METALS AND THE SEA

Papers Presented at the March 1990 Conference
of the Historical Metallurgy Society

Edited by Janet Lang

Objects from Early Wrecks
The Great Britain
Precision Construction
The Marine Propeller
Industrial Revolution and the Navy

Failure of Bessemer Steel
Attack and Defence
Metal Arc Welding
Dwarka Iron Nails
Cornish Copper and Naval Sheathing

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Janet Lang

Cover: The SS *Great Britain* - painting by J. Griffin, 1846.
Reproduced by Courtesy of the S.S. Great Britain Project

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EDITORIAL NOTE

Three or four years ago the Meetings Committee of the Historical Metallurgy decided to arrange some meetings with themes which, it was hoped, would attract a wider audience. One of the ideas was for a meeting entitled "Metals and the Sea", and it was proposed to hold it at Portsmouth, in conjunction with visits to the Mary Rose, HMS Warrior and the Royal Navy Submarine Museum. Unfortunately, there was insuffıcent support, and the conference had to be cancelled.

As organiser, I was disappointed and I felt that the contributors had been rather let down; I also felt that the theme was an interesting one, and it might be possible to re-constitute the conference if it was held in London as a shorter, one-day conference on a Saturday. Obviously the time would be restricted and I had to reduce the number of papers and their length. The theme was changed to "Metals in Shipbuilding", and most regretfully, there was no time for papers on conservation or artillery, except en passant. These subjects are so important and interesting that they merit their own conferences and it would be unsatisfactory to try to include them as "honourable mentions". I apologise to those authors who found themselves excluded - and also to those who were looking forward to hearing or reading their papers. I also apologise to those who might feel that the papers were unduly biassed towards ferrous metals - this was the result of time limitation, availability of speakers and some of the appropriate material has already been given at a previous HMS conference (Birmingham in 1984).

As the Historical Metallurgy Society Journal was unable to include the papers within a reasonable time it seemed best to attempt to publish them as a low cost Proceedings, to be available to participants at the Conference, if possible, with a limited number of copies available for sale subsequently.

Not all speakers wished to submit material for publication, and some, as usually happens, were rather tardy in submitting their material, so I must also apologise for the delay in production, and to readers who may be disappointed in not finding some of the papers published. There is however the bonus of three papers which were not presented at the conference, and one which was provided in written form only. The editing has been minimal because of lack of time and I am especially grateful to Dr Lynn Willies, Peak District Mining Museum, who has produced the neat camera ready copy from a variety of discs and typescripts very quickly, and also organised the printing.

My thanks are also due to Colin Phillips and Sue Cackett, Meetings sub-committee, HMS and I would also like to express very special thanks to Fred Walker, National Maritime Museum, for much help and advice, and most especially for providing the excellent drawing below.

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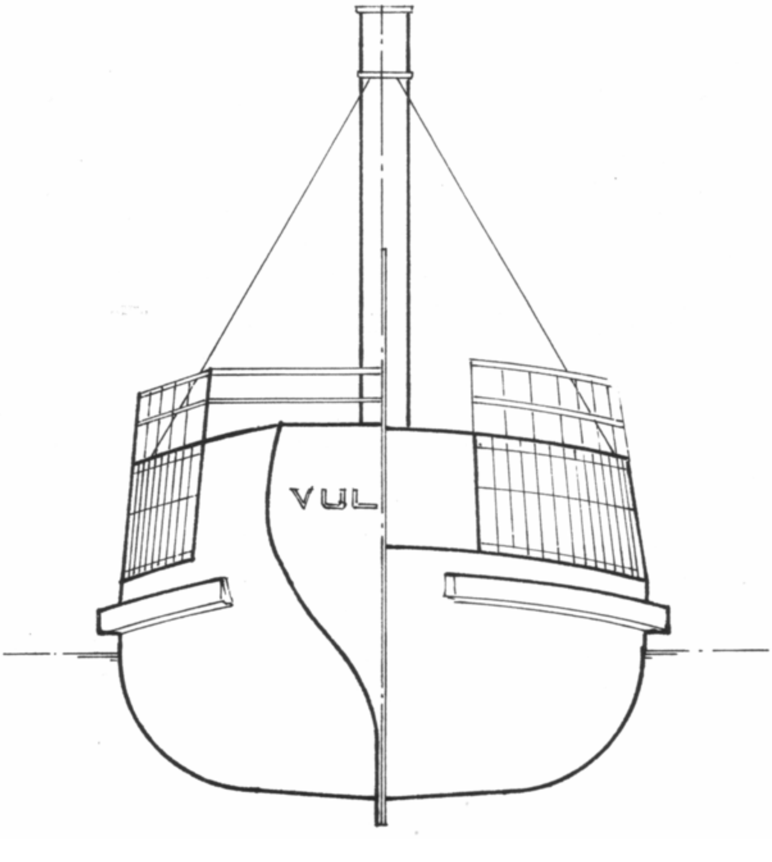


Historical Metallurgy Society Conference: Metals in Shipbuilding. March 1990.

THE IMPORTANCE OF THE S.S. GREAT BRITAIN IN SHIPBUILDING HISTORY

Commander J.R. Blake M.B.E. R.N. Retd.

Introduction: The S.S. *Great Britain* was launched in Bristol on 19th July 1843, the second of the three major vessels built under the direction of Isambard Kingdom Brunel. While the first ship, the *Great Western*, had been a logical development of the application of steam power to a conventional hull, the *Great Britain* embodied a whole series of new concepts and ideas. She was the first ocean going ship built of iron and propelled by a screw. She also had a number of unique constructional features we now take for granted such as a balanced rudder, watertight bulkheads, power driven bilge pumps, and a type of double bottom. She has thus been aptly described as the great grandmother of modern ships. The successful salvage of this vessel in 1970 not only restored to our country a unique marine exhibit, but also an important living chapter in the development of world shipping.

BRIEF HISTORY

The *Great Britain* was designed to operate as an Atlantic liner and carried sufficient coal for one trans-atlantic passage. Her engines were capable of continuous operation and her sailing rig was intended only for auxiliary power. Unfortunately, on her third outward journey she grounded at Dundrum Bay in Northern Ireland and was on the beach for nearly a year. It is a tribute to her strength of construction that after salvage, she was adjudged to be fit for further service and was bought by a new company who fitted her out for service between England and Australia. In view of the length of the voyage, and the lack of coaling facilities, she had to be converted into a sailing ship with auxiliary steam. The *Great Britain* served this company until 1876 when she was no longer economic for passenger service.

After over thirty years of almost continuous operation in all the oceans of the world, few of today's hulls would have escaped the scrapyard, and it speaks volumes for the success of her original design and construction that she was sold once again for further seagoing service. Her new owners spent a considerable sum of money to convert her into a pure cargo vessel with all the passenger accommodation, and even the engine removed. Once again she was to face the rigours of the roughest oceans on voyages carrying Welsh coal around the Horn to ports in Western America.

On her third outward voyage she met exceptionally severe weather at the Horn, and after battling against head winds for some six weeks, her crew were exhausted and the Captain wisely decided to put back to the Falkland Islands to rest and repair damage. Arrived there, the ship was assessed as beyond economic repair and thus her ownership transferred yet again to the Falkland Islands Company who converted her hull into a floating warehouse. The *Great Britain* performed this final mundane service in Port Stanley until the 1930's when she was at last assessed as unfit for further service, towed to Sparrow Cove, and sunk on the beach to rot.

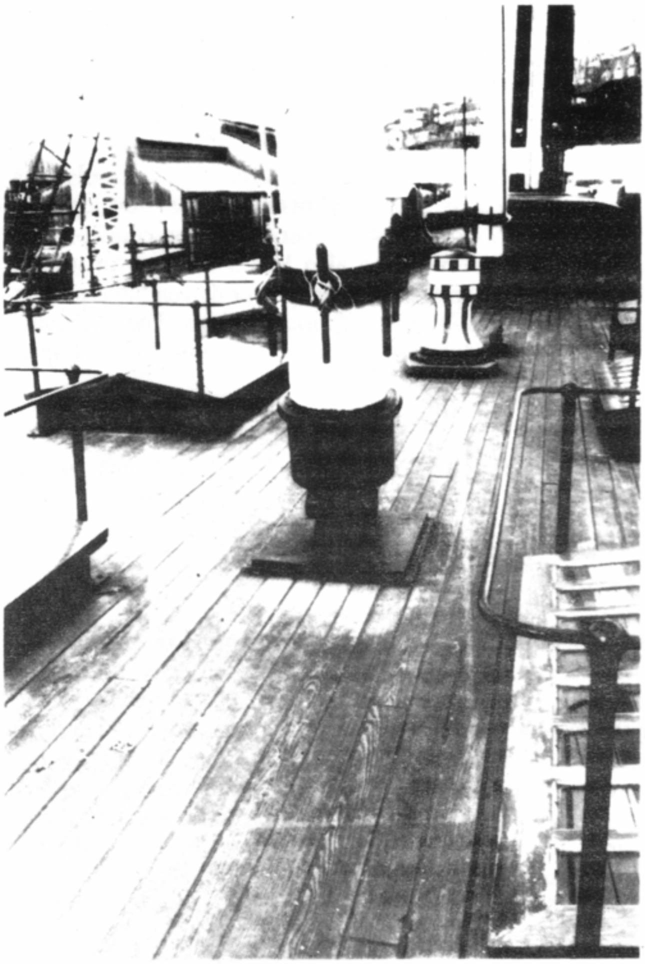
After such a hard working life, and some thirty years upon an exposed shore, it is astonishing that within a few short weeks our salvage team in 1970 was able to get the aged hull afloat once again. Obviously this was a ship built to survive, and for this meeting our interest lies in the materials used and the method of construction.

BUILDING

Let us begin by examining the background to the decision of the Great Western Steam Ship Company to build a second ship so completely different to their first. Starting anything new which depends upon both novel technology and unpredictable public support has never been easy, and it is understandable that there were many who questioned the ability of a steam ship to maintain a transatlantic service. To the relief of the company, the *Great Western* was an immediate success, and commercial pressures demanded the ordering of a second vessel without delay.

Brunel had been closely associated with the design and construction of the *Great Western* and had introduced a number of design innovations which served to stiffen and strengthen her traditional hull. Not only did he apply his knowledge of bridge building to ship construction but he also, possibly in association with William Froude who was on his staff and destined to become a world authority upon ship design, made a detailed study of the movement of bodies through water. This led him to pronounce the important principle that the resistance of the water increases approximately in proportion to the square of the ship's dimensions, while her tonnage increases in proportion to the cube. Hence for a given speed the larger the ship the greater the carrying capacity in relation to the space occupied by the machinery. It follows that the fuel requirement for a given voyage does not increase in proportion to the size of the vessel. It is this important law which has led to the production in recent years of ships of half a million tons, but Brunel set his sights lower at around 3,000 tons - nevertheless one third bigger than any other ship in the world.

At first it was planned to use the conventional shipbuilding material of wood for the new vessel, and the company even went so far as to purchase a substantial quantity of suitable timber. But there were doubts about obtaining sufficient heavy timber sections for such a large vessel, whereupon Brunel made the revolutionary suggestion that iron, a relatively untried material for ships upon the open seas, should be used for the hull. And so when construction began in 1839 in a specially prepared dock, (because a slipway launch was regarded as too risky for such a mammoth structure), it was a flat plate keel of iron, similar to that of today's ships, which the builders laid down.

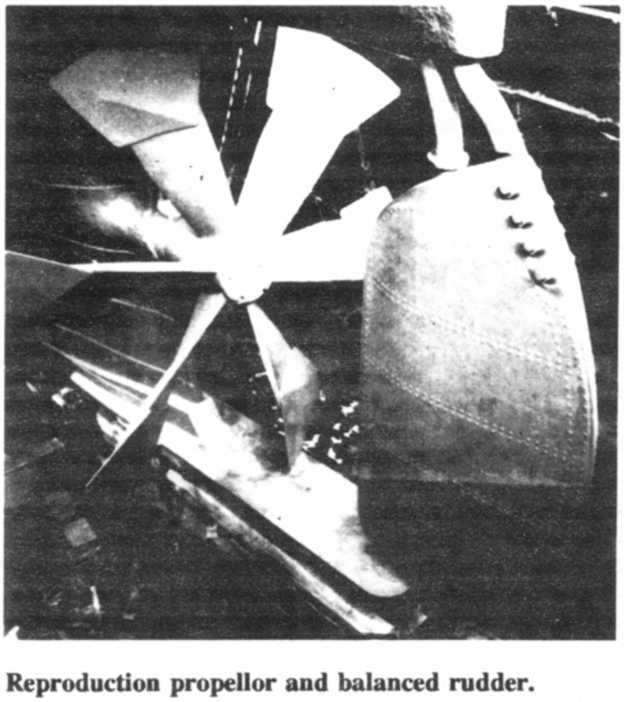


Wooden mast in hinged iron socket.

In the following year a small steam ship called *Archimedes* visited Bristol in the course of a tour around Britain to demonstrate the effectiveness of the screw propeller to Francis Pettitt Smith's design with which she was fitted. Brunel took a personal interest in this novel method of ship propulsion and produced a scientific paper examining its merits. This paper, which probably acted as a catalyst to the general introduction of screw propulsion, then was used by Brunel as the background to a proposal to the directors of the Great Western Steam Ship Company that their second ship, already in process of building, should be altered to accept screw propulsion instead of paddles. Thus it was that the *Great Britain* embodied two revolutionary changes in the form of iron construction and screw propulsion which led one eminent naval architect, Dr Corlett, to describe her as the great grandmother of all modern ships.

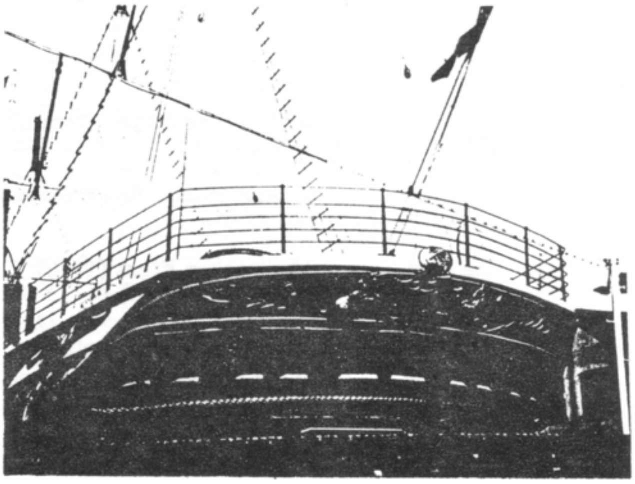
Despite Brunel's claim that only minor changes of design would be necessary to make this fundamental alteration to the ship's propulsion, it was quickly found that a number of major technical hurdles had to be surmounted. Primarily the main engines had to be turned through 90 degrees and gearing introduced to rotate the screw at least three times as fast as paddles. Humphrys had won the contract for the engines and his design for a much enlarged model of his famous trunk engine was well advanced. Its crankshaft would have been the largest ever made and the problem of forging it is said to have led to the invention of the steam hammer by Nasmyth. Sadly his engine proved to be too big to fit in the new position in the engine room, and poor Humphrys, faced with making a fresh start, suffered a stroke and died soon after. Never at a loss, Brunel determined to adapt a paddle steamer engine designed years earlier by his father. Often described as a triangle engine, it comprised two cylinders, or "engines", disposed to form an inverted "V" with the paddle shaft above them. To achieve adequate power from the very low steam pressures of the time, Brunel calculated that four cylinders would be needed, and these were arranged to drive a crankshaft running fore and aft at the level of the upper 'tween deck. Now Brunel faced the problem of gearing, and was determined to avoid the noise of meshing gears which was evident in the *Archimedes*. After experimenting with straps, he finally adopted a toed chain made of iron which meshed with wooden slats spaced around the perimeter of two wheels, sized to give a speed increase of about 3 to 1, similar in principle to the system used later in bicycles. It was reported that this mode of transmission proved to be remarkably smooth and quiet, but contemporary metallurgy could not quite match Brunel's demands and the ship's engineers had problems maintaining the smooth meshing of the iron links. This was despite the fact that all the links were meticulously bored and planed, finished on a gauging tool, and case hardened.

Aside from the power unit, Brunel had to redesign the stern of the vessel and arrange for the design and construction of a unique screw propeller many times larger than the demonstration model used in *Archimedes*. Originally the ship was to have a simple sternpost supporting the pivots of a conventional rudder, and the first task was to forge a new post embodying a stern tube to accomodate a shaft 17" in diameter. Upon this shaft was installed a six bladed propeller 15 feet in diameter and weighing nearly 4 tons. Once again contemporary technology was stretched beyond its limit. The blades were fire-welded to the boss, a



Reproduction propellor and balanced rudder.

technique which provided inadequate strength to withstand the forces of the sea and led to the loss of most of the blades during the ship's fourth crossing of the Atlantic. Before we dismiss this achievement too lightly it is well to recall that this propeller, built from the drawing board without any of our modern design aids, drove the ship on trials at 12 knots, almost exactly the maximum speed calculated by its designer. Recent calculations have revealed that its efficiency was equal to many propellers operating at sea today. Finally, in case we are still feeling a trifle smug, let us remember the early failure of the special propellers recently fitted on to the *Q.E.2*, which did not match the theoretical expectations of their designer, a specialist in the field. The Cunard Company was unprepared for this setback, but Brunel had anticipated trouble and arranged for a four-bladed propeller of improved design to be provided as a spare for the *Great Britain*, and this was fitted during her turn round in Liverpool.



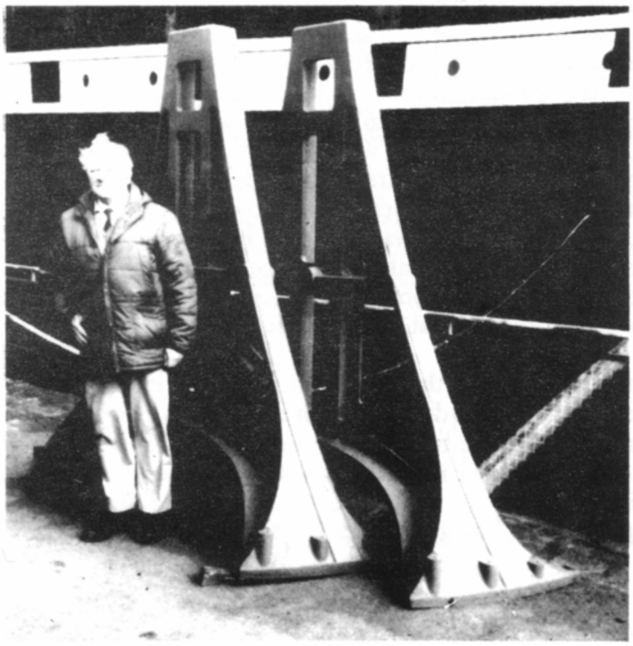
Surprisingly modern stern

It may be noted that the propeller displaced the position of the rudder, provision for which had then to be arranged behind the propeller. This led, perhaps fortuitously, to the design of a surprisingly modern looking stern frame with a bolted rudder post around which turned a balanced rudder. As a result, steering was both light and efficient and on trials the ship was said to handle like a yacht. And yet it was to be many more years before balanced rudders became the accepted design for ships.

The problems of bearing wear in early types of machinery are well known, and this has always been a special problem in the case of the stern bearing of a propeller shaft. Brunel's solution was to provide a brass bearing in a housing external to the stern post so that it was both water lubricated and cooled. Even so, wear was considerable but in such a position the brasses could be changed easily with the ship aground in port at low tide.

So far I have spent some time upon the engines and propeller but have omitted to mention the problem of transmitting power between them. Having laid the ship down as a paddle steamer, the engine room was located roughly amidships so that some 115 feet separated the new engine from the propeller. Once again Brunel devised a unique solution. From the engine a solid iron drive shaft 28 feet in length led aft to terminate upon a wood mounted bearing block; aft, a 25 feet 6 inch tailshaft led forward from the propeller to a similar bearing block; but the masterpiece was a torque tube made from iron plate rolled and riveted to connect the two solid shafts. This tube was completely unsupported throughout its length of 61 feet 8 inches and successfully transmitted some 1800 horsepower without significent vibration or defect. (Some years ago I met some engineers from a major company who thought that they were among the first in the world to use a torque tube of such proportions.) This ship was indeed host to some remarkable technical innovations.

Let us now turn to the construction of the hull and remind ourselves first of the effects of the introduction of the weight and vibrations of machinery within a classic wooden hull. For the *Great Britain* this was concentrated in the central area in the form of an engine and boilers of 520 tons plus 200 tons of water and 1,100 tons of coal. Fully laden the hull displaced about 3,500 tons of sea water. Clearly the design of this vessel demanded the fullest understanding of the forces acting upon a ship in the open ocean and of the application of iron as its primary construction material.



Copies of the original pair of cast iron crosshead guides for the engine.

MATERIALS AND METHODS

These were early days in the mass production of iron which still followed the method developed by Abraham Darby. The production of plate was limited to a maximum size of 6 feet by 3 feet and sections to simple angles of varying dimensions up to 6" x 3½" x ½". For several years after the ship returned to Bristol in 1970 it was assumed that she was built of Lowmoor iron, but we now have conclusive evidence that the Coalbrookdale Ironworks in Shropshire delivered an order of 1200 tons of material "for the Iron Ship in Bristol". Our analysis has revealed that most of the original plate was made from a low carbon iron containing 98.1% pure iron. From any other ironworks, transport to Bristol would have presented a major problem at that date, but from Coalbrookdale it was possible to load barges alongside the works, sail them down the Severn and up the Avon to unload alongside the ship's building dock.

Now came a problem of craft skills because the shipwrights, the traditional shipbuilders, could not work iron, while the platers or blacksmiths did not understand ship construction. The solution lay in a mode of construction used by the Romans who built the hull of their galleys first and then added the internal stiffening. The shipwrights built a timber mould, or female, of the hull in timber scantlings, and the platers then shaped and joined the plates to fit snugly inside. Finally the frames and beams were added to complete the hull structure. It is interesting to speculate that the traditional demarcation between shipwrights and boilermakers in British shipyards may have originated in the building of the *Great Britain*. Not a "first" to be particularly proud of.

All the hull plating was made up from wrought iron plates of about 6 feet by 3 feet and of various thicknesses. For the keel, plates 20" wide by 7/8" thick were hammer-welded together to form a continuous length of 285 feet. To these were riveted the garboard strakes in 11/16" plate with most of the remainder of the hull in 5/8" plate. The lapping follows the classic clinker construction of wooden hulls in contrast to the so-called inside/outside arrangement of later riveted hulls. The plates are connected vertically by internal butt straps which form a random pattern on the inside of the hull. The frames in 6" x 3½" x ½" angle were to be set at 18" spacing over most if the length of the vessel, but the presence of the butt straps presented a problem to the platers who had not yet learnt how to joggle an angle section. However, it was found to be possible to strike a series of straight vertical lines between butt straps and instal the frames at random intervals such that the average spacing worked out at the 18" specified.

Another feature of the construction was the introduction of exceptional longitudinal strength in the form of iron girders made up of angle bent into an inverted "U" shape, and an internal duct keel running almost the entire length of the ship. In fact it can be said that she embodied the beginnings of box girder construction.

Of course these were early days for iron, and Brunel also made full use of timber baulks clad in iron plate. Many of the pillars between decks were of timber while the planking at the lower 'tween level, which was on the waterline, was laid athwartships to provide beam strength.

Apart from the hull itself, many other applications of the use of metals can be found. For example iron wire was used for all the standing rigging of the masts, perhaps for the first time. Lead was used extensively for the heavy deck scuppers and for all the pipework of the water services, including the lavatory pans.

Aside from the many technical innovations embodied in this historic vessel, I suggest that by demonstrating the suitability of iron for her construction, she introduced a dramatic increase in the importance of metallurgy in the craft of shipbuilding. This was the key which unlocked much of our country's economic success in the last century, and led on to the construction of the bulk carriers which dominate sea transport to-day.

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Historical Metallurgy Society Conference: Metals in Shipbuilding. March 1990.

MILD STEEL AND SHIPBUILDING - THE FAILURE OF BESSEMER STEEL

J.F. Clarke

In 1900 Lloyds banned Bessemer steel for shipbuilding by requiring the "Process of Manufacture" to be "the Open Hearth process". Yet myths and misleading accounts of Bessemer's poor treatment by the Admiralty and shipbuilders persist, e.g. readers of *Engineering In History* are told "Although small Bessemer steel steam boats were built in 1858 ... shipbuilders did not use steel extensively . . . until about 1880", suggesting the later ships were of Bessemer steel. In fact, overwhelmingly, they were open-hearth! [1]

"STEEL".

