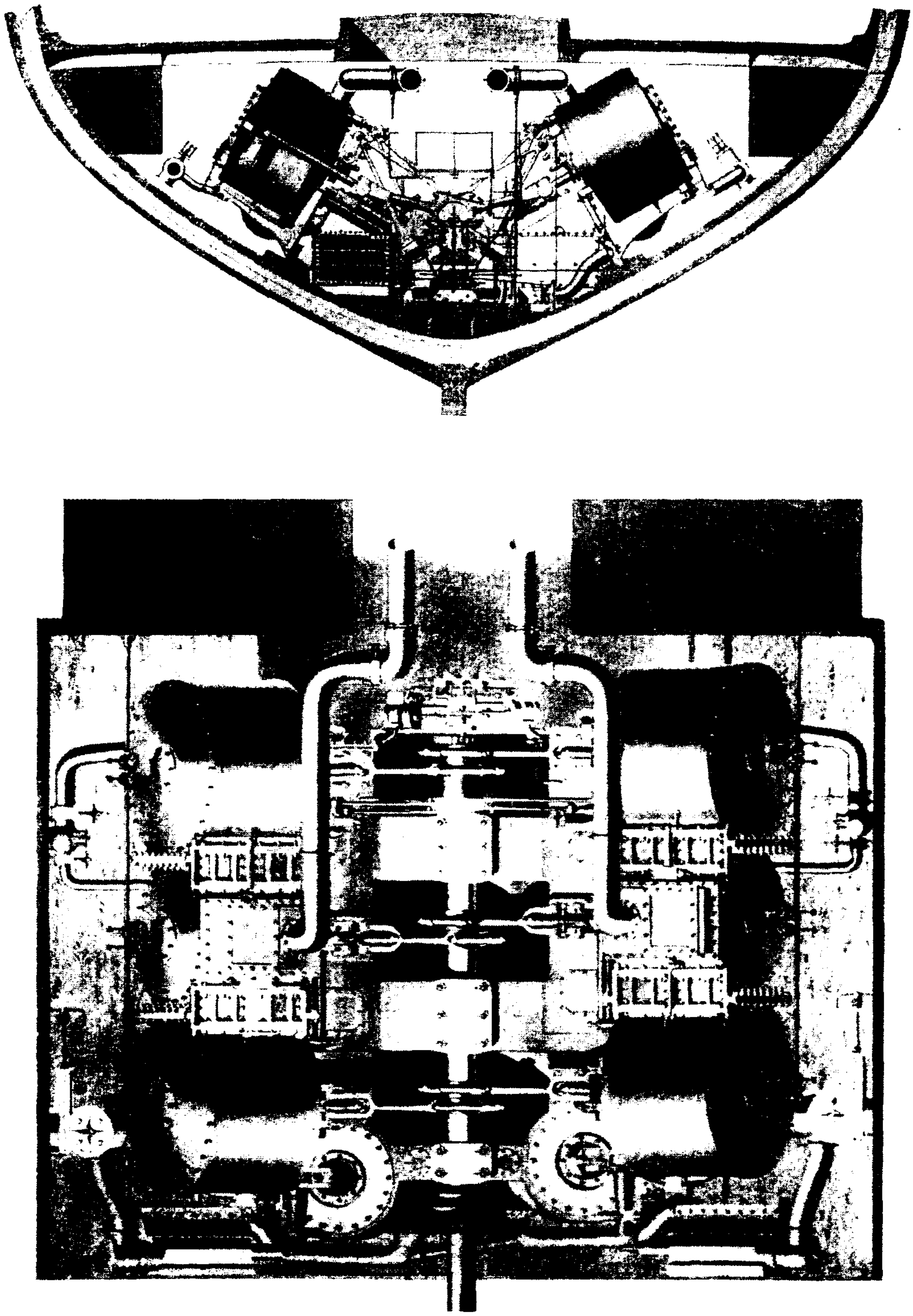

FIG. 7—THE ARRANGEMENT OF HMS 'CONSTANCE' SIX-CYLINDER ENGINE

Higher Steam Pressures

One objection to the introduction of compound engines had been the fear of the effects of high pressure steam from a boiler explosion following action damage, apparently justified by some incidents in the American Civil War. As a result, some ships were designed to use steam at low pressure in action but, perhaps surprisingly an explosion in the *Thunderer* (FIG. 8), laid down in 1869