There was some confusion as to what was "steel". "The dividing line . . . between commercial iron and commercial steel" according to Bramwell, President of the Civils (1885), could not set by chemists and material "used as steel . . . is more near pure iron" than many commercial irons. "Steel" occupied a mid-position between cast and wrought iron with a carbon content of 0.33% to 2% according to boiler inspector Wilson. A Mersey built ship of 1864 had plates with 0.51-0.565 % carbon [tensile strength of 44 tons/sq.in]; hardly a mild steel. Howell (1871) realising what was required, considered 0.2% C the maximum for steel for shipbuilding, his "homogeneous metal" was "considered the softest and most tenacious kind of cast steel produced. Being the poorest in carbon . . ." [2]

BOILERMAKING.

Boilermakers adopted "steel" many years before shipbuilders, with Daniel Adamson described by Bessemer as "the great pioneer". Only two or three fellow Manchester boilermakers followed his example of using steel for boiler shells. Some 50 boilermakers had used steel by 1880, when it was estimated there were 2500 steel boilers amongst 200,000 boilers in use in UK, [plus about 7000 with steel furnaces]. If as first claimed 5/16" steel plates replaced 9/16" iron ones, steel offered overwhelming advantages:- a massive reduction in weight and in rivetting a greatly reduced lap joint thickness. However, the inch sheared off all round the plate for testing added to cost [estimated at £1 a ton]. Rivet holes were drilled because a punched hole, in Bessemer's words, "is very much disturbed and greatly distressed". That was a production cost shipbuilders certainly could not bear. Riming out the hole and annealing were also offered as means of overcoming stresses induced by punching.

For boilers Bessemer (1869) preferred:"to use the weakest material we make . . . to ensure such an excess of toughness" as to avoid boiler fracture. In his words sudden contraction might produce fracture in 40 ton plate but "if the tensile strength is only 32 or 33 we never get a fracture." Almost twenty-five years later, Gross of Sheffield, stressed "the difference was in the rolling - a very great question in the manufacture of steel". Strangely, it seems Bessemer did not grasp this fundamental point, as he wrote: "it is physically impossible for the Bessemer process to produce a single isolated plate of such bad quality, for the simple reason that Bessemer steel is never made in less than 5-ton batches, every part of each blow being equally good or bad." [3]

MARINE BOILERS.

Within three years of "one of the most experienced engineers in London" advising against steel for marine boilers, Landore Siemens steel and the humble steel hulled *Ethel* heralded the ending of such opinions. Boyd of the Wallsend Slipway & Eng Co. reported to the Mechanical Engineers in April 1878 on his experiments to provide a satisfactory steel boiler [working at 66 psi]. The largest thickness reduction was on the end plates, 25% [3/4" to 9/16"] and only 8.33% on front & back tube plate. These were significantly smaller reductions than those claimed for Adamson. Tensile strength varied with plate thickness

	tons/sq.in.
11/16"	25.6 to 28.3
9/16"	27.5 to 31.4
7/16"	28.6 to 31.1

Boyd pointed to the "limit of elasticity", which although averaging 58% of breaking stress, was as low as 50% on one testpiece and in one case "elastic stretch" was "perceptible at a strain equal to 11 tons/sq.in". Therefore, the boiler should not be subjected to a hydraulic test exceeding twice the working pressure. The loss "of something like 33 per cent" of strength in punching made it "desirable, though not essential" that all holes were drilled. Despite such cautions, Boyd was convinced that: "Steel plates can now be obtained in which absolute uniformity can be relied on, extending over a large quantity of material."

Although some 280 marine boilers were wholly or partly built of steel in the year to 31 March 1881, Marshall felt the need to try to remove "the doubt and uncertainty, so freely expressed' in regard to steel boilers. From 1877 he had always recommended steel and stated "in no case has there been a failure of a plate after being put into a boiler, either in the process of manufacture or in working at sea". By 1885 marine boilers were "scarcely ever built of iron". [4]

Working problems continued. Tested Siemens and Bessemer steel boiler plate failed with "mysterious fractures" and "cracked without been touched" after rivetting in place. Samples from the area of the fracture when annealed they were "found to be perfectly ductile", therefore blame was attributed to "improper manipulation" of the material [usually heat treatment]. Steel required more care in the smith's fire than puddled iron and in rolling to the boiler curve. Obviously the existing furnaces were built for iron plates and the larger steel plates could be subject to uneven heating. A twenty foot plate [66" x 1.25"] drawn from the furnace was "a black heat" at "the end near the door of the furnace" and "gradually increased towards the other end to a dark red heat", after reversing, it finally ranged from "a dark red or nearly black heat" to "a blue heat". After passing through the rolls one end was cold while the other was a blue heat. [5]

BLUE HEAT

"Few or no malleable metals" according to Adamson (1878) possessed "a range of endurance at all varying temperatures . . . but nearly all . . . will endure considerable percusive force up to 450^0 Fahrenheit [232^{0}C], after which, as heat increased, probably to near 700^0, they are nearly all more or less treacherous and reliable to break up suddenly by percusive action . . .the Siemens-Martin enduring somewhat better than the Bessemer class". Leading marine engine builders recognised the dangers of working at "blue heat" [light straw to blue , i.e. 232^0 to 294^{0}C]. [6]

"IMPURITIES".

The harmful effects of sulphur and phosphorus had long been recognised but Pole's comment in 1872 of possible effects due to nitrogen, "particularly in steel" received little attention. The percentage was higher in Bessemer steel [0.164%] than in Open-hearth [c 0.01%] as reported in 1880. A Swedish metallurgist was convinced this nitrogen contributed to defects in Bessemer steel. Nonetheless after tests on Bessemer rails Harbord & Twynam (1896) concluded "in the proportion in which it is found in commercial steel [nitrogen] has no detrimental effect". By 1914 Stromeyer was in no doubt: "Nitrogen . . . shares with phosphorus the unenviable distinction of making steel unreliable." [7]

CORROSION.

Susceptibility to corrosion was hotly debated and various experimenters presenting "apparently most contradictory" results. The French decided not to use steel for "the external plating of the wetted hull." Lothian Bell (1878) argued that cinder in wrought iron would lead to more rapid corrosion but Admiralty tests indicated wrought iron was superior to mild steel. In the open air, Siemens had found that wrought iron did corrode less than mild steel but not in boilers. Interestingly, Adamson (1878) advocated the use of steel structure and wrought iron skin "should it ultimately be proved that sea water will destroy steel quicker than wrought iron." Jeans' optimism that "the probability" was that for mild steel "corrosion would set in less readily" than with shipbuilding iron was not confirmed by experience. *The Shipping World* in 1895 wrote that shipowners had "some misgivings about the durability of steel steamers" and that experience was showing steel to be "much more perishable" than iron, especially where it cannot be frequently painted". Some found "steel vessels five years old" were "not in such good condition as iron ships three times that age". [8]

"TESTING"

Boiler inspector Fletcher argued that all boilermakers should have their own machines to check material supplied. Such testing could cost as much as £1 per ton. The "subcarburised steel" plates by the Siemens process for the *Livadia* boilers in 1881, demonstrated that satisfactory tests did not guarantee success. Nearly all of 219 test pieces taken from the 154 plates met the bending test. Both the tensile strength [26-30 t/sq.in.] and elongation [15% on 6" length] specifications were met. Eight inch pieces, [area 1.07 sq. in.], were tested: results were satisfactory.

The boiler fractured in three places before the hydraulic test pressure reached 140 psi, it was designed to work at 75 psi, as Lloyds Engineer Parker pointed out: "the uncertainty as to its cause might not only retard the more extended use of mild steel" but also cast "considerable doubt upon the safety and efficiency" of existing steel boilers. [9]

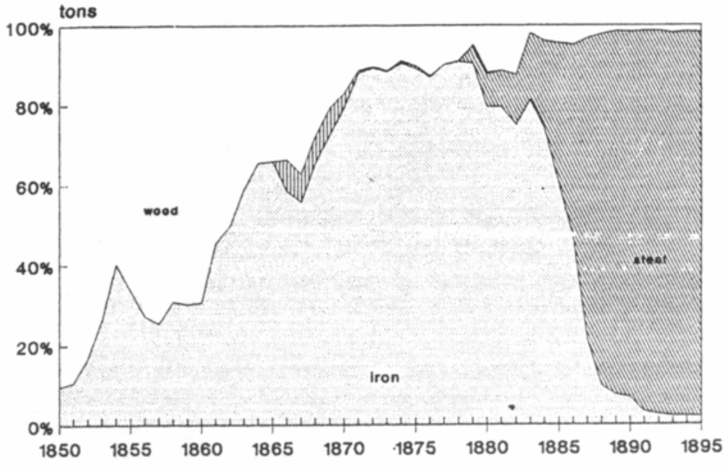
STEEL FOR SHIPS.

Few have disagreed with Clapham's view that: "No doubt, as Bessemer always and perhaps inevitably believed, sheer conservatism in the shipyards explained much". The entrepreneur pioneer of iron shipbuilding, C.M. Palmer (1870) did, stating that "the uncertainty of [steel] manufacture has . . . been so great, that few have ventured to run the risk of the reduction of scantling necessary with a more costly material." After 14 years of manufacturing Bessemer steel, Wilson of Cammell, acknowledged this difficulty remains "the want of absolute uniformity . . . we cannot yet say that Bessemer plates can be treated without extreme care in working them into structures". [10]

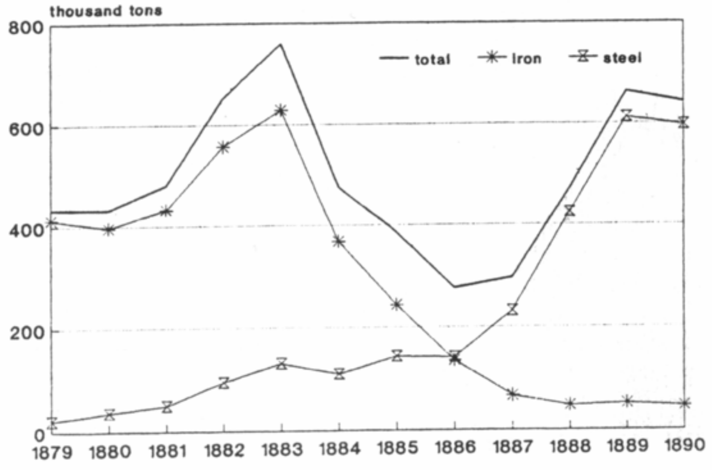
The graphs show the building of steel vessels and it must be noted that from 1862 to 1870 "puddled steel [was] used rather extensively". Shallow steel punts worked on the Rhine from about 1852 and the vessels at Greenock [the *Windsor Castle* of 93t.] and Birkenhead in 1858 were probably the first British endeavours. Laird's *Ma Roberts*, was finally completed on the banks of the Zambesi for David Livingstone. The famous explorer was not impressed and told the Society of Arts [1860]: "It is very probable that there are purposes to which the patent steel might be applied with great advantage, but eighteen months experience . . . has proved that the substance cannot be trusted in tropical waters . . . a very remarkable decomposition soon takes place . . ."

In 1859, on Tyneside Mitchell built flat bottom barges for India, and from Stockton on Tees, Pearce supplied a 375 foot steel troopship for the Lower Indus. The main plates at only 5 lbs / sq. ft. were about 0.1" thick. Nearby Richardson built the *Little Lucy*, of Mersey puddled steel. [11]

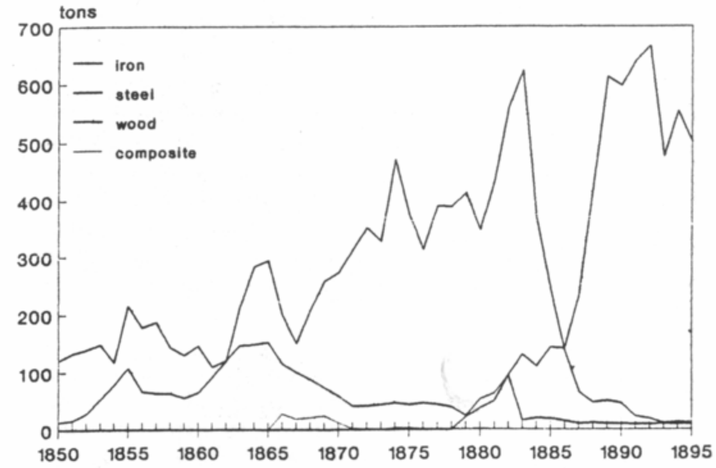
In the same year, the Samuda Brothers pioneered steel on the Thames with the 452 ton *Jason*, the first of 20 ships "wholly of steel" built up to 1870. Both "cast steel" @ £40 / ton and "puddled steel" by Mersey Steel & Iron Co [plates @ £25 to £27] were used. Four Spanish gunboats were built mainly of puddled steel. In 1861 the London, Chatham & Dover Railway Co. ordered seven steel paddle



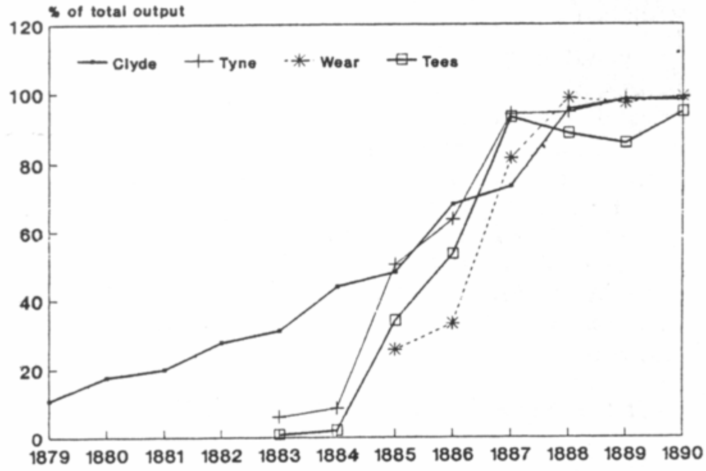
Material used in U K Shipbuilding
1850-1895



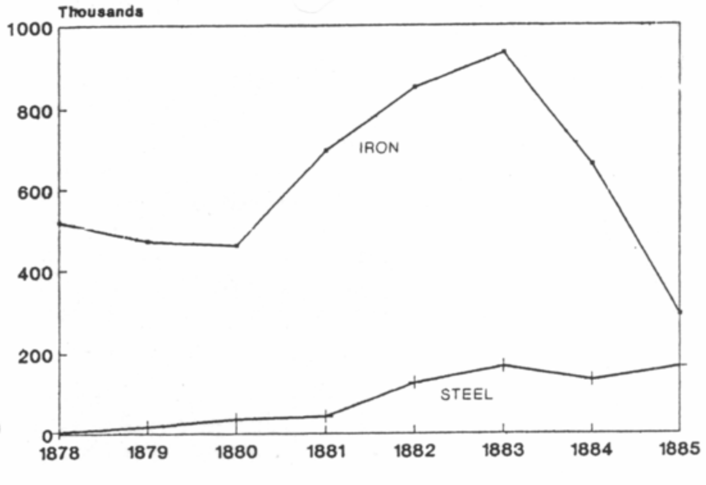
Shipbuilding Output 1879-90
total, iron & steel



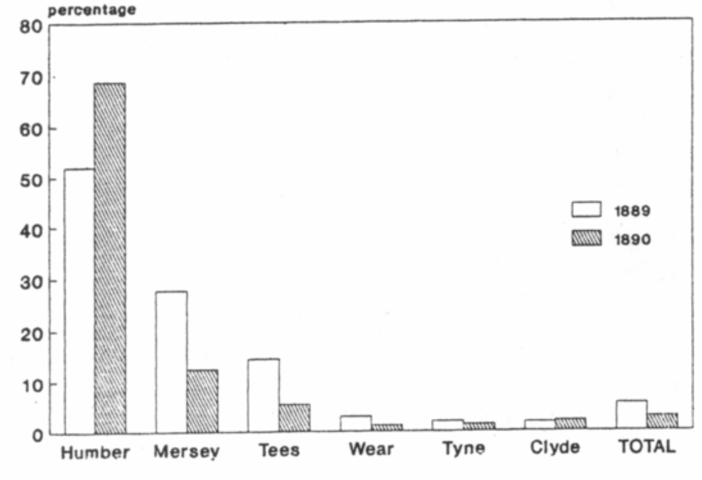
Material used in U K Shipbuilding
1850-1895



Percentage of Output STEEL HULLS
Clyde, Tyne, Wear & Tees



Iron & Steel Vessels - Lloyds Register
Martell INA 1886



Percentage of Tonnage - IRON ships.
per SHIPPING WORLD for 1889 & 1890

steamers, three from Samuda, of puddled steel, and four from Money, Wigram & Sons. [These owners ordered no further steel vessels until 1882]. From 1866-73 Samuda used "cast steel". Eight vessels were built "partly of steel" and in 1873 two 4586t Imperial German frigates had deck plating of cast steel. Finally in 1878, Siemens process steel [@ £13- £15 /ton] was used by Samuda for 20 cargo boats supplied to the Madras Irrigation & Canal Co. each a mere 16 tons. [12]

Henry Bessemer in his *Autobiography* described the following as "Bessemer steel ships":

built in 1863	in 1864	in 1865
Pelican [329t]	Clytemestra [1251t]	Curlew [1095t]
Banshee [325t]	Rio de La Plata [1000t]	Plover [410t]
Annie [330t]	Secret [467t]	Soudan [180t]
Cuxhaven [377t]	Susan Bernie [637t]	Midland [1622t]
Isabel [1095t]	Banshee [637t]	Great Northern [1622t]
	Tartar [289t]	
	Villa De Buenas Ayres [536t]	
	The Altcar [1283t]	

It must be doubted that these ships were built of Bessemer steel. Although "Steel" is written on the first page of surviving specifications of five ships, the details provide a much more complicated picture. The Keel, Stem and Stern Post were of iron. "Steel" is the word used for the *Banshee* and *Domitilla* but for the other ships, the material was as specified for *Clytemestra*: "All Steel to be understood as puddled unless otherwise stated". Bulkheads were to be "iron 3/8" bare", and as on the *Hope* the hold stanchions and floors were of iron. Steel was used for the Frames on the *Banshee, Clytemestra, Formby*. For the *Hope*, alone, was there a specific mention of Bessemer steel: "In Engine Space to stay the sides there are two 15" x 20" & angles 3 x 3 x 3/8" box beam Bessemer steel plates 3/8" & 5/16" ". Steel was used on these ships but that is far from it being the major construction material for ships or that it was 'Bessemer'.[13]

THE INSTITUTION OF NAVAL ARCHITECTS.

The Institution of Naval Architects did not exist when the first steel vessels were constructed and advocates of steel were heard at its annual meetings from 1866. Rochussen argued that ships "are likely to be of steel" in the future and contrasted the 22 ton tensile strength of iron, which "will set under a strain of 11-13 tons" whereas "mild steel of 32 tons will recover itself under a strain of 22-24 tons" [certainly an exaggerated claim compare Boyd's figures above]. An important pioneer of iron construction, Grantham, declared for "puddled steel" and he personally had "watched . . . most carefully" over the construction of three steel ships, with the plates "carefully selected" and not "a single rivet hole" cracked. He was "quite satisfied that with proper care - and it all depends upon care - steel will supersede iron".[14]

Critics did not deny a future for steel: "we all need educating in the use of steel" said John Scott Russell but added "it is very difficult to get steel of sufficiently good quality for practical purposes". Naval Constructor, E.J. Reed stated the widely held view: "over and over again, the steel breaks through its rivet holes" results do not yet "justify us in using steel wholesale in the construction of ships". William Fairbairn, campaigner for good quality ships plates, doubted if steel was suitable for naval work.[15]

LLOYD'S

Lloyd's willingly made special surveys of steel vessels. The Society consulted the Liverpool Registry, in 1866, before allowing a 1/4 reduction in scantling cross-sectional area instead of the 1/3 asked for a vessel of Barrow haematite steel. Many ship designers hoped for greater reductions in scantling dimensions than Lloyd's were willing to allow, e.g. Reed in 1878 said that in practice "our steel scantlings" could only reduce by 13 or 14%.

Although Denny (1880) said "by no means the least obstacle to an enlarged use of steel" was the practice of testing adopted by Lloyd's. Such testing was probably necessary to establish confidence in the new material. In 1882, H.H. West [Liverpool Registry] described "the elaborate and stringent tests" for steel as "beneficial" because low-priced contracts resulted in poor quality materials. Lloyd's "have taken what everyone must be satisfied is a very satisfactory course" declared Samuda "a most careful supervision [at steel works] . . . local inspectors [with] duty of testing every single plate". Shipyard manager and naval architect, John (1884) commented "the Committee at Lloyd's Register, influenced by their principal officers, were among the first to throw themselves heartily into the matter, and to propagate the new movement".

In 1878, the Chief Surveyor, Martell, noted that doubt existed until recent developments "induced shipowners . . . to look forward with the greatest interest to the possibilities of [mild steel] becoming the material for shipbuilding". Both Bessemer and Siemens materials had "abundantly proved that mild steel" with the approved properties could be produced. Later, he was specific: "it was shown to the public in 1876 that mild steel, produced by Siemens-Martin, . . . could be made of a ductile, reliable quality, suitable in all respects for shipbuilding purposes, of a much superior character to that of ordinary ship iron . . ."

Any inspecting authority should be convinced of the soundness of changes, particularly structural ones which affect the safety of human life: Lloyd's Registry exercised this care without unduly delaying technical change. *Comprehensive Rules for Steel Ships*, broadly in line with what was agreed with Elders in 1877, were issued in 1885. If this seems belated, then the role of the special survey should not be overlooked and that enough sea going experience was essential before formulating Rules, which once in existence are difficult to change quickly. [16]

THE ATTITUDE OF THE ADMIRALTY.

From the outset the Admiralty carefully examined the possibilities of steel. Nonetheless, Barnaby, Chief of Naval Construction, felt obliged in 1875 to refer to "The uncertainties and treacheries of Bessemer steel, in the form of ship and boiler plates", which therefore required all the care "bestowed upon it at L'Orient to avoid failure" [see French technique below]. Clearly plates were the problem and this Bessemer did not seem properly to grasp. The French naval yards had taken the lead using steel open-hearth not Bessemer steel!

The Admiralty was and is unjustifiably accused of sluggish conservatism in the adoption of steel. In October 1874 Admiral Sir W Houston Stewart, Controller of the Navy, accompanied by N. Barnaby visited the French yard building the *Redoubtable*. When Marc Berrier-Fontaine spoke at the INA, he doubted whether he would be able to "add any important matter of experience to "the papers of Barnaby, Riley, Denny, Martell and West" and continued if the French were first it was "necessary to admit that the British Admiralty very quickly followed in this line . . ."

Indeed, Dr D K Brown has suggested that it was William White who "persuaded the Landore works . . . to produce a steel of comparable quality" to the French. From 1864 steel was "used continuously for certain proportions of the internal framing of [Royal Navy] iron ships but always under special precautions". In 1877-8 on White's initiative, two despatch vessels *Iris* and *Mercury* were constructed of open-hearth steel, supplied by the Landore Siemens-Steel Works. [17]

James Riley Works manager explained that "long previous" to Barnaby's 1875 paper "it had been the desire of Dr Siemens that the . . . Company should turn their attention to the production of steel of the finer qualities". Experiments were carried out to achieve this objective. This is far from denying a very positive innovative role for William White, in addition to HMS *Iris* and HMS *Mercury*, he also designed, with permission, a steel warship for the Argentine Government - *Almirante Brown*. Her builder, Samuda described this ship as "the first vessel afloat which has been constructed entirely of steel and coated with steel faced armour".

Even with open-hearth steel the early days were not easy as Assistant Director of Naval Construction Narbeth recalled: "My first employment was on H.M.S. *Mercury*. Mild steel was being used for the first time at Pembroke Dock, and caused considerable trouble in H.M.S. *Iris, Mercury* and *Edinburgh* by failure in working. Zed bars being straightened cold would crack off with a report like a gun, shaped plates around the boss for the shaft, etc., gave endless trouble, and many plates were spoiled before a satisfactory job was reached in such places."

The testimony in support of the Navy's Constructors is strong. A few years ago, wrote *The Shipping World* in 1883 the use of steel "was of a most limited character", however, "It is satisfactory . . . to remark that the Government . . . had the temerity to employ it to some extent in . . . our vessels of war [and] this fact alone had considerable effect in bringing the question of its use into prominence, and in shortening the time when confidence in it should be established." While E.A. Cowper, President of the Mechanicals, said "I do think that great praise and the thanks of the country are due to the Admiralty for the way they took up steel, as soon as they were assured that good mild steel of regular quality could be made". Yet Bessemer vented his anger against 'our quietly-sleeping Admiralty officials' and "their ten years' indifference and apathy". [18]

THE FRENCH TECHNIQUE.