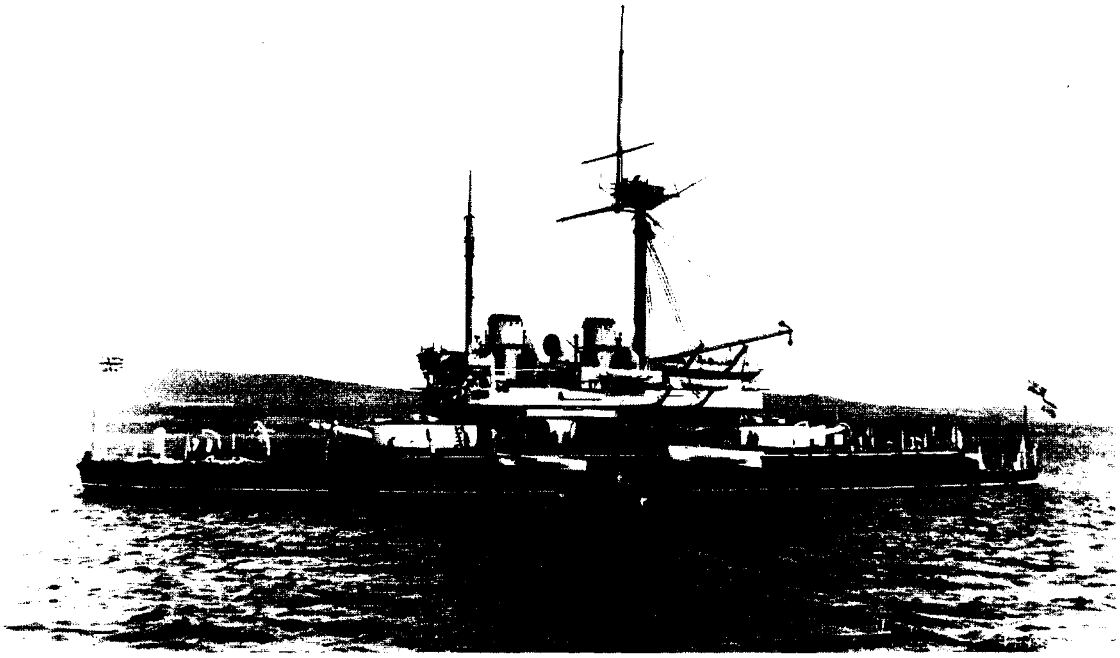

FIG. 8—'THUNDERER'; WITH HER SISTER, 'DEVASTATION', THE FIRST BATTLESHIPS WITHOUT SAIL. LAUNCHED 1872. SHE HAD A NOVEL SYSTEM OF HYDRAULIC OPERATION OF HER FORWARD TURRET

and the last battleship with box boilers, seems to have lessened the force of this objection since even low pressure steam was clearly lethal. Soon after completion, in 1876, a boiler exploded killing 40 men; this disaster was primarily due to maloperation as the stop valves had not been opened while, for different reasons, the pressure gauge and the safety valves were inoperative. The enquiry noted, with apparent surprise, that boilers were not built under Admiralty oversight, though this had no bearing on the accident[13].

Cylindrical boilers were, by their shape, better suited to resist high pressure but were seen as wasteful of space and so a few ships were built with oval boilers, top and bottom semi-circular with flat sides, stayed across. Above about 30 lb/in^2 it became increasingly unsatisfactory and even dangerous to use sea water as boiler feed due to salt incrustation and corrosion.

Samuel Hall had patented an effective surface condenser in 1831 which was installed in a number of ships, including the first Cunard liner, *Sirius*, and a few warships. There were considerable problems in keeping the joints steamtight in the larger number of small diameter brass pipes whose length changed with temperature. Deposits of tallow, then used as lubricant, formed in the condenser and were carried into the boiler where they broke down into organic acids, hastening corrosion. There were also problems with dirt in the sea water on both the cold water and steam side.

Higher steam pressures needed pure fresh water and surface condensers came into general use during the 1860s (Appendix I). There was probably a degree of conservatism acting against surface condensers but, at the low steam pressures in use, up to 30 lb/in^2, their advantage was not great while the problems were real and the cost considerable. They did improve economy by obviating the heat loss each time brine was blown out from the boiler.

Even at the lower pressures, there was a considerable number of operating problems with the boilers and steam circuit. The Admiralty set up a Committee in 1874 which, after extensive comparative studies of naval, commercial and shore boilers, issued a lengthy report in 1879, whose recommended practices were summarized in the first *Steam Manual*, published the same year; many of

FIG. 9—SIR JAMES WRIGHT, WHO REPLACED THOMAS LLOYD IN 1869, FIRST AS 'ENGINEERING ASSISTANT' AND THEN, IN 1872, AS ENGINEER-IN-CHIEF
Reproduced by courtesy of the RN Engineering College, Manadon

their recommendations remained in force into the 1930s. These included the replacement of tallow and vegetable oils by mineral oil, the treatment of feed water with lime and soda to reduce acidity, and the use of zinc anodes in the boiler. A careful log was to be kept of all feed water treatment.

New materials were introduced for jointing and for piston packing able to withstand the higher pressures. Once committed, the Navy seems to have had few problems with the package of high pressure steam and compound engines.

It is not clear why the Royal Navy had more problems than the Merchant Navy with the introduction of the compound engine but one may suggest that commercial pressures forced the latter to overcome the problems or at least to live with them. Compound engines were more complex with more cylinders and hence the weight of machinery increased by about 5–10%, more than offset by improved fuel consumption of about 30%.

The change to compound engines in 1869 also marked the retirement, in 1869, of Thomas Lloyd who was replaced by James Wright (later knighted) who came from a similar, civilian background. Initially Wright (FIG. 9) was given the title of Engineering Assistant but this was changed back to Engineer-in-Chief in 1872. The Controller, Vice Admiral Sir R. Spencer Robinson, wrote of Lloyd on his retirement 'To Mr Lloyd, more than anyone else, is due the successful application of the screw to the propulsion of steamships, and it was due to his enlightened knowledge and his zealous exertions that the Royal Navy was able to take the lead in its application to ships of war. . . . the principal marine engine makers in this kingdom have frequently consulted him and always benefitted by his advice.' Lloyd died on 23 March 1875 at Hampstead.

Twin Screws and Sail

In the early days of screw propulsion it was believed that a single propeller, operating in the wake of the ship, would be most efficient and hence twin screws were used only in shallow draught vessels where it was impossible to fit a single screw of adequate diameter. When sailing, the propeller caused unwanted drag but a single screw, behind a stern post, could be raised or, if two-bladed, turned so that the blades lay behind the post.

The Crimean War gunboats were twin screw but their shallow, flat form and light rig would have made for poor sailing anyway. The armoured corvette *Penelope*, laid down 1864, had twin screws, behind skegs, which enabled them to be lifted but, even so, she was a poor sailing ship. The AUDACIOUS Class (1867) had twin, fixed propellers and were seen as generally satisfactory, though slow under sail, due as much to their shallow forms as to the drag of the screws. They had four-bladed propellers of Mangin design, best seen as a tandem pair of two bladed screws on an elongated boss, the blades being in the same angular position so that, when stopped for sailing, the after pair lay in the shadow of the forward blades. Mangins were used in a number of ships but do not seem to have been very successful as, in *Audacious*, at least, they were replaced by two-bladed Griffiths screws. A modern propeller designer would see the tandem propeller as a difficult design problem with benefits not worth the bother.It was last seriously considered for the TON Class after World War II but model tests showed little benefit.

Edward Reed's coastal defence ship *Cerberus* (FIG. 10), designed for Victoria in 1867 to protect Melbourne (where she still may be seen), was the first

FIG. 10—THE AUSTRALIAN STATE OF VICTORIA COASTAL DEFENCE SHIP 'CERBERUS'. LAUNCHED 1868 AND THE PROTOTYPE OF REED'S BREASTWORK SHIPS WHICH LED DIRECTLY TO THE MODERN BATTLESHIP