Hydraulic equipment was introduced at Toulon Navy yard long before British builders used such machinery. A very brief extract from Berrier-Fountaine reads: "The new metal . . . will not bear, without suffering more or less, violent blows from iron hammers, or irregular tears produced by using hand chisels," and so "wooden beetles and mallets" were substituted. Two capstans driven by hydraulic engines drew the metal from the furnace and "brought to the required curvature steadily, without any sudden jar and "at a heat at which it still retains malleability . . ." Common furnaces were replaced with gas heated furnaces and "the substitution of the progressive steady pressure of hydraulic presses for the sharp violent jar of steam hammers". Jeans conceded "that a material which needed such care in its treatment would stand but a very poor chance in an ordinary shipyard". It was Riley's achievement, finally, to produce an open-hearth steel, which greatly reduced such demanding working practices. [19]

THE CHANGEOVER GETS UNDER WAY.

The changeover from wood to iron spanned more than a generation, and once underway steel hulls replaced iron in not much more than a handful of years [see graphs above]. Not until about 1862 was half the new British tonnage built of iron. If, as Bessemer liked to think, his material was immediately satisfactory, there might have been no iron phase at all!

The Scots led the way in merchant steel shipbuilding. Elders in 1877 secured Lloyd's approval to use Siemens-Martin and in the following year, built two paddle steamers for the London, Brighton & South Coast Railway Co. Denny of Dumbarton offered their customers steel vessels; for example in October 1876 to the Irrawaddy Flotilla Co., the *Taeping* [347 gt of Bessemer steel] at a mere £200 above the "iron" equivalent. Such a small differential could not have covered the full cost of the much more expensive steel.

The efforts of these pioneers continued and by 1884 all the Dumbarton yard's output was of steel. Denny, in 1879, encouraged both the Union SS Co of New Zealand and the Allan Line to use steel. The New Zealand vessel, the SS *Rotomahana*, was badly damaged by striking a rock on New Year's Day 1880, and the owners wrote: "This experience has shown clearly the immense superiority of steel over iron. There is little doubt that had the *Rotomahana* been of iron, such a rent would have been made in her that she would have filled in a few minutes ".

Steel did not immediately totally replace iron. SS *Buenos Ayrean*, built for the Allan Line in 1879 was "The first transatlantic steamer built of mild steel". However, three iron ships were built on the Wear before new iron construction ended for the Allan Line. Although in August 1879 Denny began building the P & O's first steel vessel the *Ravenna*, the next four ships were of iron. In 1881 Denny, again supplied a steel vessel, the *Clyde*, while Cairds and Harland & Woolf were both building in iron for P & O; from then on steel alone was used. Dennys made just over £1000 [a mere 1.3%] on a final price of £82,521. Pioneering innovation was not always very profitable. [20]

Not even 5% of the tonnage of metal hulls was steel in 1879. Two years later 10% was exceeded and at the nadir of the depression in 1886 the half-way mark was passed and 90% was reached in 1888. The graphs [above] show the rate of change on various rivers and the persistence of iron in places such as on the Humber.

Siemens-Martin steel enabled product champions such as Dennys, to convince shipowners to buy steel vessels, although they were not all instant converts. Nor were all builders: as late as August 1881, for John Price [Jarrow Shipyard] "only one condition . . . at present cost" justified using of steel - "the dimensions of the ship are absolutely limited by the conditions of her trade". Such conditions existed "hardly anywhere in the ordinary carrying trade". It was 1884 before Palmer's steel tonnage exceed 10% and by 1888 all output was in mild steel. Price later protested "he believed steel was a better material" but was it "the better investment"? The *Engineer* (Jan 1886) saw other reasons for Palmers adherence "as long as possible to iron - it has iron mines . . . and . . . works . . . fitted up for the production, cheaply and efficiently of iron plate". Interestingly it also commented "Whether or not the steel vessel may prove to be the best under all circumstances cannot be definitely said". So even this journal was not yet completely convinced. [21]

COST.

Unless costs were close enough to those of iron ships enough owners were unlikely to commit themselves to mild steel. The weight reduction in steel ships allowed a proportional price differential and for the deadweight trades there were possibilities of carrying extra cargo. However, a negative factor was that while iron shearings "easily repiled and rolled into plates, at the same time improving plate", steel shear scrap reduced almost to the value of pig iron [up to 10% of iron might become scrap]. Lloyds 20% reduction on scantlings could not be achieved in practice and commercial materials and design did not allow more than about 14%. In 1884 John claimed steel ships were as cheap as iron in first cost per deadweight ton carried. The prices presented by Riley [see graph above] clearly shows a downward trend. [22]

RESPONSE OF THE WORKERS.

The workforce was a key factor in the successful adoption of steel, according to Berrier-Fountaine, ". . . the increasing familiarity of the workmen" in processes where plates and bars were worked hot, has had at least an equal share" with increased homogeniety in satisfactory results.

Denny (1879) reported that mild steel "was wonderfully popular with workmen, who preferred it to working iron: and even in rivetting they did not find any mishap, or any rivets required to be condemned". "a well made round hat" was made from the first plate in the Tees yard of Raylton Dixon, whose men "liked it [Siemens steel], and . . . worked at the same price as iron." The Boilermakers' leader, Robert Knight, in his book, - *The Practical Boilermaker Iron-Shipbuilders And Mast Maker* (1880).

Although the adoption of "mild steel" largely advanced during a depression, except in Scotland [where steel exceeded 31% in 1883] which would have rendered trade union resistance more difficult. No evidence exists of resistance by workers to the use of steel, although such craftsmen as the angle-iron smiths sought higher piecework rates and the larger heavier plates did create difficulties for the platers' helpers given the grossly inadequate handling equipment in shipyards. The working craftsmen were not an obstacle to this change. [23]

BESSEMER / SIEMENS-MARTIN.

Jeans acknowledged the Siemens-Martin process was at first "the more successful in the production of very mild steel plates" adding "equally good results have been since obtained in Bessemer converters". Surprisingly as an old man Bessemer denied change - "it must not be forgotten that mild Bessemer steel has not undergone the smallest alteration in manufacture, or any improvement in quality, since the completion of the eighteen Bessemer steel ships . . . built at Liverpool". However, Lothian Bell rightly pointed out in 1886, "the steel makers . . . had not applied themselves seriously to the manufacture of plates" owing to the lack of "any great demand". The verdict of probably the most experienced user of steel of both types, Denny [1886] was - "our experience of the Bessemer steel obliged us to limit ourselves to that made by the Siemens-Martin process" was that accepted the shipbuilders and reasonably logically in the end Lloyds specified open-hearth steel only.[24]

During the debate on "steel" many who argued for "mild steel" pointed to failures in iron plates and that although tests were prescribed for iron they were much less frequently carried out. The general familiarity with iron probably meant that foremen, workers and managers could more readily detect the faulty material even without specific testing.

Cost was a central factor, perhaps for the economist **the** factor. Just how much steel ships cost was regularly debated. Finally the demand for shipbuilding plates helped reduce the price difference between steel and iron plates but that demand depended upon technical considerations. "Cheap" Bessemer plates that cracked on punching were not cheap but very costly, in money, time and reputation. The last two factors were particularly important for shipbuilders, who were not selling to a wide consumer market but to a limited number of owners, whose views with those of their marine superintendents were always critical in regard to any innovation.

Neither the Admiralty nor the shipping registries, were restricting factors, if anything the contrary view emerges. Only French naval yards acted in advance of the British industry. The professional Institutions helped establish the technical acceptability of "mild steel". Frequently, almost exclusively, the "negative" aspects of Barnaby's 1875 paper are quoted and little or no attention given to Riley's paper (1876), which "showed conclusively that mild steel of the highest quality fit for shipbuilding could be produced in large quantities [and] for the first time "awoke" a real interest . . . among the shipbuilders and shipowners . . ." When Riley died, *the INA* obituary concluded: "It is not too much to say that this paper led the way to the now universal use of this material for shipbuilding and other important structural works". A view endorsed by *Engineering*: "Mild steel . . . owes its introduction largely to him". [25] James Riley is the unsung hero of providing a mild steel suitable for shipbuilding !

Satisfactory "quality control" of "Mild Steel" was essential before it could used generally in shipbuilding. After that, unlike the scientist who basically convinces his peers, the technologist must sell to a buyer, so the price must be right.

NOTES

1. Abbreviations used: *INA* = *Transactions of The Institution of Naval Architects* [later the *Royal*], *I&SI* = *Journal of the Iron & Steel Institute*; *NECIES* = *Trans. of the North East Coast Institution of Engineers & Shipbuilders; I.MECH* = *Proceedings of the Institution of Mechanical Engineers*; *I.Civ* = *Proc. Institution of Civil Engineers*. This topic was explored in Occ. Paper in the History of Science & Technology No.1 - *The Introduction of the use of Mild Steel into the Shipbuilding and Marine Engine Industries* by J.F. Clarke & F. Storr (Newcastle Polytechnic 1983). There is further material in Frank Storr's PhD thesis *The Development of the Marine Compound Steam Engine* (1982). A paper read by Clarke to the *Newcomen Society* on 11 Oct 1989 will appear in that Society's Transactions for 1989-90 and this will contain further references.

2. *I.Civ* v.80 p.19; R.A.Wilson *A Treatise on Steam Boilers ([1879 - 5th edit); Howell at INA* v.12 p14- ; J.S. Jeans *Steel: Its History, Manufacture, Properties and Uses (1880) p.748.*

3. *Engineering* 4 Jan 1867; *I&SI* 1879 p.60; Jeans, *op.cit.* pp.750-760 - no. of stationary steel boilers to 1868, citing Sharp *INA* v.9.p.11 - 275 (there seem to be misprints in Jeans "227" and Kohn "277"); Royal Comm. on *Waste In Combustion* (1869) - Q.849; *NECIES* v.9 p.194; H. Bessemer, *Autobiography* (1905) p.255 see also Lord, W.M. The Development of the Bessemer Process in Lancashire 1865-1900. *Newcomen Society Trans.* v.XXV pp.163-180. That stout proponent of Bessemer steel, Jeans, acknowledged that many locomotive failures resulted in the use of steel being discontinued.

4. I.Mech 1878 pp.217 - Boyd; *I.Mech* 1881 pp.449-509 Marshall, compare with J.A. Rowe in *NECIES* v.1. pp.73-88 and discussion; *I.Mech* 1885 pp.320-1, and Head pointed out for non-marine boilers "the supression of iron by steel has not been so rapid".

5. *INA* v 22 p.13

6. *I&SI* 1878 p.397; *I.Civ* v.84 pp.114-217. Problem of working techniques continued, as A.E. Seaton from Hull told the INA in 1885: "I find it a most difficult thing to drum into the heads of both the foremen and the workmen the danger of working at blue-black heat. I have lent the foremen boilermaker books and papers, but he only expresses grave doubts about it, and thinks the blue-black heat is a nice subject on which to read papers, but one that does not apply, according to his ideas, to work in the boiler shop."

7. Pole, W. *Iron as a Material For Construction* (1872) p.27; *I&SI* v.1880 pt.I - Allen p.189 - v.1889 pt.II pp 383-5, v.1896 pt.II pp161-5; Stromeyer, C.E. *Marine Boiler Management and Construction* (4th edit).

8. Turner, T. *The Metallurgy of Iron* [1908 - 3rd edit.] p.419; Jeans *op.cit.* pp.740-4 & 746 - ; *I&SI* 1878 p.400; *Shipping World* 1895 p.181; *INA* v.22 pp 110-1. Head [Pres. of Mech] 1885 p.319 "it is hard to find any respect, (except corrosion) in which mild steel is not better than iron for boilers".

9. *I.Civ* v.80 p.140; *INA* v.29 p.88; *INA* v. 22 p.12 - Parker's paper & discussion; see also technical press.

10. Clapham, Sir John. *An Economic History of Modern Britain . . . 1850-1886* (1952) p.62. He also wrote "Siemens set himself to meet the Admiralty challenge, and satisfied their most exacting requirements with a uniform mild steel . . ."; *I&SI* 1870 p.46.; *INA* v.16 p.144.

11. *List of . . . Vessels built at the Birkenhead Iron Works* [1894]; Jeans *op.cit.* pp.712-3; see article in *Technology and Culture* v.72 pp.209, *"The Sinking of the Ma Roberts"*, which also discusses puddled steel and Howell's metal.

12. *INA* v.19 p.23-; Samuda's railway steamers were: *Maid Of Kent, Scud* and *Foam*, those of Money, Wigram - *Samphire, Etoile Du Nord, Breeze* and *Wave*: see - C.L.D. Duckworth & G.E. Langmuir *Railway and Other Steamers* (1968) pp.33-4 & 339-340. Steel was extensively used for railway steamers from 1880, Laird built two for the London North Western in that year.

13. *Autobiography op.cit.* 2 pp.43-4.; Merseyside Archives.

14. The following are amongst papers at the *INA*: Rochussen, T.A. *The Application of Steel to the Building of Ships.* v.7 (1866) pp.57-; Rochussen, T.A. *The Treatment of Steel Plates in the Shipbuilder's Yard.* v.8 (1868) pp.1- ; Sharpe, Henry. *The Treatment of Steel Plates (1871) pp.10-18; Howell, J.B. Steel as Applied to Shipbuilding. v.12 (1871) p.14. At The Inst. of Engineers & Shipbuilders in Scotland*: 1860-1 pp.132- and 158-; Kirkaldy, D. *Comparative Tensile Strength of Wrought Iron and Steel.* (1862-3) pp.27-, 43- ; Barber, G. *Employment of Steel in Shipbuilding and Marine Engineering.* (1866-67) pp.95-.

15. *INA* v 9 p.20-22; Fairbairn's comments p.314 of his *Iron Manufacture*, and quoted by Jeans p.720 and drawn to the attention of the Naval Architects by Scott Russell.

16. See c.20 & 21 *Annals of Lloyds Register* (1934); Jeans also discusses Lloyd's actions in both c.XXIV & XXV; *INA* v19 p1- Martell, p 27; Reed v.23 pp.167-8 and v.29 p.80.

17. *INA* v.16 pp.131-147; v.22 pp.87-143; Brown, D.K. *A Century of Naval Construction* (1983) p.48; *INA* v.17 pp.135-6.

18. *INA* v.16 p.141; Brown, *op.cit.* p.52 & 61; *INA* v.22 pp.1, 8; White, W. *A Manual of Naval Architecture.* (1877 and later edit) p.396; *Shipping World* (1883) p.42; *INA* v.27 p.142; Bessemer *Autobiography* p.254.

19. *INA v.22 p.87-; Jeans op. cit.* p.723.

20. *Annals of Lloyds op.cit*. pp.137-8; Duckworth & Langmuir *op.cit.* p.150 & 346; Lyon, D.J. *Denny List* (4 v 1975); *INA* v.19, v.21; Withy, T. *I.Mech* (1881): "a steel vessel . . . sat on a large stone, and doubled her plates considerably, and even broke some internal floor plates. The underwriters' inspector [stated] if she had been built of iron she would have inevitably cracked her plates and filled with water".

21. Diagrams are based on figures in *Shipping World*; *I.Mech* (1881) p.556 and disc. pp.558-574 followed by Price's reply; *INA* v.29 pp.106-7; *Engineer* 8 Jan 1886.

22. *INA* v.19 p.24; *I&SI* (1879) pp.54-63; Denny, v. (1884) p.139; McCloskey, D.N. *Economic Maturity and Entrepreneurial Decline: British ron and Steel* (1973) p.51 gives further information on prices of iron and steel; Bell, I Lothian. *Iron Trade of the United Kingdom* (1886); *Cleveland Institute of Engineers* (1881-2) p.94.

23. *INA* v.22 pp.90-101; *I&SI* (1879) p.65 and 69; Knight, R. *The Practical Boilermaker, Iron-Shipbuilder and Mastmaker* (1880).

24. Jeans *op. cit.* p.723; Bessemer *Autobiography* p.255; Bell *op.cit.* pp.52-3; *I&SI* (1878) pt.II, p.426; *INA* v.27, p.137; *Lloyd's Rules*.

25. *I&SI* (1884) p.139; *INA* v.53, pp.318-9; *Engineering* v.90, p.135; there is a recent short biographical account of Riley in *Dictionary of Scottish Business Biography,* edited by A. Slaven and S. Checkland (Aberdeen 1986).

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THE INDUSTRIAL REVOLUTION - ITS IMPACT ON THE NAVY.

Douglas Braid

INTRODUCTION: Dramatic changes in the navies of the major countries took place during the nineteenth century that completely revolutionised the potential for offence and defence. From the middle of the period, advances made were so great that naval fleets were obsolescent in each decade.[1] Technical advances in design and materials available changed rapidly and effectively, once the potential of new equipment was recognised.

A navy, dependent on timber for its construction, smooth bore cast iron guns for its armament and sails for propulsion, was to be changed by the 1860's and the milestone in Britain was HMS *Warrior*, established by its launching, December 1860, complete with 4½ inch thick armour plate.

Prior to the Napoleonic wars, the only advance made had been a revolutionary system of casting iron guns solid (1774) and boring them out.[2] This had been initiated by Anthony Bacon, M.P., who used the skilful ingenuity and technology of John Wilkinson of Broseley in Shropshire to change techniques that had been used in Britain for the past 200 years. The improvement in productivity and reliability in quality was remarkable.

Steam engines were not used for the propulsion of vessels until the *Charlotte Dundas*, March 1802, on the Forth and Clyde canal [3] and Fulton's *Clermont*, 1807, on the Hudson, demonstrated what could be done. Fulton was using a Boulton and Watt engine but the first successful James Watt engine had only been tested in 1775. All previous attempts had been invalidated by poor manufacturing technology until he made contact with John Wilkinson. The gun boring machine made for the new style cast iron guns also bored his first cast iron steam cylinder cast at Broseley. Because of this initial contact, Wilkinson then designed new boring machines that machined all Watt steam engine cylinders for the next twenty years.

This work established new standards of accuracy enabling better engines to be made with tremendous advantages in using steam for power in many industries. They were used to propel a first naval vessel in 1823. By 1837,[4] the navy had 27 steamers, relatively small in size, all with paddle wheels and frequently acting as tugs, often lashed alongside for manoeuvering sailing ships. In 1835, Peter Ewart had been appointed as the first Chief Engineer responsible for the Royal Navy's steam machinery with resources and facilities for maintaining it, planning new workshops at Woolwich Dockyard as the first naval establishment capable of repairing boilers and engines.

These were introductions of steam and iron technology in what is often regarded as still a traditional wooden ship period. This was also changing, providing bigger, successful wood vessels due to new approaches in design and construction being introduced by men with new ideas. The first screw propeller was used on a small steam ship of 237 tons, *The Archimedes*, 1838, but Admiralty tests in 1845 quickly proved the superiority of the screw over the paddle wheel. The approach towards the planning and building of the *Warrior* was drawing rapidly closer as each stage of development became established.

THE COMING OF THE INDUSTRIAL REVOLUTION.

Various periods are used to define the start of the Industrial Revolution, depending on the specific industry being studied and deciding how much was evolutionary until becoming revolutionary.

The textile and the iron making and working industries are often given credit independently for the major changes but they were only a substantial part of what was happening. Interdependence of industry on power, both from water and steam, displayed through the whole of the eighteenth century, only came into clearer terms during its last quarter when slow evolution became dramatic expansion.

Cast iron came to Britain at the end of the fifteenth century to provide cast iron "gunne stones" replacing missiles made of stone that fractured on impact with fortresses.[5] By 1543, guns were cast in iron as an alternative to expensive bronze guns and much less efficient wrought iron guns of crude manufacture. These not only continued using early simple techniques in manufacture until 1774 but the demand and the output remained small. It was after the invention of this technology that output rose dramatically in Britain to meet the needs of the Napoleonic war. Guns with cast bores had been slowly reamed out, one at a time, with the power of a small water wheel. Only twenty five years later, a common experience was to see eight guns being bored[6] simultaneously from the solid with the drive from a Boulton and Watt rotative steam engine. Production of guns and shot rose over the same period from 2,500 tons to about ten times as much to meet urgent needs of current wars.

Wrought iron output had been minuscule from small woodland furnaces in pre-history times to 5 tons a week from the blast furnaces and reverberatory furnaces converting cast iron into wrought iron. At the time when Henry Cort developed his method of puddling cast iron to make wrought iron in 1784, the total output of bar iron in Britain had been about 30,000 tons. By 1800 it was 125,000[7] tons but it had risen to about 340,000 tons in about twenty five years more.[8]

Throughout the period after 1760, it was not only expansion in output but technology that changed equally swiftly. When studying history of technology, there are times when developments seemed to appear as quickly then as we have experienced today in our new world of aircraft, electronics and space craft.

METAL IN THE SAILING SHIP PERIOD.

Quite apart from the metal used for armament, that used in the construction of the thousands of wooden warships built in little more than two hundred years must have been astonishing. In the 1770's, there are figures that suggest Portsmouth Dockyard was buying some 180 to 200 tons of boltstaves, nails and spikes a [9] year and it is suggested that this was repeated by three other dockyards at Chatham, Deptford and Plymouth. One hundred tons of Swedish iron was purchased each year for each dockyard for chains and anchors and an equal amount of lower grade iron for a wide range of items made by the Dockyard smiths for fittings. Cast iron ballast weighed from 50 to 150 tons for individual ships and copper sheet for sheathing against weed or boring by teredo worms and the like was considered essential for use in warmer seas.[10]

Guns on the larger ships could approach 200 tons and the shot about half the weight. The list of metal objects shown in lists of stores are also an astonishing reminder to those who have given little thought as to what was needed to put such a vessel to sea.

A new strengthening of the ship's structure came into use in 1811 with timber diagonals introduced by Sir Robert Seppings [11] to give greater strength to the hull. In later ships from the time of John Edye, he introduced the use of iron diagonals.

All the water carried on board had been stored in casks until 1814, presenting a problem of securing them at the lowest tier of the vessel, sunk to a third of their diameter in a level bed of shingle. These usually had to be brought up from a hold to extract the contents. With the development of a manual pump for distribution and wrought iron tanks for storage, an improved system for water handling came into existence. [12]

Rectangular in shape, made to suit individual ships, numbering as many as one hundred in a 100 gun ship, they held more water in a given space. They made better use by fitting closer together than round casks and eliminated shingle ballast, "difficult to keep sweet and clean", from its proximity to bilge water. A main suction pipe installed above the hold had connections with caps screwed on at suitable points for a flexible length of hose to be directed to the tank to be emptied. The amount of manpower used was substantially reduced in handling casks as the water was pumped to a storage tank on the quarter deck or direct to the boiler in the galley. The scheme had been put forward by Lieut. Truscott who devised the pump and apparatus between the hold and point of use. In 1815, 3343 tanks had been installed after the scheme was generally adopted and Truscott promoted to the post of Commander.

As ships got larger, the securing of ships by their anchors and cables became progressively more difficult. Heavy chain cables were in position with mooring buoys in harbours and rivers but were not considered suitable for use at sea. Lieutenant Samuel Brown [13] had approached the Admiralty with a suggestion for an improved type of chain cable which passed various trials and as a result, he was promoted to Commander, 1 August 1811. His ideas were patented in 1816 conjointly with Phillip Thomas. Several advantages are obvious over hempen cables in their resistance to weather and sharp rocks but the less obvious one was the use for anchorage when firing at land fortifications. Rope cut by shells or splinters could leave a vessel in a perilous position. A combination of chain cables and wire rigging followed in later ships.

He is possibly better known for his famous Chain Piers (1823 at Brighton) but more especially for the design of chain suspension bridges, predating the use of wire cables a few years later. His links were adopted by Telford for the Menai Straits bridge [14] for the Holyhead Road with chains 580 feet long. It was opened to traffic on January 30 1826 and the wrought iron links survived until they were replaced with steel in 1939. He was knighted as Sir Samuel Brown (1838) for his services, but lesser known is his setting up a tensile testing machine in 1816; one of the earliest of this type of machine; to test his cable links. At that time, his was a mechanical system but there were variations between the results obtained for the Navy Board between this and the Bramah hydraulic testing machine at William Brunton's Patent Chain Cable Works in the City Road. This earlier machine was probably ahead of Brown's but these were the first signs of large scale tensile testing this early in the 19th century. He is also known for a Vacuum Pumping Engine using coal gas as a fuel, generated on the spot, to raise water for various purposes. His first idea was described in Mechanic's Magazine, No.53, August 28th 1824 but a later, improved design was also described in the same magazine, No.468, July 28th 1832. An odd association with naval vessels but demonstrating the ability that was enrolled in the service.

GUNS AND THE BOARD OF ORDNANCE.

Henry VII and Henry VIII probably did more to establish supplies of guns, their provision and eventual production in Britain, and strengthening of the Board of Ordnance. Principal officers of the Board had technical and administrative experience in dealing with supply problems but they had to provide armament for both naval and land forces. The cast iron guns were first produced in the Sussex Weald to arm new forts being built to protect dockyards and harbours while bronze guns were supplied to ships and wrought iron guns as siege pieces in the mid sixteenth century. Various changes took place in design, types of guns and sizes but the major changes began in the middle of the eighteenth century.

NINETEENTH CENTURY STRATEGIC CHANGES.

The revolutionary adoption of steam power for naval vessels meant that they were no longer dependent on wind to bring them into engagement. At the same time, changes to rifling and elongated shot ensured that projectiles could easily pierce wooden ships and explode inside. A need for armour became apparent after the various phases of basic reorganisation during the 1830's [15] and finally resulted in the prime antagonists of *The Warrior* and *La Gloire* as fore-runners of armoured fleets. By the mid 1850's,[16] tests were in progress of various types and forms of armour in which wrought iron was the vital component. Cast iron would never have been effective as it lacked ductility and would never have resisted the impact of shot and shell. Steel was still being made in crucibles by carburising wrought iron but these were only 50 to 60 lbs of metal in each one. It was another twenty or more years before steel advanced in technology and volume to forge tubes for guns and show promise for armour. Bessemer steel[17] first made in 1856 was adequate for railway lines and industrial use but never evolved to the stage of adequacy for high stressed uses. Acid Open Hearth steel[18] with the reliability demanded only came into production in the 1870s but its advancement was rapid, British output reaching over half a million (574,000) tons in 1885 and continuing to grow every year.

NINETEENTH CENTURY CHANGES IN SHIP CONSTRUCTION.

Wooden walled ships now used iron joints with wood construction to make larger vessels possible but wrought iron frames were considered very pioneering. It was the influence of the ironwork on the magnetic compass that created problems until Sir George Airey, Astromoner Royal, offered a solution in 1839 of using magnets to correct deviations built into an iron ship. The paddle gunboat, *Nemesis*, was built in 1839 by Lairds for the East India Company but paddles and their engines were unsatisfactory for fighting vessels. They were vulnerable to damage, restricted the number of guns in a broadside and impaired the use of sails.

In 1846, the first screw Fourth Rate, *Arrogant* was to have a significant part in the development of steam battleships but the lack of protection of thin plating gave them no part in aggressive action. They were converted to transports but the value of the screw was established. The development of the P & O *Himalaya*, in 1852 had quickly established the benefits of iron hulls which were 40% cheaper and 30% lighter. The problems of cost and supply during the Russian War of 1854 had a great impact on thinking about the merits of future use of timber. Fighting ships presented a number of problems of construction by the limitations of the current technology of the mid 1850's but the pressures and challenges of designers and constructors brought advances rapidly to the fore.

DEVELOPMENTS IN WROUGHT IRON ARMOUR PLATE.

Wrought iron made rapid strides in output after the Henry Cort Patent No.1420 of June 1784. In 1788, the output of a good furnace was never more than 5 tons a week with an annual total of 32,000 tons for the whole industry. Dr.R.A. Mott estimated that only twelve years later, the output in 1800 had risen to 125,000 tons and by 1827, it was between 338,000 and 354,000 tons. The increase in demand for rails for expanding railways was probably an important catalyst but wrought iron was the major material in all aspects of manufacturing.

From 1854 up to the late 1870's,[19] its use for guns and armour was continually expanding and the growth in size of equipment and machinery producing it in larger areas and thicknesses was dramatic. Making the 4½ ins thick plates for armour was a new problem and much of it was still being made under the new steam hammers. The first plate rolled by Beale's at Parkgate in 1853 was only 2½ tons and it was 1859 when John Brown improved on this with a labour intensive production of a 5 ton plate. Rapid advances are shown by the demonstration to Lord Palmerston in 1863 by Brown of a 20 ton plate 12 ins thick. It was obviously to demonstrate their potential at the time because current armour had only reached 10 inch thickness three years later.

The revolutionary *Warrior,* built on the Thames, May 1859 and launched December 1860, used 950 tons of 4.50 inch iron with a backing of 355 tons of 18 inch teak. [20] By 1866, the *Monarch* was designed with turrets using 8 and 10 inch armour although the main armour was only 4½ to 7 inches thick. It totalled 1,364 tons, was 16 per cent of the displacement and already 46 per cent heavier than armour used for our first ironclad. This was quickly surpassed by the *Rupert* laid down in 1870 with 14 inch armour on the turret and 9 to 12 inches for the main armour.

Only another six years later, the *Ajax* had 18 inch armour and a minimum thickness of 12 inches except for 3 inch deck plating. Designers had virtually reached the optimum thickness as further increases became counter productive with added weight and space diminishing within structural limits. This was at a time when more powerful machinery and guns were needed for higher speeds and greater hitting power. Physical sizes of vessels were restricted by the needs for docking facilities for essential repairs, not only in Britain but across great oceans as naval power was expanded and extended.

The result of this revolution in naval armour and armament did not start until 1860 but it proceeded in this astonishing manner for sixty years. Only about ten years elapsed between a fleet putting to sea and becoming obsolescent.

PHASING OUT WROUGHT IRON GUNS AND ARMOUR FROM 1886.

At various stages, political jockeying ignored the essential needs of the navy during the 1870's-1880's but war scares often arose from sabre rattling by the Russians. Moves by the British Navy in the summer of 1885 brought apologies from St Petersburg but it also demonstrated the need to recover some of the stages of delay and decay that had spread within naval defence policies.

Steel had also advanced metallurgically and an effective change in armour and guns was not only feasible but became operative. Wrought iron was no longer used for ships frames and it was [21] decided to eliminate wrought iron for both armour and guns with a higher tensile strength and consequent reductions in overall weight for the same benefits.

The *Resistance*, laid down in 1859 was allocated as a target ship in 1885 and was used to test forms of protection against gunfire and torpedoes for future decision making. Changes came forward with rapidity and test of new formulations for armour continued to be tested over the next several years.

An all steel plate, 4 inches thick, was available in 1888 but was quickly superseded in 1889 by a nickel steel plate from Jessups with striking results, quickly adopted by all the competitors, but this was only the start of intense competition. The manufacture of armour was receiving so much technical attention that users soon began to realise that there was little to choose between rival systems. As soon as ship designers recognised this, they began to pay even more attention to the design of their ships and guns.

INTERNATIONAL MOVES IN MAKING ARMOUR.

The main objective was now to provided a hardened face backed by a resilient main body of armour that would not shatter under the heavy shock loading of a hit.[22] This was finally achieved by carburising the face of the plate and hardening this by quenching. The Harvey system, invented by Hans Augustus Harvey, met these needs and John Brown, together with Cammell and Vickers, each took out licenses to use this method. Brown also developed in 1891, the important technique of the Tressider system of quenching plates with jets of high pressure water. To look after British patent rights, these three formed the Harvey Steel Co. in 1893 but an international syndicate was then formed, aligning most companies in the world for an agreed use of patents and avoiding cross marketing in 1894.

These companies included Acieries de la Marine, Bethlehem Steel, John Brown, Cammell, Carnegie, Dillinger Huetten, Krupp, Schneider-Chatillon and Vickers. Beardmore obtained a separate license from the American Harvey Company to treat their armour by a process described as carburising the outer face for 17 to 18 days, then final machining before heating and quenching. Krupp, like some other early forgemasters, made his money by providing the expanding railways with specialised products, in his case heavy springs and tyres made in improved metal for wheels. He later became a specialist in guns but followed this by developing and patenting a "cemented" armour in 1896-97 with a high quality nickel-chrome basis. The importance of this can be seen when comparing various armours relative to wrought iron as the base line. As a direct comparison, 5 1/4 inches of Krupp armour was equal to 7 1/2 inches of Harvey steel, 12 inches of compound iron and 15 inches of wrought iron. The result was that the British Admiralty decided to specify the Krupp type of armour and paid them a royalty of £4-10s. on every ton used until the expiry of the patent in 1910.

Armstrong had not been in the original syndicate but joined them in 1901 while Beardmore, becoming William Beardmore & Co Ltd., under control, of Vickers in 1901, were licensed to make Harvey and Krupp armour in 1904.

THE NEXT STAGES IN DEVELOPMENT.

As usual, challenges from improved armour resulted in heavier guns with higher muzzle velocities and greater muzzle energy from propellant improvements and changes in gun design. New projectile developments for armour piercing such as the 'capped' shell had better aerodynamic properties and better penetration. Strategists had to be prepared to fight battles at even greater ranges to make existing armour effective against improving gunnery with little hope on either side of achieving checkmate.
Improvements in metallurgy and design had to be followed by larger and more remarkable machinery[23] to produce these new products. Hydraulic presses of 4,000 tons in 1886 had increased to 10,000 tons in 1895 and 12,000 tons in 1896-98 whilst 12,000 H.P. was installed to drive rolling mills with rolls up to 48 inches diameter and to 15 feet in width.

Buildings increased dramatically in size when it is realised that the largest turrets were built there carrying two 15 inch guns that weighed almost a 100 tons each.

The *Hood* was laid down in April 1916 with a designed displacement of 41,200 tons of which the armour weighed 13,800 tons up to 15 inches in thickness. Battles between designers of guns and armour had been waged with more enthusiasm and effort than was often expended in the sea-borne conflicts for which the ships were planned and made. The final outcome of all this effort has been the virtual disappearance of big guns and most big ships needed to carry them.

We have seen remarkable advances in technology but we have great difficulty in forecasting what might be the outcome in twenty years time. We are in the same position as those responsible for the remarkable *Warrior* when we look at it with hindsight. They were not able to imagine what it might be doing in twenty years time. It would never have entered their minds that it would be a treasured object in our lives 130 years later.

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ATTACK AND DEFENCE

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Introduction: The battle between attack and defence began in earnest for warships during the war with Russia (1853-56). From then on the competition between armour makers and gun founders was fierce with the balance of advantage swinging one way then the other. Since the design of battleships was dominated by weight, there was always a limit to the thickness and extent of armour which could be applied to a battleship and, increasingly, schemes of protection became specialised, applied to vital areas of the ship and to resist specific types of projectiles. This paper will concentrate on British developments but, where relevant, comparisons will be made with those of other countries.

EARLY HISTORY

Whilst there are legends of the use of protection in classical times,[1] the first real application was to the Spanish floating batteries used in the siege of Gibraltar in September 1782. These ships had sides built up of three successive layers of timber, each three feet thick with inside this, layers of wet sand and wet cork to protect against red hot shot and splinters. Even without this special protection, the wooden battleship was hard to sink by gunfire.

Iron hulls brought new problems. The first, that of correcting the magnetic compass, was solved by the Admiralty in 1838 and as a result, a number of sea going iron ships were built. It soon became apparent that the behaviour of iron plates under the impact of gunshot was inconsistent and though the first such ships did well in battle, shot holes being clean and easily repaired, later careful trials ashore showed that plates of half-inch thickness or more would break the cast iron shot into a cloud of lethal splinters. Shot impacting at long range and low velocity would tear jagged holes in iron plates, difficult to seal. The reason for these problems will be discussed later; the immediate consequence was that the Admiralty decided, rightly, that iron was not a suitable material for warships (1846).[2]

WAR WITH RUSSIA 1853-56 [3]

The opening battle at sea was at Sinope on 30 November 1853 when a Russian fleet destroyed a small Turkish squadron lying at anchor. It was believed that the Russian use of shell firing guns caused most of the damage and urgent thought was given to protection against shells. The Emperor Napoleon III and his brilliant naval architect, Dupuy de Lome, devised a scheme for floating batteries to attack forts, with the gun deck protected by boxes of cannon balls. Another great naval architect, Thomas Lloyd, Engineer in Chief of Royal Navy, suggested the use of rolled plate armour and, following extensive tests at Vincennes, this was adopted.[4,5]

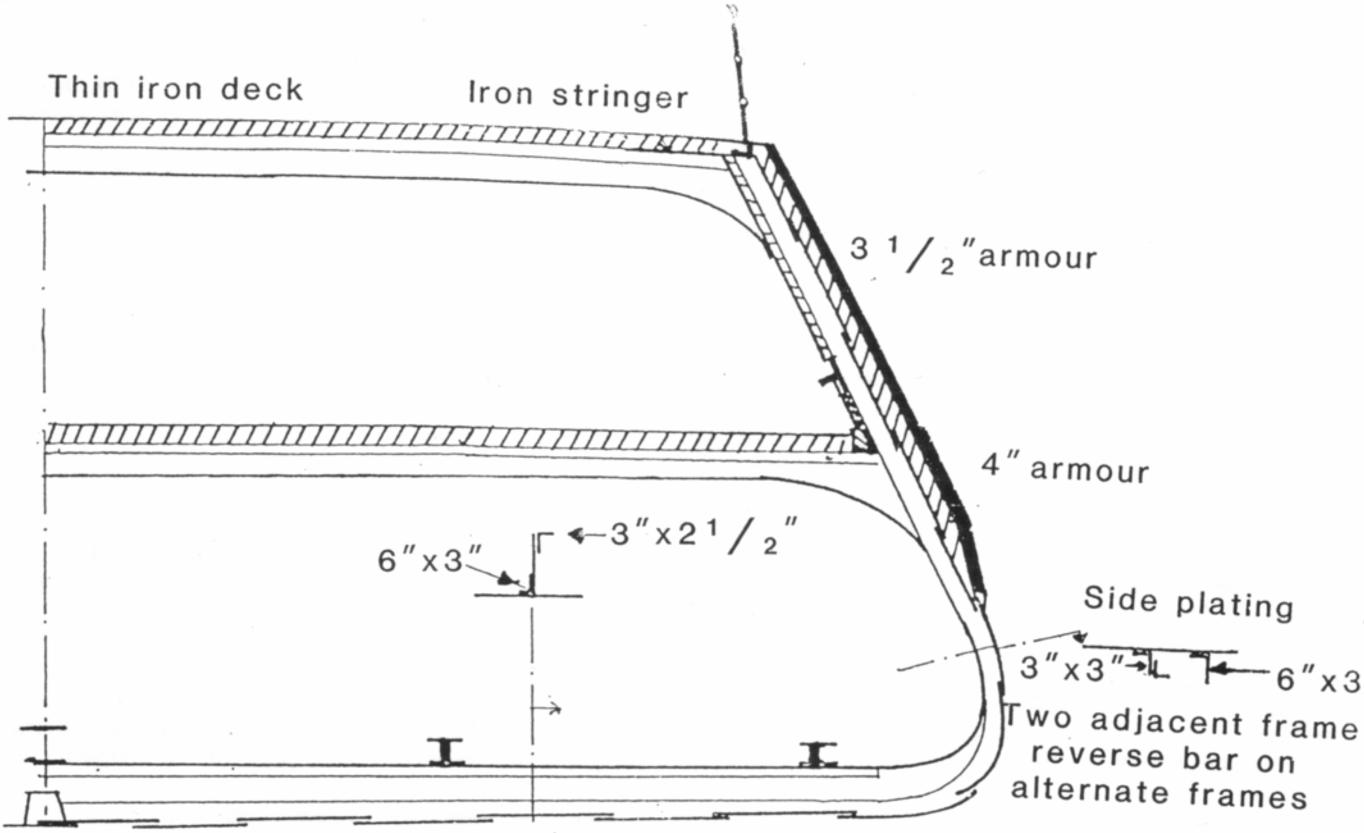
Five ships were built, each carrying 16-50 pounder (pdr) guns protected by 100mm plate. Five generally similar ships to British design were ordered by the Admiralty in October 1854 following further extensive and unnecessary tests at Portsmouth required by the First Lord, Sir James Graham, notorious for his lack of comprehension of technical matters. A replica of the side was made, 9 feet square, with 4 inch plate backed by 4 inch fir planks. This target resisted 12-32 pdr and 68 pdr shot at close range but failed under the impact of the last two 68 pdr shot.

The French ships went into action at the bombardment of Kinburn on 17 Oct. 1855 and impressed observers with their ability to resist both shot and shell. In December 1855 the Royal Navy ordered three more ships with iron hulls, the first iron hulled, armoured ships to go to sea (fig. 1).

After the war, Britain and France resumed their traditional naval rivalry and a building race ensued in unarmoured, wooden hulled, steam battleships. In 1857, Dupuy de Lome began studies for an armoured battleship, called a frigate, but still with a wooden hull. This ship, *Gloire*, was completed in August 1860. She was of 5630 tons, carried 30 6.4 inch guns and had an armour belt covering her whole length with thickness varying from 110 - 120mm.[6]

It was a grave error for mid-19th century France to challenge Britain in technology where her enormous industrial power gave her such an advantage. The British response, *Warrior*, was bigger (9180 tons), faster (14 knots against 12.5), more heavily armed and had a rigid iron hull, so necessary to accept the vibrating loads from powerful machinery. Her iron armour was 4½ inches thick and had been proved in a series of tests.[7] In 1856-7 plates from different manufacturers had been tried as a result of which it was clear that wrought iron plates of about 4 inches thickness and properly supported would resist all contemporary shot at fighting ranges. In October 1858 trials were carried out using two of the Crimean batteries, *Meteor* with a wooden hull and *Erebus* with a hull of iron. *Erebus* had 4 inch plate with 5-6 inch oak backing, behind which was the 5/8 inch hull plating. Hits with 68 pdr shot caused severe damage, particularly to the securing bolts, and the hull was driven in. The *Meteor* fared much better. She, too, had 4 inch armour backed by 6 inch oak but behind this were timbers 10 inches deep, filled in solid with a further layer of oak up to 9 inches thick behind that. She resisted 68 pdr shot at 400 yards with only minor damage.[8]

From these trials it appeared that thick timber backing was a necessary component of the protection scheme. Between 1858 and 1861 there were other tests of iron protection for forts as well as ships. In 1861, the War Office set up the "Special Committee on Iron", chaired by a naval captain and



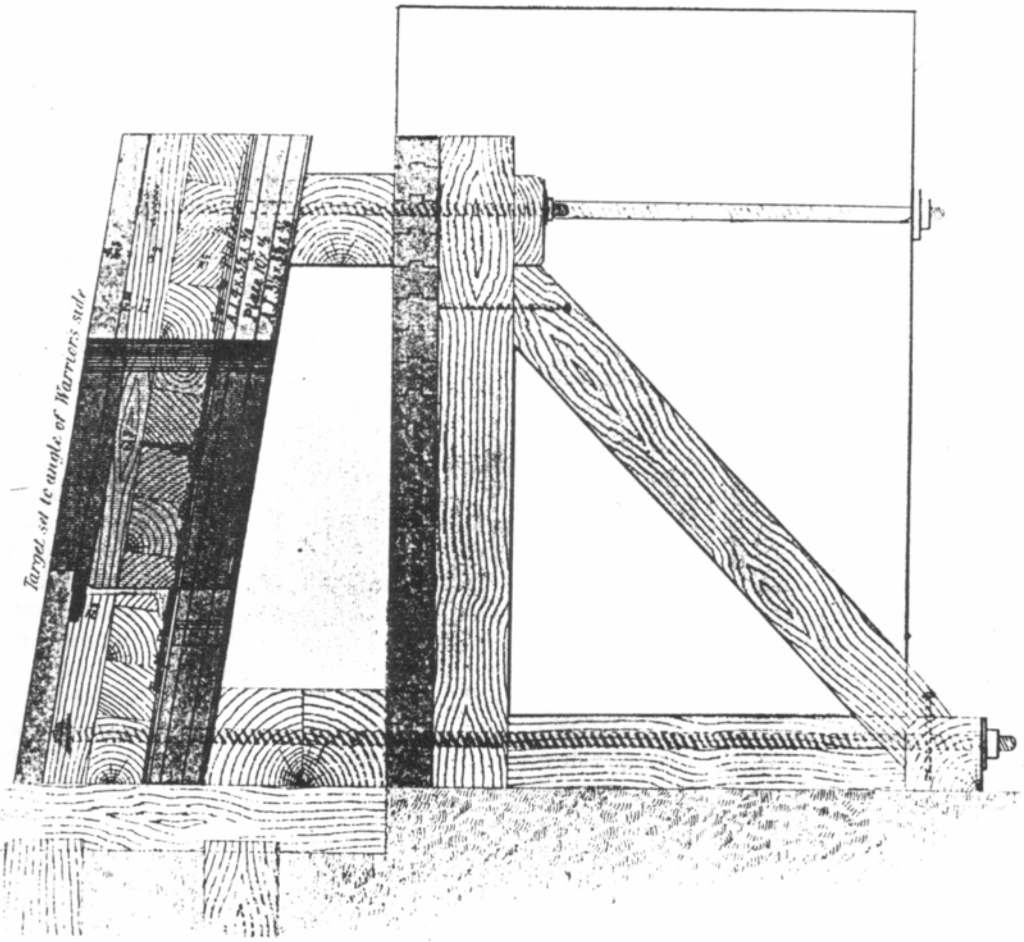


Fig. 1 ***Erebus*** **- iron-hulled, armoured ship (top).** **Fig. 2 Test of protection for *Warrior* (bottom).**

including engineers and shipbuilders, to develop iron protection. They carried out a wide ranging series of tests and, even with hindsight, there is nothing to criticise in what they did and there were very few omissions. Their report began with the results of a very detailed survey of the composition and physical properties of iron from different sources. Tensile and compressive strengths were measured as well as the energy required to break a bar on impact. Claims by ingenious inventors were tested and rejected; solid wrought iron was the best protection.

Several large targets representing different styles of protection were built and fired against, mainly investigating different thicknesses and arrangement of backing. It would now seem that the evidence was misinterpreted; most failures were due to fracture of the securing bolts which passed through armour, backing and shell plating, with the heads exposed to shot. The impact of a shot on this exposed end of the bolt would initiate a compressive shock wave which would be reflected at the inner, free end as a tensile wave and break the bolt. In fact, it would seem that the action of the thick timber was to damp out the shock wave in the bolt. The French had correctly identified this problem and *Gloire*'s armour was secured with wood screws into the timber hull. Not many years later, armour in all navies was fastened by bolts tapped into the rear face of the plate and and only very thin backing was used.

In October 1861 a target was tested representing the final scheme of protection for the Warrior. It was 20 feet x 10 feet, with a gun port in the middle (fig. 2). The 4½ inch plate was backed by two layers of 9 inch timber arranged crosswise, behind which was the 5/8 inch hull plate; the space between the frames was filled in with more timber. The securing bolts were about 18 inches apart with countersunk heads on the face of the armour and double nuts inside the hull plating. The plates were connected to each other using "tongue and grooving". This was not repeated on later ships as it was found that the shock of impact on one plate could be transmitted to its neighbour but, more important, replacement of damaged plates was made very difficult. The *Warrior* target was hit by 29 projectiles with weight ranging from 68 - 200lb, none of which penetrated and only one bolt was broken. *Warrior*'s protection was not very efficient in terms of weight but it was effective in resisting all available weapons.[2,8]

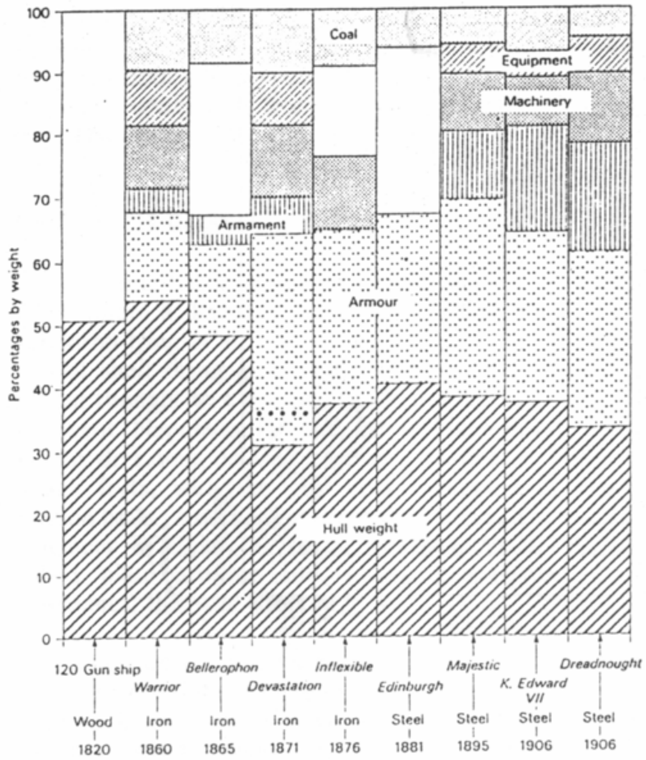


Fig. 3 Weight devoted to armour.