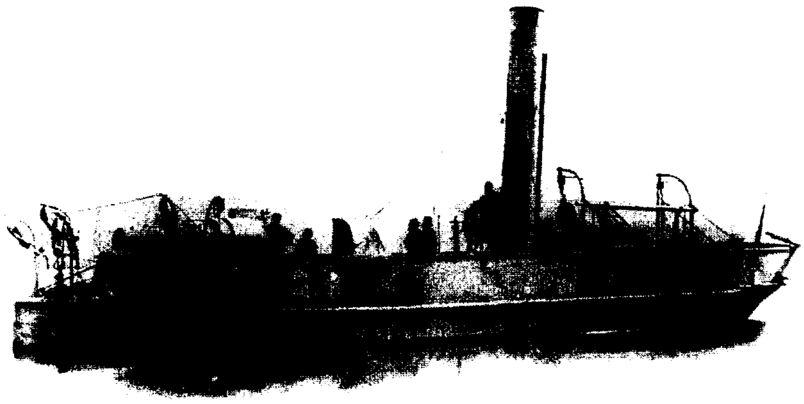

FIG. 11—'STAUNCH'. A SMALL COASTAL DEFENCE GUNBOAT, LAUNCHED IN 1867, WHICH WAS THE FIRST SHIP OF ANY SORT IN THE RN BUILT WITHOUT SAILS

significant seagoing warship without sails. (*pace Monitor*, and noting the small gunboat *Staunch* (FIG. 11) as the first RN ship without sails in 1867). Her twin shafts, though needed for shallow draught, also offered redundancy against engine failure. Her success led Reed to design the *Devastation* in the same style in 1869, the first battleship without sails. There were many advantages; the drag of masts and rigging in still air reduced top speed by about 1½ knots and much increased fuel consumption at cruising speed. *Warrior*'s consumption of coal per horse power hour was 3.75 while *Devastation*, also with Penn trunk engines, burnt only 3.12 pounds. (Some of this may have been due to improvement in the engine). Perhaps more important, *Devastation* needed a complement of 358 while the rigged turret ship *Monarch* with a similar armament need 575 men.

Sail did not disappear overnight*, coaling stations were few and far between in more distant parts of the Empire so that small ships used sail until the end of the century, finally disappearing with the loss of *Condor* with all hands in 1901[14]. Some battleships retained sail for a few more years as an Atlantic crossing in *Devastation* would have been marginal on coal capacity. There was a degree of conservatism, perhaps less than is often claimed, and *Inflexible* (1874) was rigged as a brig for peace-time training though the rig was to be removed in time of war.

The largest number of commercial sailing ships in service was in 1868 but the largest number to be built in one year was in 1892. Sail died hard.

The early screws were similar to Petit Smith's design for *Rattler* (displayed at the Naval Museum), with very broad tips, and were known as 'common' screws. This design led to heavy loading (circulation) at the tip which caused strong vortices to be shed and hence led to vibration and which also heavily stressed the blade roots where they entered the small boss. In the Griffiths design there was a much bigger boss and the maximum chord was at about 2/5 radius curving in to a narrow tip. Probably by chance, this gave an almost elliptical radial loading distribution giving improved efficiency, as in Mitchell's Spitfire wing, as well as reducing vibration. Many common screws were modified by rounding off the tip at the leading edge.

Griffiths also designed his propellers so that, in dock, the blades could be turned in the boss to change pitch. Since there was no way of selecting the geometry of a propeller, other than trial and error, until the Froudes' work of the mid 1870s, the ability to alter pitch and improve performance was most useful.

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*The wooden steam battleship *Edgar* was said to be the last major ship to sail out of Portsmouth, in 1865. In 1869–70 the 'Particular Service' (training) squadron of two frigates and two corvettes, all with engines, went round the world under sail and, on their return, Admiral Phipps Hornby told the men that they were fortunate to have this chance of sailing as the future lay with iron hulls and steam engines.

William Froude opened his ship tank for the Admiralty at Torquay in 1872 and the following year he designed and built a dynamometer with which to measure the performance and efficiency of model propellers and showed how to scale the results to ship size. Gradually, he and his son, Edmund, developed the technique of designing and testing propellers and interpreting the results. The solution of the probems of *Iris*'s propellers in 1879 (see later) justified their work, and by about 1890 tabulated data were available from their tests from which the correct propeller diameter, pitch, blade area and rotational speed could be chosen for any new ship, except those of the highest speed such as destroyers. Propellers were originally of gun metal, with HT bronze used from 1893. Torpedo craft usually had forged steel propellers.