PROPERTIES OF WROUGHT IRON [7]

During the restoration of *Warrior*, J. Bird at the Admiralty Research Establishment, Dunfermline, was able to carry out a series of tests on samples of her armour. The in-plane properties were in accordance with expectation.

Plate strength - longitudinal (N/mm)
(1 N/mm = 144 lbs/in.)

	0.2% Proof	UTS	Elongation %	Reduction of area %
Sample 1	220	284	11	1
Sample 2	212	253	8	2

The same properies were then measured at right angles to the plane of a 4½ inch armour plate for 12 samples.

Armour - perpendicular to the plane

	0.2% Proof	UTS %	Elongation of area %	Reduction
Mean Range	121	149	5.1	2.25
(max-min)	170-99	195-111	10	1-3
	(40)	(43)		

Note - The figures in brackets refer to one particularly bad sample, ignored in the mean, but which could have been an Achilles heel in action.

The impact strength (Charpy V-notch) was then measured over a range of temperatures on samples taken through the thickness of the plate.

Impact Strength at Various Temperatures

Test Temp °C	-20	0	15	40	100	140
Energy Joules	11	11	17	24	26	25

The inconsistency perceived in the behaviour of wrought iron in the 1840s is now explained. It so happened that all the battles involving iron ships took place in warm water whilst Woolwich in December took wrought iron well into the brittle range. Temperature was the only parameter missed by the Special Committee in their otherwise comprehensive studies.

Warrior's armour covered 213 feet of her length with the ends unprotected since it was thought that the weight of armour at the ends would impair sea keeping. The ends were closely subdivided and even if completely flooded her draught would have been increased only by some 30 - 40 inches had little effect in performance. However, from *Achilles* (1863) onwards, end to end protection was provided. Already the emphasis was shifting from protecting the guns' crew to protecting the flotation of the ship.

Name	Launch date	Displace- (tons) (1)	Material	Max thickness	Weight (tons)	% (2)
Warrior	1860	9210	iron	4½	1305	14
Bellerophon	1865	7550	iron	6	1093	14
Devastation	1869	9330	iron	12	2540	27
Inflexible	1876	11880	iron	24	3275	28
Edinburgh	1882	9150	comp	18	2414	26
Royal Sovereign	1889	14150	comp	18	4560	32
Majestic	1895	14900	Harvey	9	4535	30
Canopus	1896	12950	KC	6	3600	28
King Edward VI	1903	17009	KC	9	4175	25
Dreadnought	1906	17900	KC	11	5000	28
Queen Elizabeth	1914	27500	KC	13	8600	31
Hood	1918	42670	KC	12	13650	32
Nelson	1925	33500	KC	14	10250	31
King George V	1939	36700	KC	15	12413	34
Vanguard	1944	44614	KC	14	14741	33

Notes:
1. Displacement is "Normal" (about half fuel) until *Hood* then "Standard", (without fuel).
2. The distiction between armour weight and thick hull plating is inevitably blurred and these figures should be taken as a guide only. There were quite significant differences between definitions used in different countries.[15]

THE RACE BEGINS

The competition between gun and armour was now launched and in a very few years *Warrior*, herself, would retire into obsolescence. *Warrior* had to be a long ship in order to carry numerous guns, widely spaced, on the broadside. The *Minotaur* class (1866) were even longer. They had some 16,000 sq. ft. of armour, 5½ inches thick (4½ inches at the ends), and every additional inch of thickness would have added 300 tons to the load on the ship.[9] Ship design is always a compromise; weight and funds devoted to armour must usually be paid for by reductions elewhere, fewer guns or less powerful machinery. Only rarely was the ship itself allowed to grow significantly over its predecessor so that all aspects could be increased. The percentage of the total weight devoted to armour is shown in the table above (see also Fig. 3).

The centre battery ship, due to Edward Reed, was a bigger advance in design. The *Bellerophon* (1865) mounted fewer, bigger guns so that armour could be concentrated over a short battery and on the waterline. With only 7,500 sq. ft. to be protected, thickness could be increased to 6 inches whilst still reducing the overall displacement of the ship.[10]

The increasing weight of guns led to the introduction of the turret mounting, first by Coles in HMS *Trusty* (1861) and later by Ericsson in USS *Monitor* (1862). The weight of the turrets forced designers to adopt low freeboard which also reduced the extent of side to be armoured. Such ships were dangerous and both *Monitor* and Coles' *Captain* were lost in bad weather before Reed devised a happy compromise in *Devastation* (1871). This ship had only 6,200 sq. ft. to protect and since further weight was saved as she was the first large warship built without sails, she was able to carry 12 inch armour.

INFLEXIBLE - COMPOUND ARMOUR

By the 1870s monster guns were appearing with barrel weights escalating rapidly from 35 to 81 tons (16 inch bore) and even 100 tons (17.7 inches). These guns were rifled muzzle loaders firing pointed Palliser shot of chilled iron. The propellant charge was still gunpowder, a fairly violent explosive, and until slow burning propellants became available, able to utilise longer barrels, there was little point in going to the complexity of breech loading. After several changes, Barnaby designed *Inflexible* (1876) to carry four 81 ton guns in two twin turrets, loaded and trained hydraulically. These guns could penetrate 22½ inches of iron at 1,000 yards range and at best, could fire every 2½ minutes. The two turrets and the machinery were grouped in an armoured box 106 feet long (1/3 length) amidships which would float - and float upright - if the two ends were flooded.[11]

This box was protected by two thicknesses of 12 inch iron, which, together with 36 inches of teak backing weighed 11,000 lb/sq. ft. The ends had a thick armoured deck intended to preserve flotation even if the upper works were destroyed. The underwater portion of the hull was closely subdivided. Clearly the thickness of wrought iron required was becoming impractical. Italy and France had changed to steel armour but tests at Spezia cast doubt on its performance under repeated attack. *Inflexible*'s turrets were protected with compound armour in which a hard steel face was bonded to a tough iron back.

There were several methods used to produce compound armour; in the Wilson process a red hot iron plate was placed in a mould and molten steel run on to it. The surface of the iron melted and fused with the steel giving a complete and reliable bond with a gradual transition in properties. The plate was cooled and then re-heated before being rolled to the final thickness. In one example,[1] a plate, cast 30 inches thick was rolled to 18.9 inches with the steel face 6 in. thick. In the *Royal Sovereign* (1892) compound armour was used for the belt, 18 inches thick and equivalent to at least 24 inches of iron. The weight of individual plates increased and continued to increase eg.

Ship	Launched	Weight of plate (Tons)
Warrior	1860	4
Hercules	1866	10
Inflexible	1876	24
Trafalgar	1887	30

The hard face of compound armour could break up chilled iron Palliser shot but in 1886 Holtzer and later Firth (Cammell & Co) developed forged steel armour piercing shot which could penetrate compound armour without breaking. It should be noted that though these shot had a hollow interior, they did not usually have an explosive filling. A gunpowder burster would not break the casing and fuses had not been developed which would stand the shock of impact and explode after passing through the armour.[12]

The French company of Schneider had developed much improved steel armour and by 1888 Vickers were able to demonstrate the quality of their own steel armour. It was a very competitive era and, since there was no Official Secrets Act, the results of the numerous trials in all countries, though not precise details of processes or composition, were widely publicised. Barnaby, the Director of Naval Construction (DNC) was well justified when he said

"There never was a target fired at for many years at Shoeburyness that I did not go behind to see what had happened. For a great many years I was more familiar with the war that was going on between armour and guns than any naval officer in any navy, and I say that my experience of what happened behind these targets has been to me sometimes only too dreadful." [13]

In designing the *Royal Sovereign* class, the new DNC, William White, had to overcome another problem. The main belt, to keep out heavy armour piercing (AP) shot, could only cover a small area of the ship's side. The remainder of the ship was very vulnerable to high explosive (HE) shells fired by the newly introduced quick-firing guns. In consequence, he introduced a 5 inch upper belt of steel armour to give some protection to spaces above the main belt. (Fig.4) The problem of protecting against both AP and HE shell was continuing and insoluble.[13]

HARDENED STEEL

The requirement for an even harder face was first met by Tresidder in 1887 who developed a method for rapidly chilling the face of compound armour using water jets. Then, in 1891, the American metallurgist, H.A. Harvey, carried out successsful tests of cemented armour at Indian Head. A fairly soft steel plate was kept at a high temperature in contact with finely powdered charcoal which penetrated the steel to a considerable depth. When the plate cooled to a dull red heat it was water chilled. The American tests seemed to show that a nickel steel gave the best results but British tests did not confirm this and RN "Harvey" armour usually omitted the nickel. On the other hand, the Tresidder chilling process was used as it was found better than Harvey's process. Harvey armour was first used in the Royal Navy in *Renown* which had a 10 inch belt replacing both the 18 inch and 5 inch belts of the previous class and equivalent to about 20 inches of iron.[1]

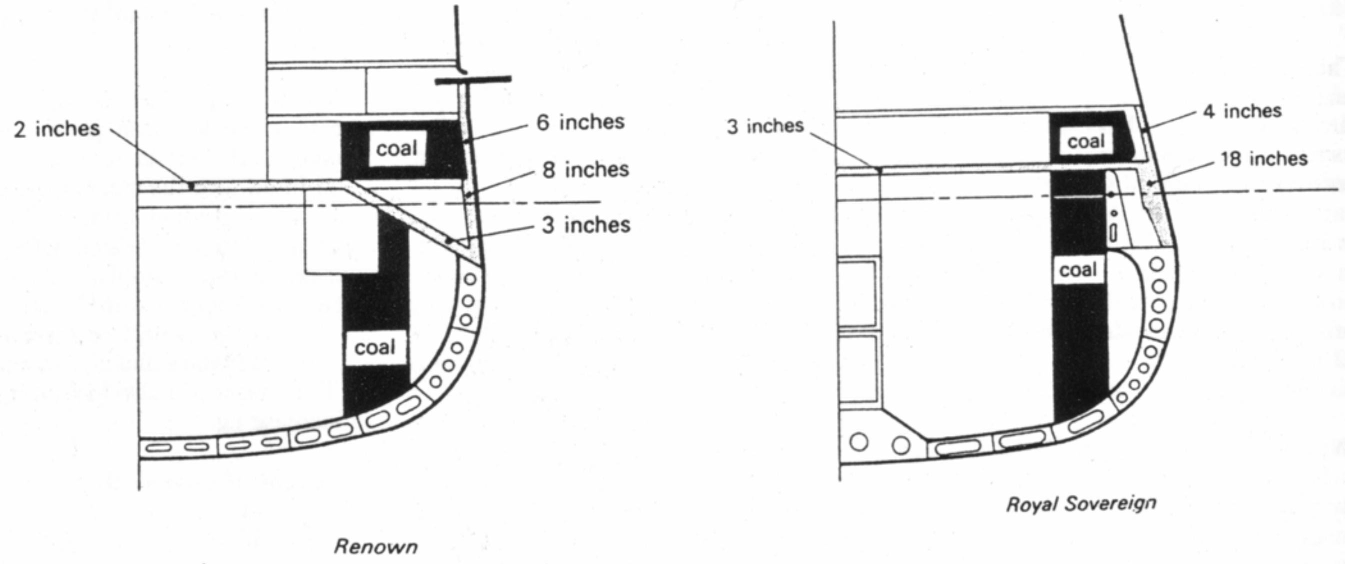
KRUPP ARMOUR

Harvey armour suffered from a back which was insufficiently tough and a too rapid change in properties behind the cemented face. Krupp tried various compositions and by 1894 had introduced a much improved nickel chrome alloy. The composition varied a little but the table shows typical values.

Element	%
C	0.35-0.5
Ni	3.5-4.0
Cr	1.5-2.5
Si	0.15

The addition of chromium allowed the carburised face to extend deeper into the plate and an elaborate differential heating was used in which the face was chilled from a high temperature to give a glass hard surface whilst the back was kept at, and chilled from a much lower temperature, giving a very tough material.

The ingot was slabbed down in a press and rolled to the finished thickness with allowances for machining and wastage and was then annealed, cooled and straightened. Two plates were usually carburised together with a layer of fine charcoal between them. The plates would then be kept in the furnace for about three weeks after which they would be quenched in oil. Any holes required would then be drilled before the plates were re-heated prior to the final treatment with differential heating and chilling. A single plate might be 12.5 x 10 feet and weight up to 30 tons. The



Renown

Royal Sovereign

Fig. 4 Compound Armour.

Brinell hardness would be about 650 on the face reducing to 220 some 25% into the plate. (Fig. 5)

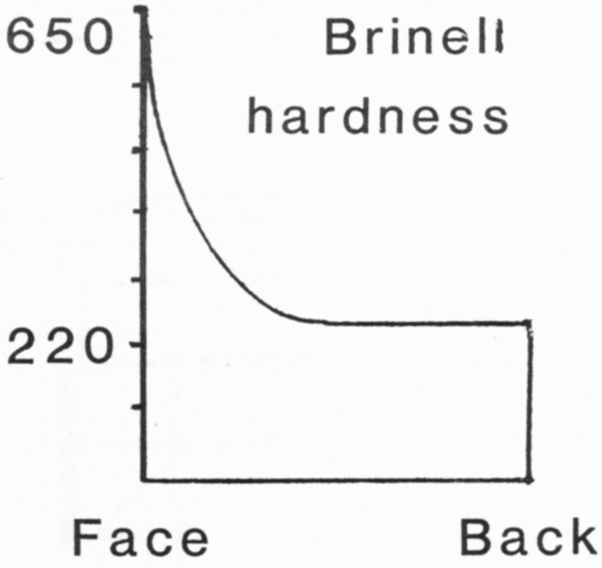


Fig. 5 Hardness of Krupp Armour.

Tests showed that Krupp armour had resistance equal to iron of 2½ times its thickness. (Fig.6) Krupp armour was introduced to the Royal Navy in *Canopus* which was usually described as "second class" because of her 6 inch belt, even though it was more effective than the 9 inch of *Majestic*. There were no further changes in the material used for belt armour of battleships though minor changes in composition and in heat treatment would give significant gains in performance.

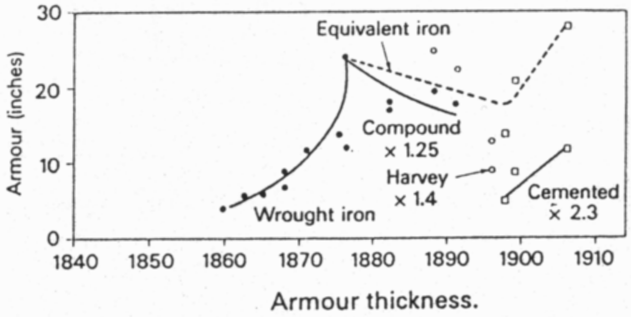


Fig. 6 Resistance of Armour.

PRE-WAR TRIALS

Up to the turn of the century, the majority of armour piercing projectiles were shot - ie they did not contain a bursting charge. Technology gradually produced a fuze which might explode a shell after it passed through a thick plate and an explosive filling which might not detonate on impact with the armour. Large capacity, high explosive shells were available for use against unprotected parts of the ship. It became increasingly important to carry out tests against representative ship structures and not only against single plates. (These were still needed for proof tests of both shell and plate). The main British tests were against the old battleship *Edinburgh* which had been refitted with sections of modern protection. The results of these tests were fully described in the Gunnery Manual 1915, and should have been generally known before Jutland.[14]

The trials confirmed earlier tests on the devastating effect from both blast and splinters from large, HE shells exploding above the protection. Common shell, with thicker walls and a gunpowder filling produced fewer, but larger splinters and caused much structural damage. Protective decks were less effective than had been thought in preventing damage to vital spaces low in the ship from splinters when shells burst above the deck. It must be realised that expected battle ranges were 10,000 yards or less at which the angle of descent of shells was small (about 5° to the horizontal) and direct hits on decks would be rare, even with the deck rolling. Since the deck was unlikely to be hit directly, its purpose was to keep out fragments of shells bursting above it.

It was also discovered that British armour piercing shells were seriously defective; intended to pass through and burst behind armour of thickness equal to their own diameter, shells would either break up or explode on impact due to their over sensitive filling (picric acid - known as Lyddite). The Royal Navy concluded from these trials that areas of thin armour were needed, above the main belt, to keep out HE shells and to initiate the fuze of AP shells hitting the side high up so that intact shells could not hit the protective deck. Most other major navies reached similar conclusions from their trials.

The exception was the USN who, in the *Nevada* class, adapted the "all or nothing" philosophy. (Fig. 7) In such a scheme of protection all available weight was put into the main belt and deck with no thin armour anywhere. It was argued that thin armour might set off a shell which if it hit thin plating only, would pass through without exploding. On the other hand, the increasing complexity of battleships meant that there were many important systems and compartments open to attack by small guns. In the close range fighting expected in the North Sea this did not seem a sound basis for protection.[15]

PROOF OF WAR

Perhaps the most important lessons of World War I was that armour was rarely attacked by shells. There was only one major encounter between battleships and even at Jutland hits on armour were rare.[6] More resources devoted to torpedo protection might have paid a better dividend.

Jutland - hits on armour

Navy	Rounds Fired*	Hits on Capital ships	% hits/ rounds	6" and above
British	4480	104	2.3	18
German	3547	85	2.4	34

* not all against capital ships.

There were significant differences in design philosophy between British and German battleships, the former having larger guns but thinner belt armour. In neither navy was there any thick, horizontal armour; protective decks were 1-2 inches thick and intended only to resist splinters. In this battle hits were scored at up to 18,000 yards to which distance shells would fall at 20° to the horizontal but, since the fuze would be initiated in hitting the top deck, and the shell would burst within 30 feet of first impact, such protection was, probably, just adequate. Of the surviving

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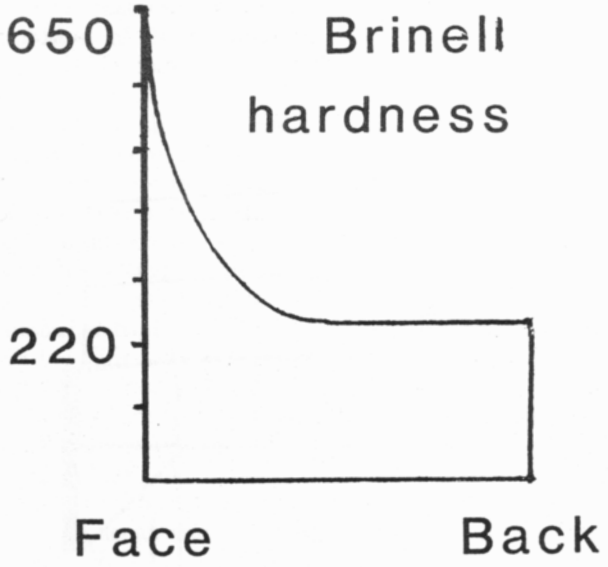

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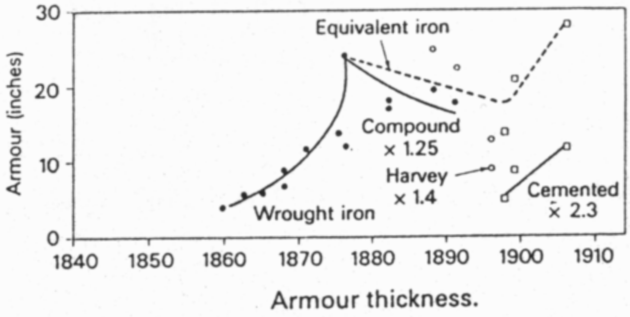

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British ships, some of them with numerous hits, only in three cases had even a splinter pierced the deck. It is possible that one or more of the battle cruisers lost by explosion of their magazines may have had a shell pass through the deck.

No German shell hit British belt armour thicker than 9 inches. Seventeen British shells hit German armour 10 inches or more in thickness, of which 7 broke up or burst without penetrating, and another 4 made a hole but the force of the explosion remained outside the ship. Only one shell functioned correctly. Even against thin armour, 6-9 inches, the majority of British shells failed as in the *Edinburgh* trial. The nose was over-hardened and brittle and the filling was too sensitive. The shell case was weak and would break except under normal impact; finally, the best procedure for batches of shells was badly planned and had little chance of weeding out defective batches.

British cordite was inclined to be unstable and ships were lost from accidental explosions. When exposed to the flash from bursting shells it would explode whereas the solventless German propellant would only burn. Defective shells nullified the British advantage of bigger guns while unstable cordite accentuated the risk from thinner armour. Ships of both navies showed an impressive resistence to shell fire, provided that the magazime did not explode. The most heavily hit ships were:

Ship	**No of hits**	**Notes**	**Date repaired**
German			
Lutzow	24	sunk	-
Derfflinger	21	in action	15 Oct.
Seydlitz	22	sinking condition	16 Sept
Konig	10	in action	21 July
British			
Lion	13	in action	20 July*
Tiger	15	in action	1 July
Warspite	15	in action	20 July

* As a 3 turret ship.

There were detail troubles on both sides such as weak turret roofs, the framing behind armour on British battlecruisers was not strong enough while German ships suffered from poor subdivision in way of their torpedo compartments and too many penetrations in their watertight bulkheads. Post war tests with armour plates taken from the *Baden* showed that British armour was about 10% more effective than German.

POST WAR PROBLEMS

It was clear that improved gunnery control would lead to fire being opened at greater range, the shells descending more steeply and hitting decks rather than sides. Heavy bombs, too, were a growing threat. Instead of a tough steel deck resisting splinters, the new requirement was for thick cemented deck armour. Since the area of the deck is much greater than that of the side of a ship, the weight of such protection was a major problem leading to very large designs in the early post war programmes. (e.g. The G3 battlecruisers of 54,000 tons with 8 inch decks.)

The Washington Treaty imposed a limit on the displacement of new battleships and also prohibited, with the exception of two RN ships, all such building for ten years. The *Nelson* had inclined side armour, 14 inches thick, to increase the obliquity of striking and to help in the venting of torpedo explosions. The deck armour was 6 inches thick. (Maximum). The extent of armour was reduced by grouping all three turrets forward. They were slow ships since weight was saved by installing low powered machinery.[17]

There was considerable debate between the wars on the arrangement of deck armour. A single thickness is more effective in resisting penetration than is the same thickness in two or more layers. On the hand, a thin deck, high up, would prevent serious damage from small bombs and would initiate the fuze of AP bombs and shells so that they would explode above the main deck. Such a thin deck could also strip the ballistic and armour piercing cap from AP projectiles, rendering them impotent to attack the main armour. A shell exploding on the thick deck could break off a scab from the back of the armour (spalling) and the USN had a thin deck below the main one to catch such scabs and splinters. British designers retained faith in a single thick deck after trying for alternatives, though the uppermost deck had to be thick or structural reasons.

It was soon found almost impossible to carry out trials of bombs by dropping them as even against a stationary target hits were rare. For example, in trials against *Monarch* in 1924, only eleven out of fifty seven bombs hit despite the use of practise bombs first to determine wind effects. Luckily, it was found possible to fire bombs against targets from howitzers. Bombs could then be detonated statically in selected positions in target ships. The armour gratings at the base of the funnel were recognised as a weak point and many trials were carried out to find a satisfactory solution. In World War II there were seventeen battleships hit by bombs with six cases of serious damage but no sinkings.

There was a particular problem concerning the exposed roofs of turrets. To withstand the oblique impact of shells it was best to use tough, non cemented armour while attack by bombs was best resisted by cemented armour. The RN used non cemented, others used cemented; since hits were few, there was no clear answer. The French *Dunkerque* suffered major damage when her cemented turret roof was hit by a 15 inch shell from *Hood*. However her sister ship *Strasbourg* was hit by a 1000 lb SAP bomb on her turret roof which was successfully resisted.

APPROACH TO WAR

During the early to mid thirties, the three remaining armour manufacturers, English-Steel Corporation, Beardmore and Firth-Brown made a number of trial plates both of thick cemented belt armour and thinner, non cemented deck plate. These were fired at with armour piercing shells and bombs respectively. As a result the depth of the hardened face was increased to about 33% of the plate thickness and at the same time the carbon content was reduced to increase the toughness. This is said to have produced armour whose resistance was equal to that of American class A armour of 25% greater thickness.[18,19] It would seem that similar advances were made in Germany.

Corresponding developments were made to armour piercing shells.