Before the Froudes' work many people believed that 'hydraulic propulsion'—internal pumps driving a jet—would be more efficient and less likely to be damaged. Later, Rankine and R. E. Froude developed the axial momentum theory which showed that for efficient propulsion, the propulsor must move a large mass of water slowly. The leading exponent of jet propulsion in the UK was Ruthven and after some trials with a small vessel called *Nautilus* in 1865 the Admiralty built an armoured gunboat of 1279 tons, the *Waterwitch*. She had a centrifugal pump, 14 feet in diameter, with 12 radial vanes working in a chamber 18 feet diameter and driven by a three-cylinder engine. Water was taken in under the bottom and expelled through two pipes 27 × 25 inches. She managed 9¼ knots on trial with 775 horse power, considerably less than her twin screw sisters, but never exceeded 5–6 knots in service and was not trusted out of sight of land[15].

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APPENDIX I—PARTICULARS OF ENGINES

Ship	*Date of trial*	*Engine builder*	*Type*	*Shafts*	*Cyl/ engine*	*Diam*	*Stroke*	*rev/ min*	*Piston velocity*	*IHP nat (SHP for turbines)*	*Pressure*
						in	ft in		ft/min		lb/in^2
Warrior	1861	Penn	trunk	1	2	112	4	54	432	5469	22
Octavia	1861	Maudslay	ret con rod*†	1	3	66	3 6	69		2265	20
Constance	1862	R & Elder	cmpd*	1	6	60/78/78	3 3	54		2301	30
Conqueror	1863	Ravenhill	horiz	1	2	71	3	61	366	2050	20
Bellerophon	1866	Penn	trunk*	1	2	112	4	74	592	4708	30
Northumberland	1867	Penn	trunk	1	2	112	4 4	60	520	6620	25
Hercules	1869	Penn	trunk	1	2	118	4 6	71	639	8530	30
Devastation	1872	Penn	trunk*	2	2	80	3 3	77	500	6652	30
Raleigh	1874	Humphrys	horiz.	1	2	100	4 6	74	666	6160	30
Shah	1876	Ravenhill	horiz.	1	2	117	4	65	520	7477	32
Inflexible	1878	Elder	vert*	2	3	70/90/90	4	73	584	8483	60
Nelson	1881	Elder	vert cmpd*	1	2	60/104	3 3	79		6282	60
Agamemnon	1881	Penn	vert*	2	3	54	3 3	86	559	6362	63
Edinburgh	1883	Humphrys	vert cmpd	2	3	58/75/75	3 6	88	616	6820	64
Howe	1886	Humphrys	vert cmpd*	2	3	52/74/74	3 9	94	705	7730	90
Sans Pareil	1888	Humphrys	triple*	2	3	43/62/96	4 3	87	742	8070	135
Blenheim	1891	Humphrys	triple*	2	3	36/52/80	4	95	760	14925	155
Apollo	1892		triple*	2	3	33½/49/74	3 3	140	850	7000	155
RoyalSovereign	1892	Humphrys	triple*	2	3	40/59/88	4 3	97	824	9660	155
Royal Arthur	1892		triple*	2	3	40/59/88	4 3	100	850	10000	155
St George	1894	Earle	triple*	2	3	40/59/88	4 3	100	850	10500	155
Prince George	1896	Humphrys	triple*	2	3	40/59/88	4 3	97	824	10465	155
Terrible	1897	Thompson	triple*	2	4	45¾/70/76	4	112	896	25648	260
Diadem	1898		triple*	2	4	34/55½/64	4	110	880	16500	300
Canopus	1899	Greenock	triple*	2	3	30/49/80	4 3	108	918	13780	300
Implacable	1901	Lairds	triple*	2	3	31½/51½/84	4 3	108	918	15250	300
Drake	1903		triple*	2	4	43½/71/81½	4	120		30000	300
Albemarle	1903	Thames	triple*	2	4	33½/54½/63	4	120	960	18300	300
Amethyst	1905		turbine*	3	—	—	—	wing 680 cen 480		10000	300
New Zealand	1905	Humphrys	triple*	2	4	38/60/67	4	120	960	18400	210
Black Prince	1906		triple*	2	4	43½/69/77	3 6	135		23500	210
Dreadnought	1906	Parsons	turbine*	4	—	—	—	328		24700	250
Shannon	1908		triple*	2	4	41/65½/75	4	125		27000	275
Lord Nelson	1908	Palmers	triple*	2	4	32¾/52¾/60	4	125	1000	17450	235
DESTROYERS											
Ferret	1894	Laird	triple*	2	3	19/29/43	1 6	360	1080	4474	175
Janus	1895	Palmers	triple*	2	3	18/27½/42	1 6	367	1101	3789	210
Desperate	1896	Thornycroft	triple*	2	4	20/29/30	1 6	398	1194	5796	215
Quail	1897	Laird	triple*	2	3	21/32½/48	1 6	367	1102	6057	220

*Surface Condenser   †return connecting rod

APPENDIX II—PARTICULARS OF BOILERS WITH OVERALL WEIGHT AND FUEL COST

	Date of trial	Type	Heat Surf	Aux Eng		Weight			ihp/ton	Coal/ihp/hr	Floor	Cost
				No.	ihp	Eng	Boiler (wet)	Total				
			ft²							lb	ft/ihp	£/ihp
Warrior	1861	Rectangular	22500	8	350	422	477	898	5.67	3.75–5	0.78	13.6
Octavia	1861	Rectangular	6500						6.09	3.48	0.8	14.7
Constance	1862	Rectangular	6276						5.41	2.95	0.79	14.8
Conqueror	1863	Tubular	14400	6	280	141	209	350	5.87			
Bellerophon	1866	Tubular	19000	9	500	471	517	978	4.78			
Northumberland	1867	Rectangular	25500	10	680	464	680	1145	5.77	3.8		
Hercules	1869	Tubular	22800	12	600	567	643	1210	7.05	3.14		
Devastation	1872	Tubular	13000	16	880	484	488	972	6.85	3.12–4.42	0.65	9.1
Raleigh	1874	Rectangular	17800	14	900	404	547	951	6.48	3.77		
Shah	1876	Rect. Tubular	21000	21	1500	548	721	1270	5.87	3.2		
Inflexible	1878	Oval	21200	82	1400	654	712	1366	6.2	2.38–2.74	0.725	14.2
Nelson	1881	Oval	22460						5.74	2.14	0.65	12.9
Agamemnon	1881	Oval	17700	30	1050	543	602	1145	5.55	3.12		
Edinburgh	1883	Oval	18400	40	1200	471	568	1039	6.55	3.51		
Howe	1886	Oval	19300	56	2800	542	609	1151	6.72	2.16		
Sans Pareil	1888	Cylindrical	19600	92	2100	509	581	1090	7.4	1.88–2.6	0.51	16.3
Blenheim	1891	Cylindrical	38500	66	2080	788	754	1542	9.68	2.2	0.48	10.9
Apollo	1892	Cylindrical	15770						9.6	2.7	0.54	9.4
Royal Sovereign	1892	Cylindrical	19500	70	3435	563	596	1159	8.34	2.0	0.54	
Royal Arthur	1893	Cylindrical	24550						8.42	1.98	0.49	9.7
St George	1894	Cylindrical	23250	53	1895	491	671	1162	9.1	1.65		
Prince George	1896	Cylindrical	24400	146	2080	624	703	1327	7.9	1.82(50%)	0.56	
Terrible	1897	Belleville	61800	89	2900	1076	1148	2224	10.76	2.0	0.42	7.6
Diadem	1898	Belleville	40490						10.93	1.76	0.39	9.5
Canopus	1899	Belleville	33807	66	4140	665	566	1231	11.17	1.72	0.42	
Implacable	1901	Belleville	37164	69	4250	770	639	1409	10.82	1.87		
Drake	1903	Belleville	40490						12.24	1.81	0.35	10.1
Albemarle	1903	Belleville	43310	68	4260	838	770	1608	11.37	1.96		
Amethyst	1905	Yarrow ST	25968						18.51	1.45	0.31	10.4
New Zealand	1905	Cyl, Niclausse	46050	61	3540	868	921	1789	10.28	2.1		
Black Prince	1906	6 Cyl, 20 Bel	62457						10.87	2.11	0.39	12.8
Dreadnought	1906	Babcock	55400	86	5200	973	924	1898	13.0	1.52	0.45	13.9
Shannon	1908	Yarrow LT	80424						12.37	1.82	0.39	11.9
Lord Nelson	1908	Babcock	46200	47	3900	786	785	1551	11.22	2.0		
DESTROYERS												
Ferret	1894			19	150	59	64	124		2.3 at 11kts		
Janus	1895			20	170	49	71	120		2.5 at 13kts		
Desperate	1896			18	230	61	66	128		2.5 (1.67 at low power)		
Quail	1897			17	230	69	76	144		2.64 (1.64 at low power)		