The last British battleship to see war service, *King George V*, had side armour 14.7 inches thick over the magazines (13.75 inches over machinery) and a deck of up to 5.9 inches. The side armour extended 12 feet below the design waterline to protect against diving shells. The re-armament programme in the late thirties ran into problems when it was found that many armour manufacturers had closed during the slump. After an embarrassing search, armour was purchased in Czechoslovakia and delivered days before war broke out.

It is not easy to compare the battleships built by the leading powers just before the war. Treaty limits were ignored in some countries and revoked in others. The table below attempts to give some correct figures but may still be misleading since only maximum thickness is given; the longitudional and vertical extent and the way in which thickness was reduced is not given.

The last generation

Ship / Country	Displace-ment tons	Belt Max in.	Deck max in.
King George V [UK]	35500	14.7	5.9
North Carolina [US]	35000	12	4.1
Littorio [Italy]	41400	13.8	6.0
Bismarck [Germany]	41700	12.5	4.7
Richlieu [France	37800	13.5	6.8
Yamato [Japan]	64000	16	7.5
Sovietski Soyuz [USSR]	59150	16.75	?

In the Second World War there were even fewer cases of hits on armour than the first. *Prince of Wales* was hit seven times in action with *Bismarck* and *Prince Eugen* but four failed to explode, and the other three only partially detonated; none hit the main armour. One shell, which failed to explode, killed or wounded many most of those on her bridge, highlighting a difference between RN ships and those of most other navies which had a heavily armoured conning tower to protect the command team in battle. The heavy weight, high up, was seen by the RN as an unnecessary extravagance particularly since when such protection had been provided in World War I, it had rarely been used. Overall there were thirty seven cases of damage to British battleships of which six were due to shells. The result was one sunk (*Hood*), two seriously damaged and two slightly damaged.

Bismarck was heavily hit in the closing engagement when, early in the battle a British shell penetrated the thick turret armour and burst inside. It is clear that British shells were now effective. Later in the war *Duke of York*'s shells were effective in destroying *Scharnhorst*.

During the war bombs got bigger and bigger and the thickness of armour shown on the drawing boards for future battleships grew to match; 12 inch decks were being considered. *Tirpitz* was depatched by 12,000 lb bombs against which protection was clearly impossible but even much smaller bombs could be lethal to quite well protected ships. In 1948 2,000 lb armour piercing bombs were dropped against the *Nelson* by *Barracuda* dive bombers. With a release height of 8,000 feet the first 39 bombs missed the stationary and undefended battleship but the first dropped from 6,000 feet hit, penetrated and caused very serious damage even though it was unfilled.[20]

By this time there was little suggestion of armour to keep bombs or shells out ot the ship. Protective plating on the outside was still necessary to keep out splinters from near miss explosions and cannon shell. Thick plating was also being considered for internal bulkheads to confine the effects of an explosion to a limited area of the ship.

The battleship died when its carapace became too heavy and its power to harm the enemy diminished to vanishing point. There were so few hits on armour during the two wars that one may well wonder if it was worth having them at all. The presence of armoured ships limited the freedom of action of enemy unarmoured vessels and forced him to use AP shells which, with their small bursting charges, were less damaging than high capacity shells. It would have been a very brave man, even a foolhardy one, to have decided to reduce, or even omit, armour during the design of the *King George V* in the thirties.

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PRECISION CONSTRUCTION: IRON'S CONTRIBUTION TO MODERN SHIPBUILDING

Fred M. Walker

At the beginning of the 19th century, thanks to the pioneering efforts of men like Henry Cort, John Wilkinson and David Mushet, iron was used increasingly in construction, engineering and ultimately in shipbuilding. Iron usage in the United Kingdom was quite short lived, and within shipbuilding was a mere 50 or 60 years - a half century however, that was to change the face of the industry and to pave the way for the scientific development of naval architecture and the evolution of modern shipbuilding techniques which are in use to this day, not only in the U.K. but also throughout the world.

THE AGE OF IRON SHIPBUILDING

The iron shipbuilding age in the U.K. is generally taken as the years 1830 to around 1885, the period in which this material began to dominate the output of Britain's shipyards and to become the main constructional material for all ships world wide. In the United States of America, this "iron age" is taken as being about 10 to 15 years behind the British, and was neither so dramatic nor had it such international repercussions.

The earliest recorded (and authenticated) use of iron for the construction of a ship, is the barge *Trial*, built by John Wilkinson of Coalbrookdale in 1787. It was manufactured from iron of unspecified quality, but records show that the vessel was 70ft. 0 in. long, 6ft. 8½ in. broad and in light condition had a draft of 8 or 9 inches. Full load displacement is believed to have been 40 tons in fresh water when carrying 32 tons of cargo and on a draft of nearly 4 feet. This bears out our understanding that the iron shell plates were just over 0.31in. thick and the hull had a block coefficient of about 0.86. Wilkinson built other barges, all of relatively simple design and construction, but all capable of strenuous canal work and to the best of our knowledge all with adequate longitudinal strength.

The real breakthrough in the use of iron for shipbuilding was to come in 1819 with the launch of the fast passage barge *Vulcan* for the Forth and Clyde Canal service between Glasgow and Edinburgh. This remarkable vessel built by Thomas Wilson (1781-1873) with the assistance of John and Thomas Smellie, not only instituted methods of shipbuilding that were to set the Clyde yards on their fast rise to supremacy, but also to set standards that have been adhered to throughout the world ever since. The design of the *Vulcan* has been ascribed to Sir John Robison the secretary of the Royal Society of Edinburgh, but it is known that many other notable people were consulted including James Watt (who incidentally built the Monklands Canal on which the barge was built), Professor Joseph Black of Glasgow University - the founder of modern chemistry, Vice-Admiral John Schank the noted experimenter on ship forms and a civil engineer known only as Mr Crichton. The *Vulcan* was to serve for several years as a horse drawn passenger barge taking up to 200 persons on the delightful 8 hour journey between the two cities. Ultimately she was relegated to freight work on the canal and sometimes on the River Clyde, before being broken up in 1873.

The celebrated iron steamship *Aaron Manby* was to follow only three years later and to create history by being the first iron steamship as well as being the first to make an international voyage under power. She was about 107 ft. between perpendiculars and was driven by unusual paddles known as Oldham's Revolving Oars which in turn were powered by a simple steam engine. Her construction was of interest, being temporarily assembled by Aaron Manby a Staffordshire ironmaster, then knocked down, transported in pieces to Rotherhithe on the Thames, re-erected and sailed across the English Channel and up the Seine to Paris. This is probably the first example of "knock down" shipbuilding, a skill which was developed by British shipbuilders for export work.

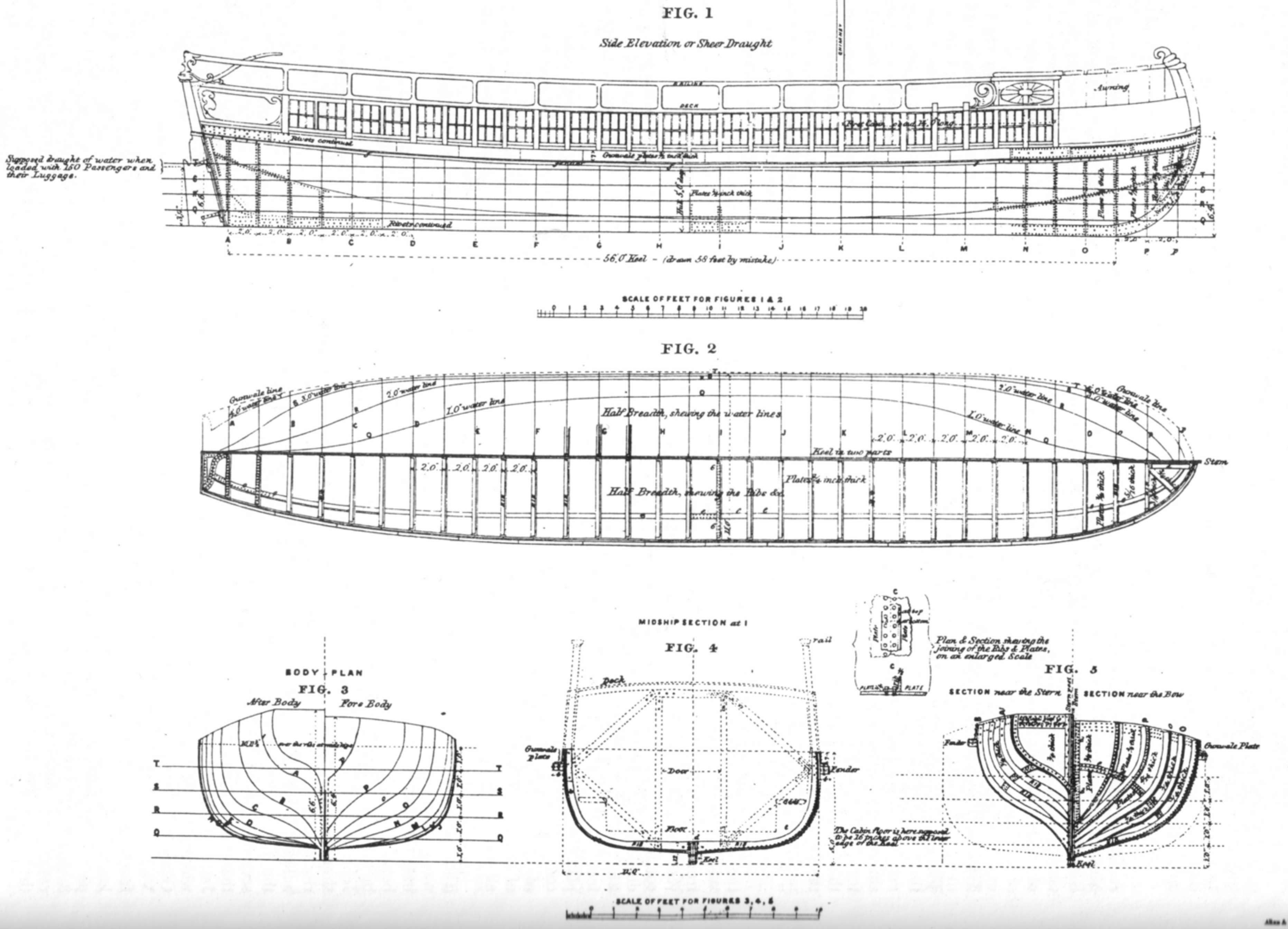
Further iron ships were to include:

1825 *Marquis of Wellesley* a twin hulled paddle steamer built at Horseley and re-erected at Liverpool.
1825 *Codorus* built at York Pa., and considered to be America's first steamship.
1827 *Aglaia* an iron paddle steamer built by David Napier and erected on the shores of Loch Eck in southern Argyll.
1831 *Fairy Queen* of 97 ft. length, built by John Neilson at Hamiltonhill, Glasgow, and then transported to the Clyde by road and launched by crane.
1831 *Elburkah* built by Laird of Birkenhead for the Niger Expedition of 1832.
1831 *Lord Dundas* by Fairburn and Lillie of Manchester and her sister ship *Edinburgh* built by Thomas Wilson for the Forth and Clyde Canal.
1834 *Garry Owen* built by Laird and the first iron ship to introduce transverse watertight bulkheads.

Once the principles of iron construction had become understood, many shipbuilders throughout England and Scotland started to build with this revolutioary material. This required retooling, retraining of staff and in the long term the setting out of shipyards in a novel and purpose built manner. Neglecting the very early "one off" iron shipbuilders, the earliest commercial constructors include:

1828 William Laird of Birkenhead
1830 * Sir William Fairbairn of Manchester
1833 Thomas Vernon and Co. of Liverpool
1834 Tod and MacGregor of Glasgow
1835 * Sir William Fairbairn of Millwall, London
1837 Thomas Wingate of Glasgow
1837 Ditchburn and Mare of London

Drawing of a Passage Boat proposed for the Forth & Clyde Canal, Decr. 27th 1816.



Allan & Ferguson lith.

1838	Barr and MacNab of Paisley
1838	Jackson and Jordan of Liverpool
1839	T.D. Marshall of South Shields
1839	John Ronald of Aberdeen
1841	Robert Napier of Glasgow
1842	Caird and Company of Greenock

This was the greatest metamorphosis in the ancient history of ship construction. It brought about unexpected social upheaval and long term technical changes that were unforeseen at he time. The most remarkable feature was the ready acceptance of iron by the shipbuilders, a situation encouraged by the rise in the demand for the product, followed by a dramatic drop in the price of iron. Major producers set up in various parts of the country, notably in the coal and iron ore fields of the Midlands, the North East of England and the Monklands district of Lanarkshire.

The Clyde in particular embraced the iron construction and by the 1860s all work on the River was with the new material, timber being reserved for small vessels and yachts. The last large wooden ship built on the Clyde was the paddle steamer *Arabia* built in 1853 for the Cunard Line - she was followed some three years later by the renowned iron paddler *Persia* for the same owners.

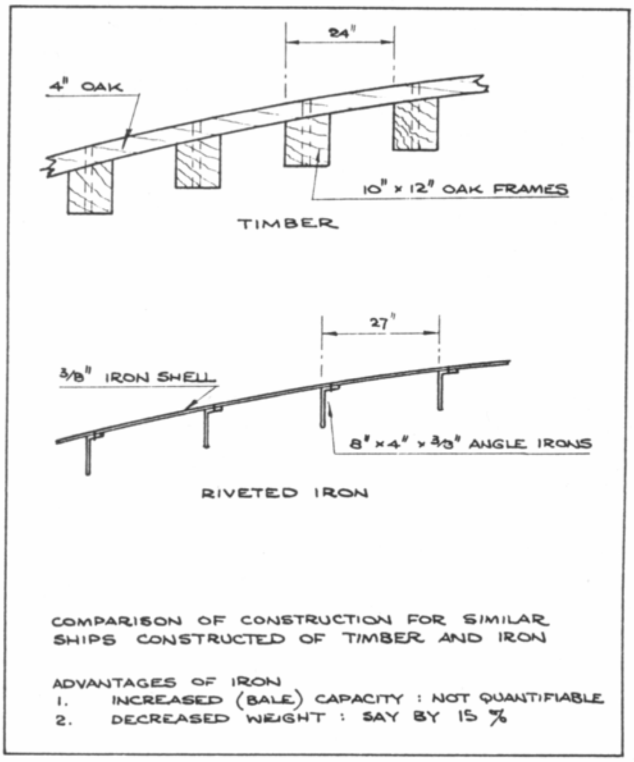
It is interesting to note that the demise of iron shipbuilding was more rapid than its beginning. High tensile steels had been introduced in 1858 by Cairds of Greenock for the P.S. *Winchester Castle* and by Laird of Birkenhead for Dr. David Livingstone's Zambesi steamer *Ma Roberts* and this trend continued with specialist ships (such as the blockade runners for the American civil war) where first cost was a secondary consideration. However the breakthrough came in 1879 when Denny of Dumbarton built the *Rotomahana* for the Union S.S. Company of New Zealand and the *Buenos Ayrean* for the Allan Line of Glasgow using mild steel. Within a decade mild steel became used universally throughout the British Isles and again the price fell. The advantages of stronger and lighter material became apparent giving ships an increase in carrying capacity of nearly 10%, and at no significant cost to the shipbuilders who were already tooled up for working in iron.

THE RATIONALE FOR IRON

The invention of iron puddling by Henry Cort in 1784 was one of the most significant events of the industrial revolution. From the shipbuilding point of view, it came at a propitious time as U.K. timber stocks were depleted and with a European raging, importing lumber had become more than difficult. Just before Trafalgar, the Royal Navy had over 800 ships - all built of wood, and supported by the Royal Dockyards, organisations with an insatiable appetite for timber of all kinds. Two short term solutions to the timber problem were available; first the importing of softwoods both as lumber and also as completed ships with their holds loaded with the same commodity for immediate resale. Secondly the building of ships in teak and other tropical hardwoods in countries friendly to the interests of Britain.

On the technical front, timber vessels had some almost insurmountable drawbacks including limitations to overall length (approximately 80 m.) through reduced longitudinal strength of the ship caused by local weaknesses at the points where the timbers were connected by spikes, nails and treenails. This shortfall in length leads in turn to reduced capacity, low speeds, and ships that are labour intensive and inefficient. The close spacing of large wooden frames further reduces the "bale space" or capacity for cargoes, and all in all the wooden built freighter of the 1800s was a structure costly in both timber and shipwright manhours.

In a short period of time, iron enabled larger vessels to be built, and this in turn with steam machinery or in some cases more efficient sailpower, ensured that speeds could be attained that were economically sound. Integrated and fully planned construction conferred strength and thin shell plating with widely spaced frames and stiffeners allowed the maximum quantity of cargo to be carried.



COMPARISON OF CONSTRUCTION FOR SIMILAR SHIPS CONSTRUCTED OF TIMBER AND IRON

ADVANTAGES OF IRON
1. INCREASED (BALE) CAPACITY : NOT QUANTIFIABLE
2. DECREASED WEIGHT : SAY BY 15 %

Wood compared with iron.

PROBLEMS ENCOUNTERED IN EARLY IRON SHIPBUILDING

From the outset, the principal problem affecting the shipbuilders was the low and variable quality of puddled iron. This became evident in different ways, first by minute interstices and laminations which made it necessary to cut plates to small size to be assured of their integrity - in the case of the *Vulcan* they were as small as 24 in. wide, and secondly by the size limits imposed by the normal methods employed in the puddling process.

As the years passed and other processes came on stream the size of plates increased and by 1860 had reached 16ft. 0in. wide by 3ft. 0 in. or say 5 x 1 m. This made great savings in labour and also in the weight of overlaps and rivets, all leading to a stronger ship with greater natural integrity. It is interesting to note that the *Great Britain* had variable frame spacing in order to accommodate an infinite number of plate sizes each being made individually before being delivered to the Bristol shipbuilding site.

Until the 1830s the shipbuilders had no recourse to machine tools and all cutting and boring was by hand. Bending was by hammering after heating, and all profile sections were manufactured by blacksmiths from heated bar on the anvil. The process was costly in time and backbreaking labour. In 1839 the invention of the steam hammer by James Nasmyth and the subsequent work of the machine tool builder was to change the face of the industry - and indeed even more was to create a massive new industry in the West of Scotland for the manufacture of shears, guillotines, bending rolls, straightening mangles and other implement for which there was a ready market both at home and overseas.

In passing, two other difficulties encountered by the new iron ships should be mentioned: first the phenomenon of underwater fouling, a matter only resolved satisfactorily within the past few years, and second the problem of magnetic deviation which was overcome by the combined efforts of the Admiralty Compass Committee, Sir George Airy and Sir William Thomson (Lord Kelvin). These however were not difficulties encountered directly on the building berth.

THE PROCESS OF SHIPBUILDING IN THE EARLY YEARS

Neglecting barge shaped vessels, which can be built with a minimum of design work, in all other cases it is essential to draw a full lines plan or sheer draught of the vessel to be constructed. From this the offsets or tabulated internal dimensions can be measured and the moulds and scrieve board prepared. This ensures a ship that is built in exactly the manner shown on the drawing board.

Ship plans (as we know them) have been in use for well over 300 years and one must presume that many 17th and 18th century ships were built as designed. However there is no question that in the case of many wooden ships the ultimate shape was influenced by the shipwright in charge for a variety of reasons:

1. The original lines plan was not properly "faired" or drawn with sweet lines which tallied correctly in all three views.
2. The lines plan neglected to detail the bearding and similar lines and possibly also the varying angles or bevels on the face of each frame.
3. On preparation of a full size mould a shape would be found that defied building into the ship at full size. In such cases the men on the building berth would be forced to "fair by eye".

In the case of iron construction inadequacies as in the above list were unacceptable, as all parts had to be manufactured by hand, fitted together with bolts and finally riveted before completion. For this reason the ship plan was a vital tool giving the exact shape of every plate and frame, and also the bevel of each frame (which can vary along its length). Once the plates, frames and other members were cut to size, they had to be drilled for rivet holes and then bent to shape as required. All this entailed the development of codes of working practice which ensured accuracy and minimised the risk of misunderstanding on the fabricating shop floor.

The longevity of iron was noted upon favourably by shipowners, and to this day examples of early 19th century vessels are still to be seen - although very few of them are working now. Despite any cost increases over wooden ships, iron ships quickly came to favour with their better return on capital through higher speed, larger cargo deadweight, improved reliability and a longer life span on which to amortise the original costs.

REFINEMENTS IN SHIP DESIGN

The *Vulcan* of 1819 was remarkable in that it defined so many aspects of iron (and steel) construction without the benefits of previous experience. The bar keel was a massive plate formed of thinner plates laminated by riveting, and it conferred great strength on the hull. The method of framing did not alter much from the systems then in regular use on wooden ships - at least not until one looked more closely and appreciated the principle of what is now called a sectional profile, or angle iron. This innovation allowed for good connections to the shell plating, while conferring the great strength of a deep web to the shell without impeding too much the capacity of the hull. Flush butted plates with close riveting were incorporated - a practice that was seen right through to the last days of riveting in the 1960s. The most unusual part of the Vulcan design was the vertical 24 in. shell plates running up from frame centre to frame centre; this practice quickly changed to horizontal straking as the size of plates increased and shipbuilders found the practice more economical and simpler to work.

Sir William Fairbairn throughout his long and well documented career drew the attention af engineers to the benefits of proper girder construction in ships' hulls. This means that the advantage of a top deck, intermediate decks and double bottom structure could be incorporated in the design giving a hull that has vastly improved longitudinal strength over all previous ships. From this emanated considerable original thinking and in the course of time, shallow draft vessels were built using shade and awning decks for strength in place of the old fashioned hogging trusses.

The skills of riveting and caulking (that is the sealing of the riveted seam by a percussion tool) were appreciated from the earlist days and it was not long before this concept was used to prepare internal waterproof tanks for the carriage of water ballast. Such ballast is cheap, can be stored in spaces that are otherwise useless and can be taken aboard at any time - even at sea! This invention gained great credibility by the success of the shipbuilders of the North East of England in incorporating such tanks, often known as McIntyre Tanks, from 1852 onwards in their great fleet of North Sea colliers which require accurate trimming to handle the bridges of London in varying states of the tide and in different conditions of loading.

With the coming of scientific naval architecture and ship design in the middle of the 19th century, methods of construction and rigorous dimensional control were in force in shipbuilding. This enabled the two sides of the business, namely design and production, to work together to make the industry admired world wide.

CONCLUSION

The skills of ironworking created not only a craft, but also an industry in which iron, one of the world's commonest elements became used regularly to manufacture complex shapes for seagoing vehicles. It is a mark of the success of a host of great men - like Robison, Wilkinson, Fairbairn, Brunel, Napier, Kirkaldy, Laird and others that the skills of this great industry were formed in the two old Kingdoms of Great Britain, and now are to be found in every corner of the world. The improvements in ship safety - going by sea is probably the safest form of transport - is another reason to give credit to the pioneers of early iron shipbuilding and also to subsequent generations of shipbuilders and naval architects.

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Historical Metallurgy Society Conference: Metals in Shipbuilding. March 1990.

THE EARLY HISTORY OF MANUAL METAL ARC (MMA) WELDING IN UK SHIP CONSTRUCTION

G.S. Barritte

INTRODUCTION: The history of the welding industry is essentially confined to the 20th century, indeed its true commercial life span lies within two generations. The heart of the industry is in the welding of steel, so it is natural that key heavy industries, such as shipbuilding, have shaped and prompted developments.

THE EARLY HISTORY

Kjellberg (1907) and Strohmenger (1911) can be regarded as the forefathers of the modern welding industry (Flintham 1984) establishing patents in Sweden and the UK respectively for the manual metal arc process. By the end of the First World War the technology was sufficiently advanced to allow the first structural use of MMA electrodes for shipbuilding in the UK. This was the construction of the all-welded seagoing barge AC 1320, a 240 ton vessel built at Richborough in 1918. An extract from the Times in July of 1918 stated:

"Though the process itself is not new, as certain auxiliary work has been done by electric welding in the past, considerable developments have been made in the last twelve months and this is the first time that a vessel has been produced entirely by this method . . . It is computed from results obtained on this experimental vessel and other Admiralty work that a saving of 20% or possibly 25% could be effected in time and material".

1920 heralded the construction of the first all-welded ship to Lloyds rules - *The Fullagar*. This was fabricated by Cammell Laird using Quasi-arc MMA electrodes and is illustrated in figure 1. The welding supply industry was now well established with several firms having manufacturing plants to produce MMA electrodes of general low metallurgical quality. In parallel, similar constructions were being carried out in Scandanavia (fig.2).

Subsequently, 1933 saw the construction of the *Peter G Campbell* at the Swan Hunter Yard, a 1620 ton tanker and the first ship specifically designed for welding. Formal standards were now available for MMA electrodes, indicative of a general understanding of welding technology and acceptance by the main insurance and classification societies eg. Lloyds. The manual metal arc process was clearly offering the shipbuilding industry three key opportunities viz.

1. Flexibility.
2. Major weight saving in comparison with riveted constructions.
3. Improved structural integrity.

The growth of the commercial consumable supply industry is reflected in archive records of the AWR and subsequently MWP company records. These, for the period 1918 to 1949, show a rapid increase in the tonnage of MMA consumables, as illustrated in figure 4.

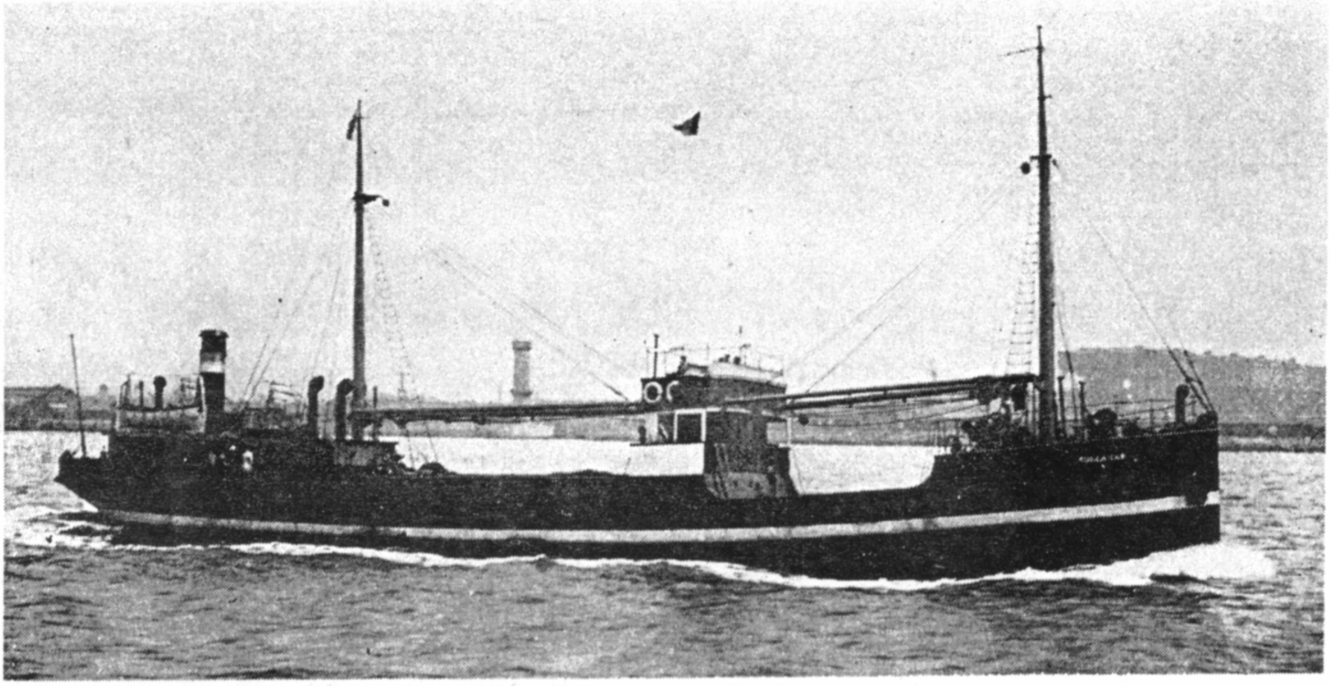
The phase "the welding of liberty ships" has haunting memories for both the shipbuilding and the welding industry in the 1940s. Fortunately, the common misconception that the dramatic and catastrophic brittle failure of these and similar ships was due to welding has long been displaced (Acker 1954; Wright 1953). The Admiralty Ship welding committee reported that "welding as a process for building ships has been entirely vindicated. Given sound design, good workmanship and tough steel, the reliablitiy of welded ships is beyond question". It seems appropriate, therefore, to illustrate the brittle failure of an ALL-RIVETED ship (fig 3), particularly in a paper on the history of welding.

By the beginning of the 1950s the clear commercial advantages welding was offering the shipbuilding industry were well documented (Mellanby 1948).

METALLURGICAL HISTORY

To investigate the metallurgical structures produced by early MMA consumables, two commercial consumables produced by MWP Ltd during the Second World War were studied (fig 4). Samples of the autowound "OVERHEAD" electrode were located at the Waltham Cross Research and Development Department and the plain extruded electrode "VODEX" were considered. This latter consumable has survived to the present day unchanged and is now an industry standard. For the welding expert, the silicate systems used for manufacture bear the distinctive trade mark of the Joseph Crossfield Company, Warrington, and are still used to this day.

3.2 mm samples of the "OVERHEAD" electrode dating circa 1943 were welded in the downhand position using AC current at 100 amps. Sections were prepared for optical microscopy and examined after etching in a 2% nital etching solution. The resulting microstructure is illustrated in fig. 5 which shows a mixture of phases not untypical of a modern general purpose E6013 type electrode!



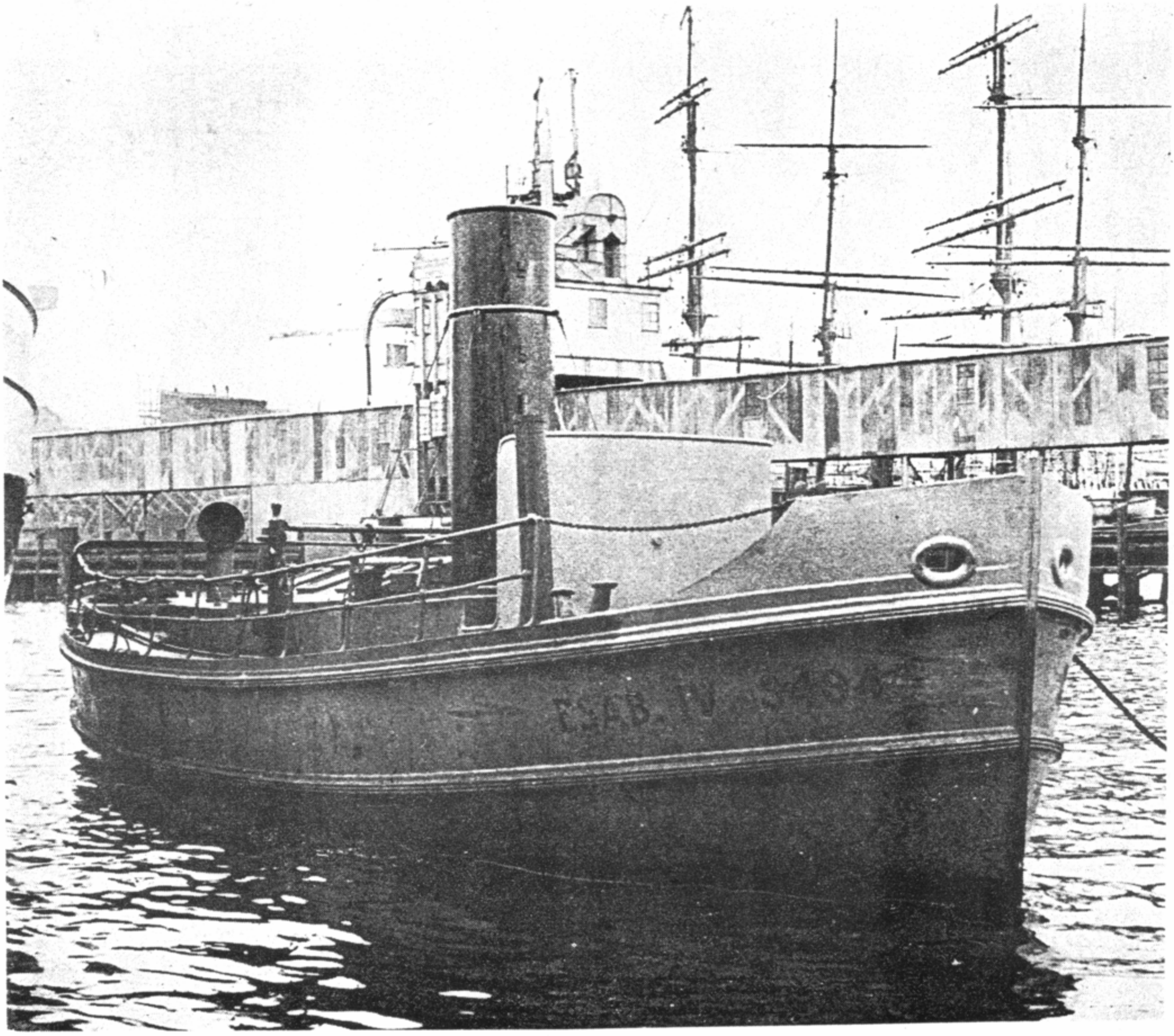
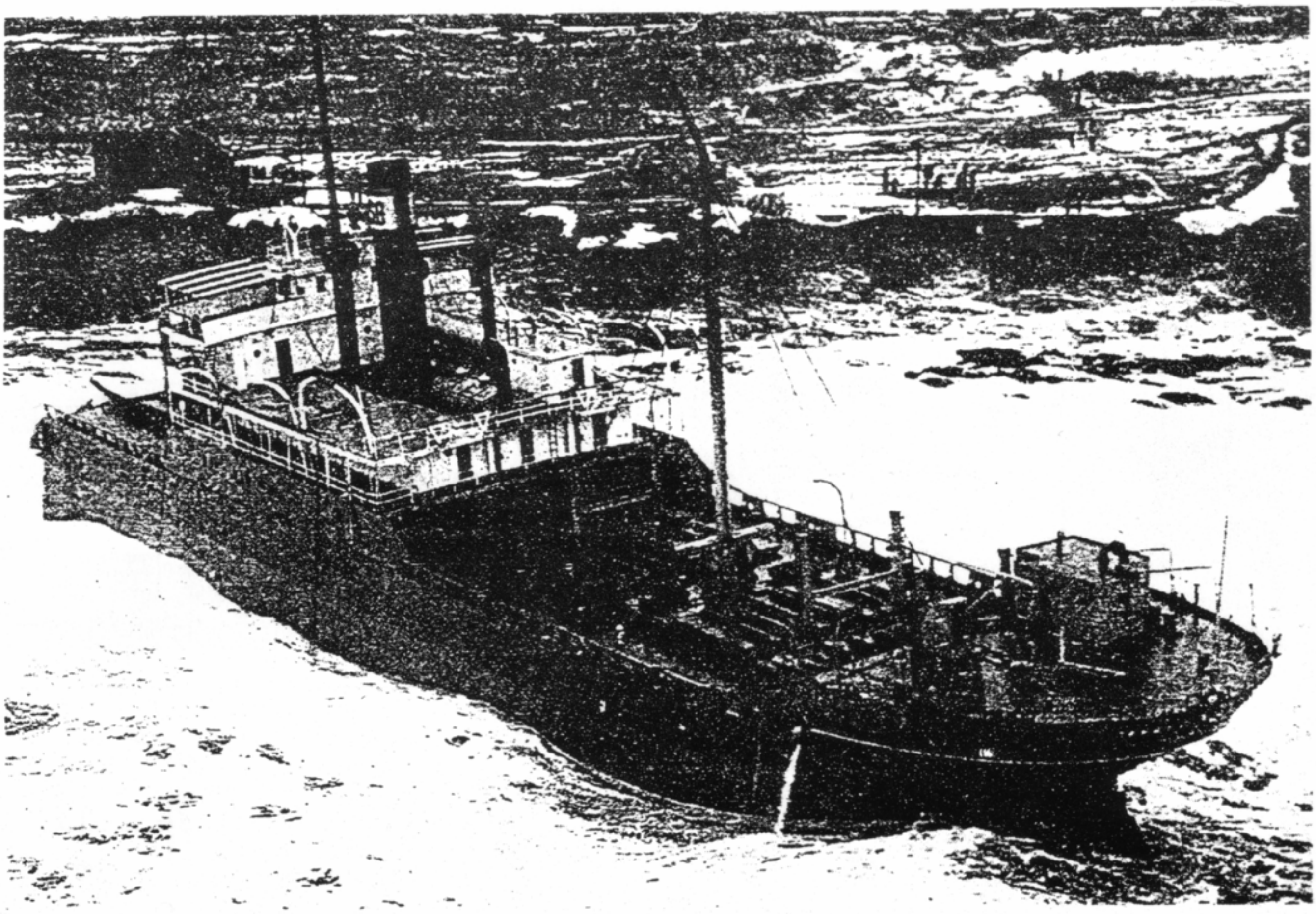


Fig. 1 (top) The first all welded ship built to Lloyds' rules.

Fig. 2 (bottom) Its Scandinavian equivalent.



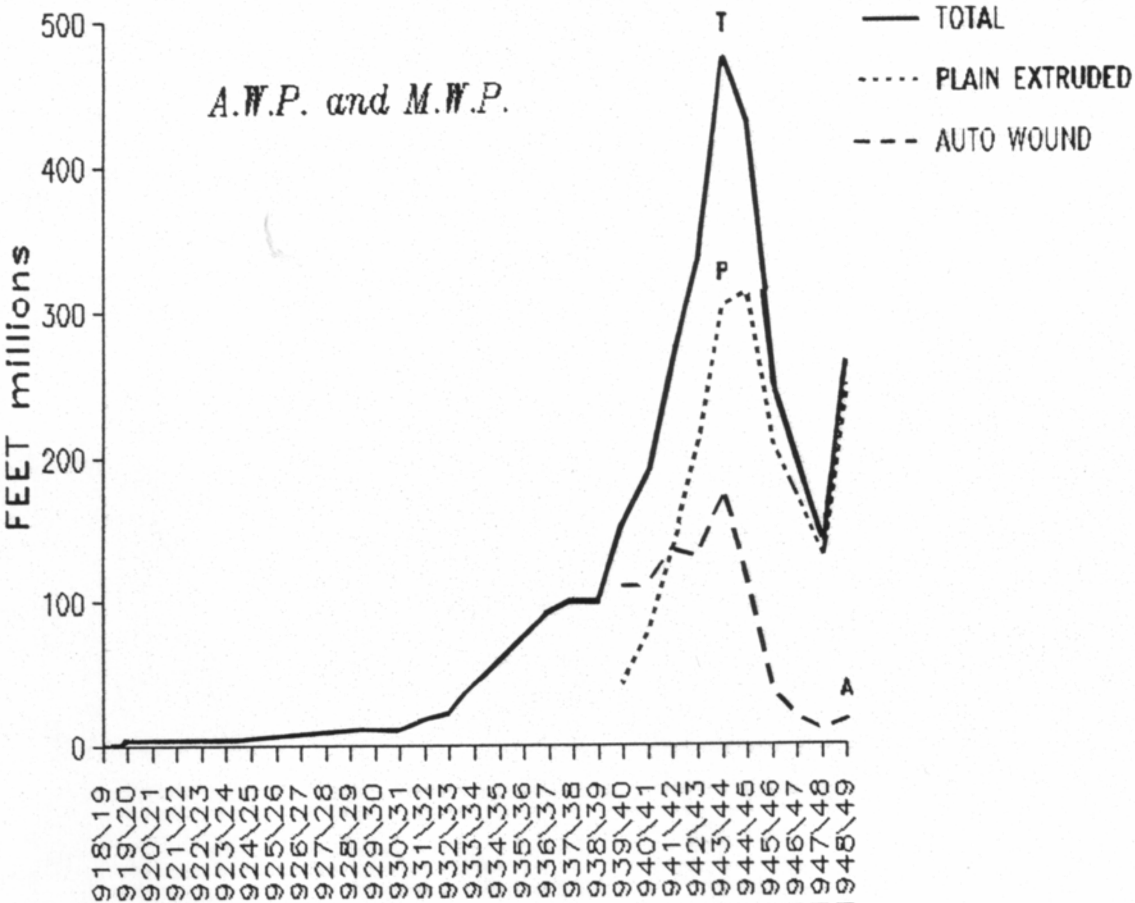


Fig. 3 (top) Brittle fracture of the all-riveted ship ***Oakley L Alexander.***

Fig. 4 (bottom) Production of MMA electrodes.

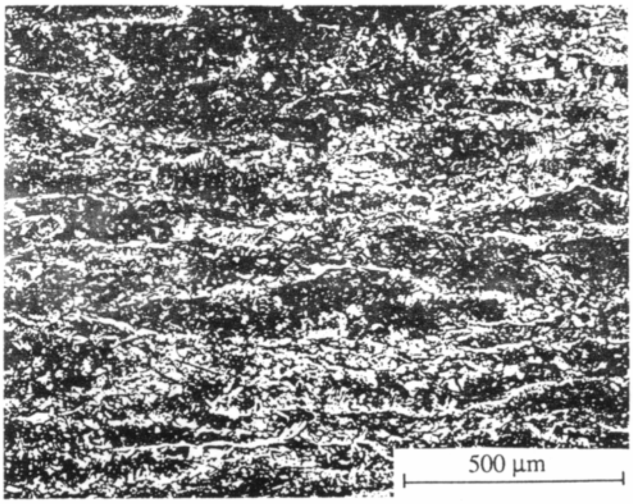


Fig. 5 The microstructure of a weld deposited using overhead electrodes produced in 1943.

SUMMARY

The MMA welding process has been the flexible friend of the shipbuilding industry. Sadly however, whilst the process has contributed significantly to both the birth and the formative years of welded ship construction, it has unwittingly aided the demise of the UK shipbuilding business. Failure to mechanise and move to more productive processes in the 1960s and 1970s are,in part, factors leading to the rapid shrinkage in shipbuilding in the UK.

History will record the following epitaph:-

MMA WELDING - UK SHIPBUILDING
BORN Circa 1904
MARRIED 1918 in Liverpool. After a long happy marriage
the couple are now living in
semi- retirement.
In hindsight, they should have divorced in
1960.

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A METALLURGIST'S VIEW OF THE HISTORY OF THE MARINE PROPELLER.

A.R. French

In the development of the marine propeller from the simple designs of the early days, to the highly developed designs of recent years, the designer has had the leading role, with his highly mathematical skill, in handling a subject often more in the field of aerodynamics than that of hydrodynamics. Probably it is he who should write the history of the marine propeller; but it would probably be more suitable for presentation to members of the Institution of Naval Architects than to metallurgists. A paper entitled "Progress in Marine Theory, Design and Research in Great Britain", was presented by Professor L.C. Burrell in 1964,[1] a leading authority in the field.

However the achievements of the designers would not have been possible without the contribution of many metallurgical developments, from the early introduction of the high tensile brasses (then known as "manganese bronzes") to the more recent high strength alloys. It is these with which this contribution will be concerned.

EARLY HISTORY TO 1900

Probably the history of the marine propeller should open with a reference to the "Archimedes Screw", and its use by the ancient Egyptians to raise water from the Nile. It is said that the early Chinese, as well as others through the ages, propelled small craft fitted with propellers, by manpower. A propeller was fitted to a French submarine used in the American War of Independence. There were many proposals in Europe for the use of the screw propeller during the eighteenth century, and in 1787 a steam propelled boat was driven by a primitive propeller. At the beginning of the nineteenth century came the paddle-wheel - the first in Scotland in 1802 - but in the early 1830's when steam and paddle-wheels were being used ancillary to sail, it was being said that steam would never take the leading role. During the opening decades of the century, numerous experiments were made with propellers made to various designs in available materials. Among these was one, three turns of an Archimedes screw. As a propeller it was quite inefficient: but there came the day on which the vessel unexpectedly leapt forward to proceed at a considerably increased speed: it was found later that the propeller had shed half of its length. It was Francis Pettit Smith who invented the propeller, a shorter Archimedes screw, fitted to his ship, the *Archimedes*, 237 tons (fig.1), which was the first ship to cross the Atlantic entirely propelled by screw propeller, in 1839. Close behind, in 1843 came Brunel's "iron" ship, the *Great Britain* (fig.2), fitted with a propeller weighing four tons, 15ft.6in. diameter, six blades, said to be the forerunner of all ships of significance afloat today, which crossed the Atlantic in 1845. Steam might have been said to have arrived in 1840, but the argument for propeller versus paddle-wheel continued and in 1849 a trial was arranged between two warships, identical, save that one the *Niger*, had a propeller while the other, the *Basilisk*, was equipped with paddle wheels. Attached stern to stern the *Niger* towed the *Basilisk* by 1½ knots. It could be said that by 1850 the principle of the screw propeller had been established.

By 1875, all-steel ships with cast steel propellers were crossing the Atlantic at 16 knots. While cast steel was used for ships in which high performance was the primary consideration, for other ships the much weaker cast-iron was used. The consequence of low strength was that sections of the blade roots had to be much more bulky, therefore the efficiency of the propellers was considerably reduced. Because of the high rates of corrosion and erosion of cast steel propellers they had to be replaced after two to three years.

Competition to carry the Royal Mail and for the "Blue Ribband" of the Atlantic had been joined by 1886. Warships of high speed were also required, but the only high-strength alloy available for propellers was cast steel. While for merchant ships, engaged in commerce, crossing the Atlantic to and from a home port, where spares could be stored, short propeller life could be tolerated; for warships spread around the globe it would be very different. Other materials than steel or cast-iron with which the Navy would have been familiar at the time were the tin bronzes, but these were no stronger than cast-iron and quite unsuitable for making large castings.

The first "manganese bronze" was patented by P.M. Parsons in 1876, and in 1882 the Manganese Bronze and Brass Company was set up to make propellers and supply ingots in the alloy. The alloy had been derived from an established wrought brass, Muntz metal, 60/40 brass, made resistant to sea water by the inclusion of 1% tin. Iron and manganese were introduced into the cast alloy to refine the grain and to improve the strength. A manganese bronze of different composition was introduced by J. Stone and Company, then a long established company who among other things had supplied tin bronzes to the Royal Naval Dockyard at Deptford for many years, and had been making cast iron propellers since 1880: "Stone's Bronze" was registered in 1889. Their alloy, also an alpha-beta brass, also resistant to sea water by the inclusion of tin, contained the new commercially available aluminium for added strength, and again iron and manganese. These two companies would go down in the history of marine propulsion as those who introduced the bronze propeller to the world. At that time any name to associate the alloy with brass would have been most inappropriate: for

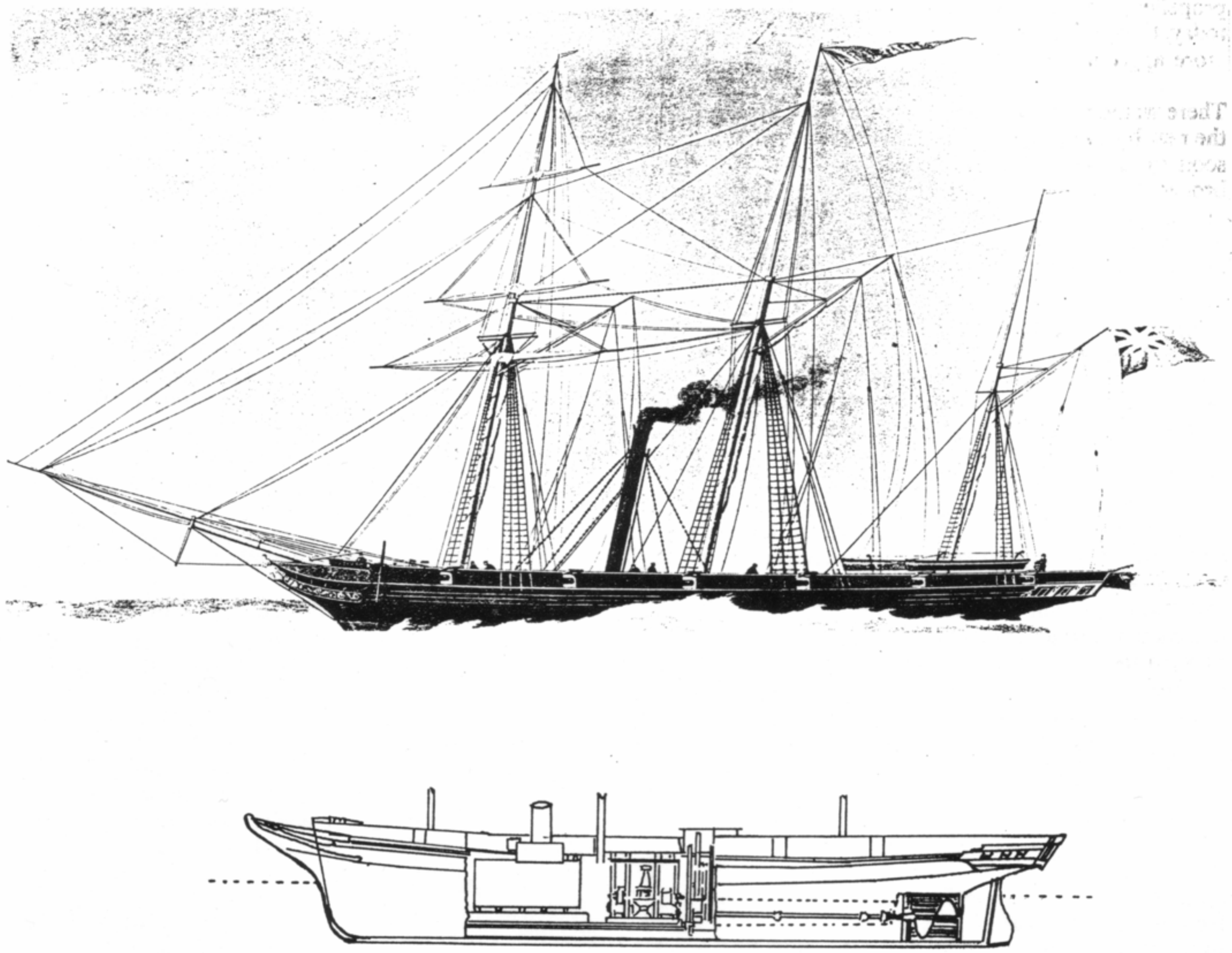


Fig 1. (top and centre) The *Archimedes*.

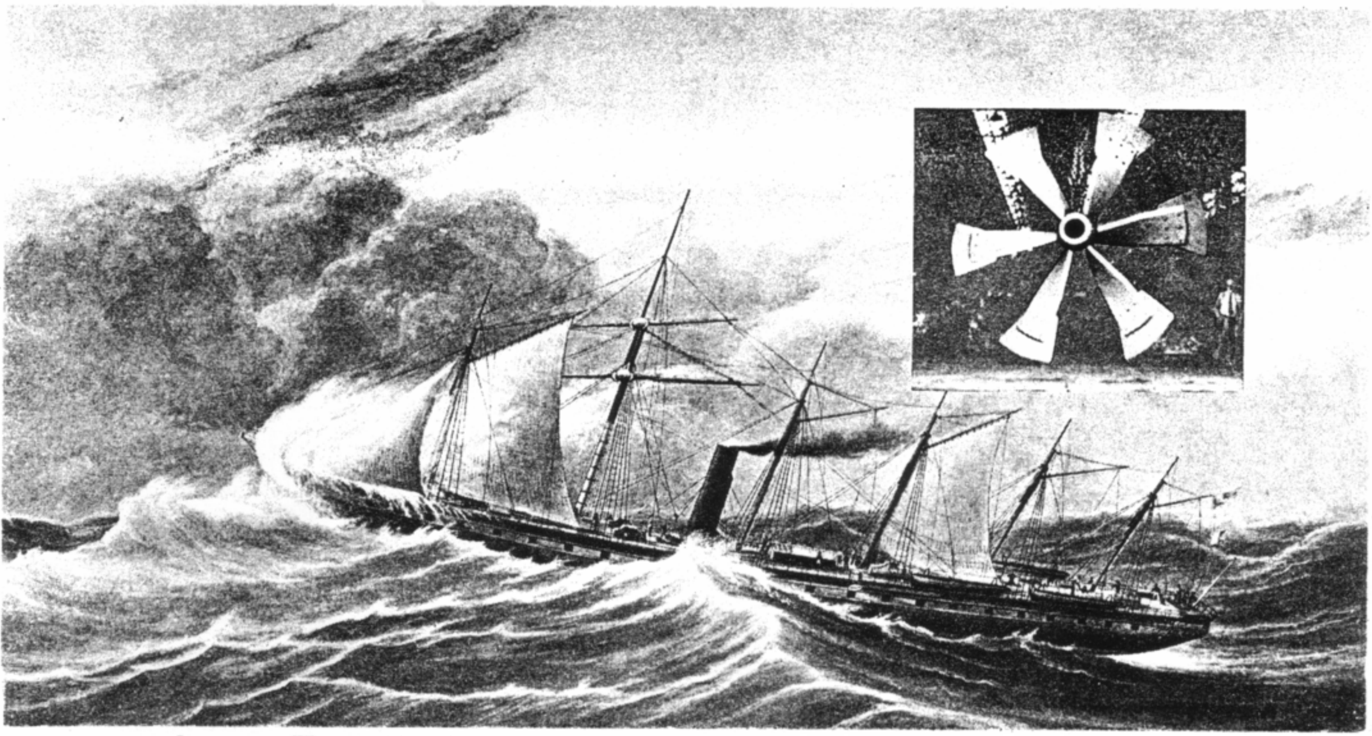


Fig 2. (bottom) The *Great Britain* and propeller.

propellers "manganese bronze" remains the name in use today, though for other applications "High Tensile Brass" is more appropriate.

There would probably have been little difficulty introducing the new bronze propellers to the Navy: the Admiralty were soon to introduce their own specification for manganese bronze, based on the Parsons' alloy. However, being based on copper, the new alloys would have been expensive when compared with steel, and would need selling to the owners of merchant ships. In 1900 it was shown that while a bronze propeller weighing ten tons would cost £1150 it would last the life of the ship, possibly twenty years or more, whilst a similar propeller in steel would cost £450 but last only two to three years. Taking into account dry-dock costs, losses due to the ship being out of service, over fifteen years there would be a saving of £10,600, by using a bronze propeller.

The introduction of the manganese bronzes must have caused many problems to the foundryman of the day: the alloys behaved very differently from copper-based alloys well known at the time. Steps had to be take to minimise the formation and entrapment of oxide particles, and contraction during solidification would have had to be made good by the use of feeding heads; rod-feeding as used with cast iron was employed. However by 1890 the more serious casting difficulties had been surmounted. For ships driven by reciprocating steam engines the same alloys remained in use well into the future: alloys of a similar type still remain in use today.

1900 - 1939

In 1902 the steam turbine had arrived: the first ship driven by a steam turbine to cross the Atlantic did so in 1905. With increased speeds and greater loading on the propellers evidence of cavitation erosion appeared. Changes in propeller design were introduced and stronger manganese bronzes developed for use with steam turbines. It was in these early days of developing stronger alloys that it was discovered that all-beta alloys were liable to stress-corrosion cracking: both companies supplied propellers, which rapidly failed when the ships to which they were fitted put to sea.

In 1906 Guillet [2] published his work on zinc equivalence. Between 1929 and 1934 Bauer and Hansen [3] published their work on the ternary systems of various elements with copper and zinc. In 1935 A.J. Murphy [4] then Chief Metallurgist with J. Stone, published work correlating mechanical properties, chemical composition and microstructure of the manganese bronzes.

The manganese bronzes afforded a particular advantage in that when propellers made in them were damaged they could be repaired without great difficulty. Propeller blades are liable to damage in service, particularly due to striking floating debris or brushing against quays. Such damage can take the form of anything from small deflections at the blade edges to major bending; from small notches to large pieces gouged out. More serious damage can set up such vibration as to make it necessary for the vessel to reduce speed, while even the most minor damage can lead to significant further damage due to erosion. Small deflections can be dealt with cold, while larger bends can be straightened after heating the blade to change the normal alpha-beta microstructure into the readily hot-worked all beta form. Pieces broken out can be replaced by "burning" in new pieces. The metal can be welded; in early days gas welding techniques were used, later, manual-metal-arc, with aluminium bronze electrodes. It was important, however, always after heating to ensure that the microstructure was restored to the alpha-beta condition.

Most ships had single screws situated behind the hull, the stern post, in the aperture in front of the rudder. When greater power was required than could be absorbed by a single propeller, two or four propellers were used, on each side of the hull at the stern. Most propellers consist of three to six blades evenly spaced around the central boss, set at the required pitch. Early blades were of simple ovoid form, with the flat helicoidal "faces" (those surfaces facing aft) and rounded backs (those surfaces facing forward). It was in 1865 that the principles of propeller design were first set down by Scott Russell. In the same year by Rankine and later by Froude in 1889, early attempts were made to treat the subject mathematically. Early propellers were normally made by the engine builders, and other than boring the boss, were left unfinished.

It was with the coming of the steam turbine that pitch was varied across the blade face and at the end of the First World War, that rounded backs were replaced by the aerofoil shape. The designer, given details of the ship for which a propeller was required, its engine, and hull form, had to determine pitch, diameter, number of blades, blade width and thickness, the shape of the sections and the form of the blade outline to achieve the maximum performance. For the determination of blade sections a cantilever theory was set down in 1911 by Admiral D.W. Taylor which, with refinements, has been used until recent times. The material

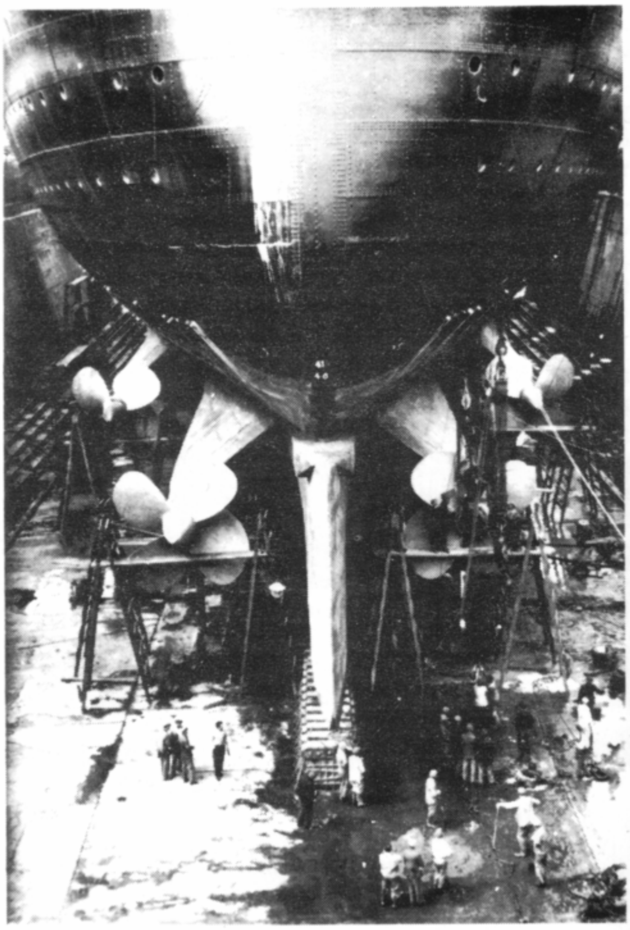


Fig. 3 Heliston Propellors on the RMS *Queen Mary*.

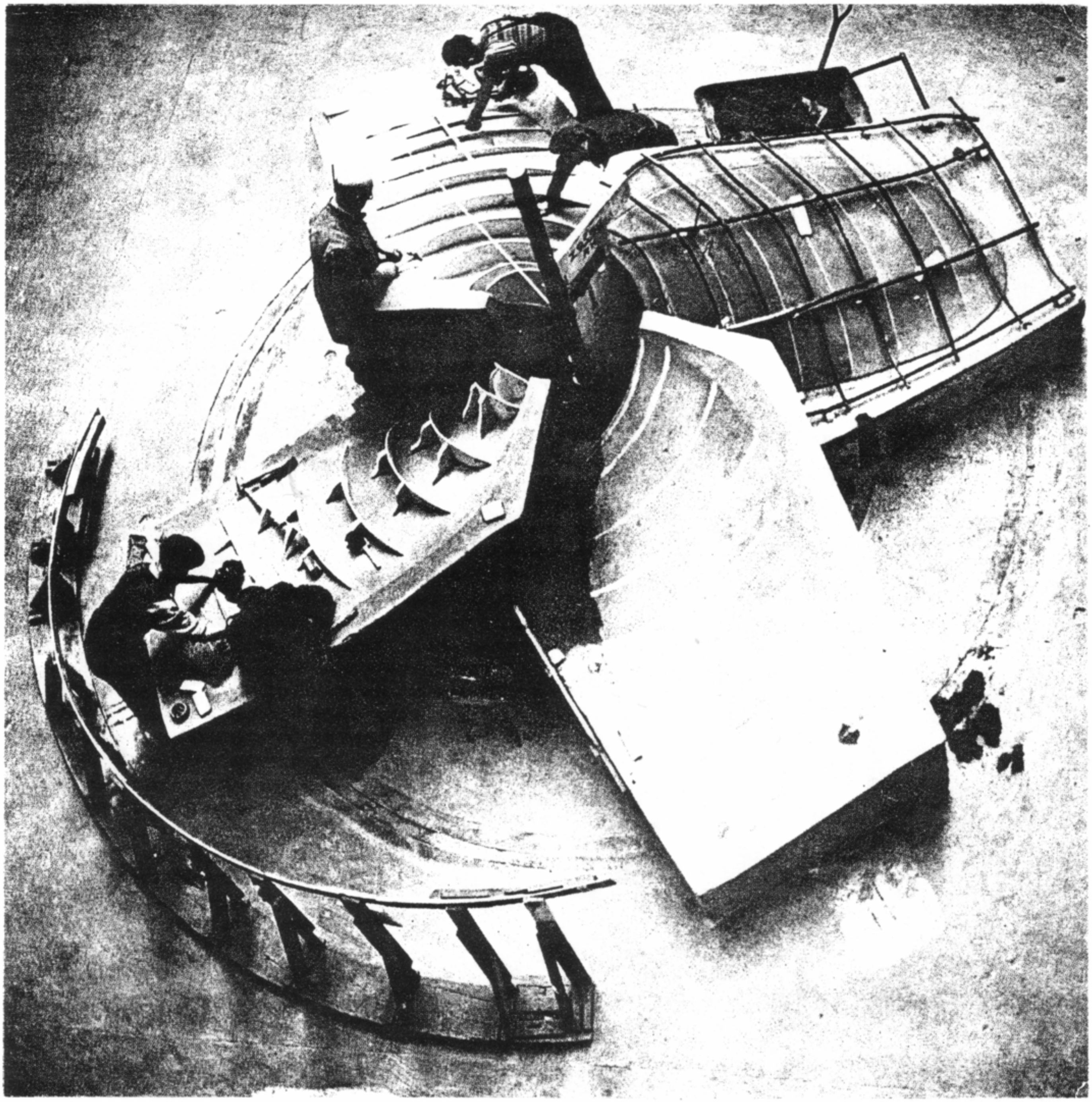
was represented by its tensile strength, and a large factor of safety, of the order 13, was included.

Each propeller would be unique to the ship for which it was designed. The designer has had to progress by building on experience on a more or less empirical basis, not knowing the actual stresses to which the propeller would be subjected in service.

During the First World War the demand for propellers increased enormously, for merchant ships and particularly for the wide variety of naval ships from the small minesweepers to the large battle- cruisers and battleships of the day. It was in 1916 that J. Stone built a large plant, foundry, machine shops, and finishing shops specifically and solely for the manufacture of propellers.

Considerable progress was made in the development of design after the manufacturers had set up their own well-equipped design organisations for research and development, to offer a service to their customers, who quickly appreciated the advantages of having their propellers designed as well as made by the specialist companies. This led in due time to the manufacturers offering their own designs for "maximum service performance" under the names Heliston and Scimitar. A peak in achievement before the Second World War might be regarded as having been reached when the largest ship in the world, the R.M.S. *Queen Mary*, 81237 tons, 1020 feet long, crossed the Atlantic in 1936 to win the Blue Ribband at 30.63 knots (later, in 1938, 31.64 knots): the vessel was equipped with four Heliston propellers, the largest then ever made, 30 tons finished weight each (50 tons cast weight), each capable of transmitting 50,000 shp (fig.3).

Fig. 4 (below) Preparation of a mould for a propeller. Each blade illustrates a different stage in construction.



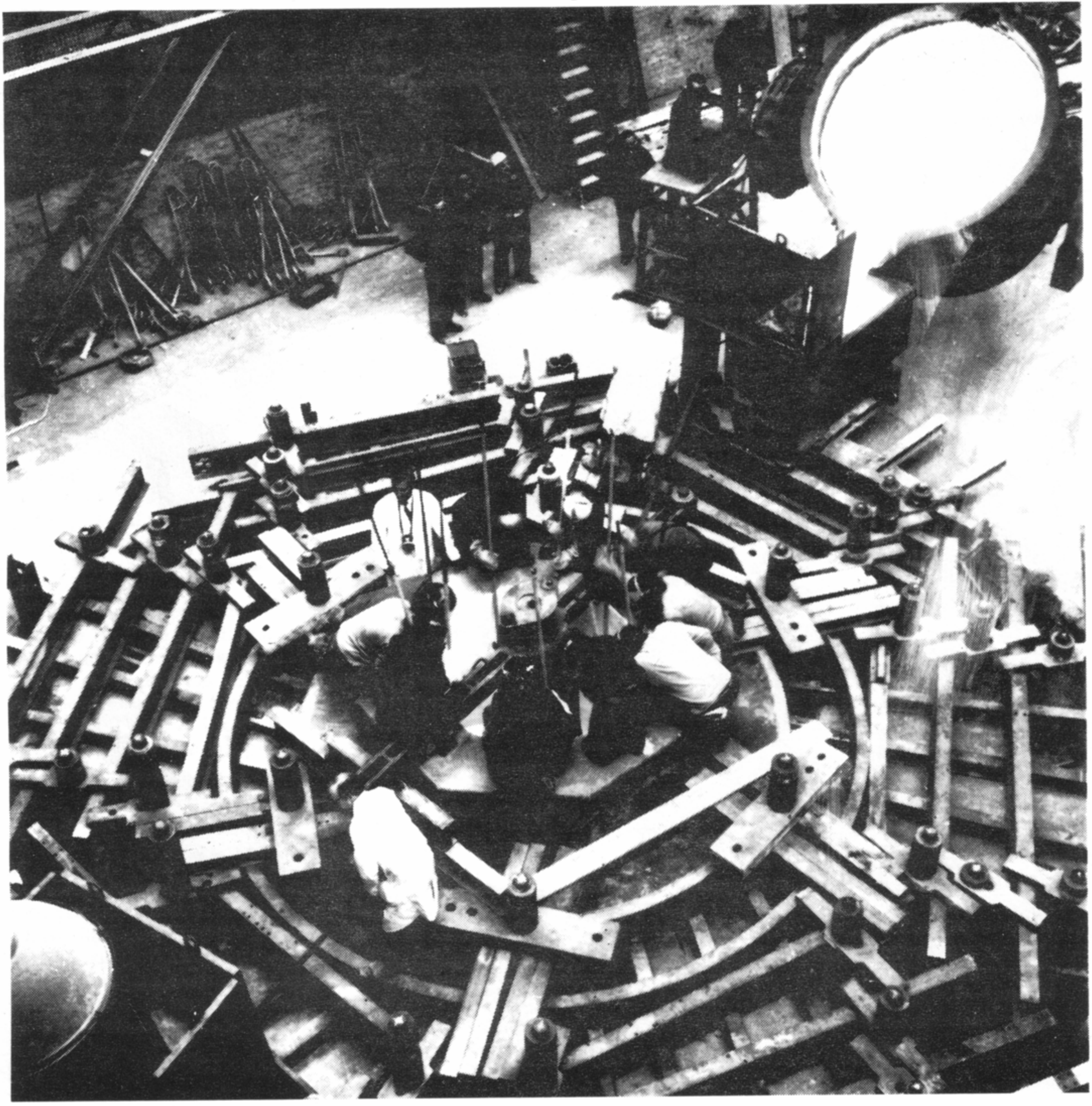
Up to the time of the war one major event occurred: a giant step forward in manufacturing methods. In early days when larger propellers could not be cast in one piece, known as "solid" propellers, boss and blades were cast separately and bolted together, "built-up" propellers. An advantage was that in the event of damage, only the damaged blade need be removed to be replaced by a spare; the disadvantage was that where the blade joined the palm, by which it was attached to the boss, the width of the cross-section was limited, and to maintain the required cross-sectional area, the root section had to be thicker, and efficiency thereby impaired. As manufacturing facilities were improved more propellers were made solid.

Until 1937/8 moulds had been constructed on heavy iron base-plates using bricks and loam. The completed mould could be very heavy, up to 80 tons or more, and had to be lifted to a drying stove before being secured and buried in sand in a pit, for safety purposes, and casting.

In 1937/8 procedures were greatly facilitated by the introduction of the "Randupson process" which made use of a moulding medium consisting of washed graded sand, Portland cement and water in a mixture, underhydrated so that the mould could be broken up after casting and the sand-cement reclaimed. Wooden shuttering was used to contain the mixture during moulding, and removed after the mould had set hard. After a period of pre-heating with hot air the mould could be closed and secured for casting, on the moulding site.

The mould was constructed, using a heavy iron-base plate fitted with a vertical central spindle. To form the surface against which a blade face would be cast, a striking bar was moved up and down the spindle at one end, while following a rail at the other end, set at the required pitch, to form a helicoidal surface: any variations in pitch required over the surface were then introduced by hand using templates.

Fig. 5 Pouring a large propellor, early seventies.



Next, skeleton patterns defining the blade sections were fixed in appropriate positions at set radii along the surface and infilled to form the blade pattern and define the blade back surface. Then the mould top was constructed, suitably reinforced for lifting after setting, to remove the pattern work and finish and dress the blade surfaces. The boss wall was formed with a second striking board as the moulds for the blades were built up (fig.4).

A bottom pouring system was used, under the boss, with one or more cross runners set under the blade parts of the mould, which also carried the down-sprues. Before casting, the running box(es), with valve(s) to regulate the flow, would be set in position, a feeding head-ring placed over the boss space, and finally a core secured into place (fig.5).

Manganese bronze was made in crucible furnaces from virgin metals, and large pigs poured and analysed. These, with runners and risers from previously made castings, were top charged into reverberatory furnaces, together, to provide the required charge weight. The furnaces were coal-fired up to the war , but later converted to oil. The melting operation took place overnight. Before reliable pyrometers became available, about wartime, the temperature would have been checked by the shop foreman disturbing the metal surface and observing the degree of zinc flare.

The charges were constructed so that all elements apart from copper and zinc were at the required percentages in the charge; however zinc was left slightly short. Samples were taken,and as chemical analysis would take too long, special fracture, later metallographic, tests [5] were made for correction of the composition by adding spelter. When temperature and composition had been adjusted the metal was tapped into one or two ladles, as required.

After cooling down, the casting would be fettled, lined out, and put into a special horizontal boring machine to part the head and to machine the tapered bore and the forward and aft ends of the boss. Next a key-way would be slotted into the bore, to match with a corresponding key-way cut into the tapered end of the shaft, for a key to be hammered home, after the boss had been pushed by impact onto the shaft. The blade and boss surfaces were finished by chipping, grinding and polishing to within the required limits for dimensions, surface finish, and static balance.

After inspection, and acceptance of the metallurgical test results, chemical and mechanical, by the Classification Society's inspectors the propeller was ready for dispatch to the shipyard.

1939 - 1945

During the war years there was a great increase in the volume of propeller production: large numbers of propellers of all sizes, to meet the requirements of the Royal Navy, as well as the considerable number for ships being built in British yards.

In America, for the first time anywhere, all-welded ships were built, using fabrication and sub-assemblies for minimal times on the slip-ways between keel-laying and launching, with an average time of 40 days (even 10 and 4 were achieved). These were the "Sam" and "Liberty" ships which played a significant role in the outcome of the war. Of course the original propellers were made in America, but after the war in this country, replacements were required in such quantities that solid patterns, cast to facilitate production, were kept in continuous use for the production of a propeller every 2 or 3 weeks for a considerable period of time.

The design of Naval propellers was very different from that of propellers for merchant ships: service requirements were different. While merchant ships are required to spend as much time at sea as possible, operating at design speeds, warships spend much more time in port or cruising but are required to be capable of spells at the highest possible speeds, when speed could be crucial. The slimmest possible root sections of the blade, compatible with security, for maximum possible speed, were important. So, when it was disclosed, after the war that being unable to obtain supplies of copper, the Germans had turned to stainless steel, with a much higher tensile strength than that of manganese bronze, the propeller designers were very interested.

1945 - ONWARDS

The demand for high strength alloys was such that response was essential. Stainless steel was the only known material available which could meet the requirement. But to be suitable for marine propellers a new material would require more than high tensile strength. It would be required to be suitable for the production of very large castings, for being machined, chipped and ground, for finishing to dimensions with close tolerences, and for polishing to a high degree of surface finish; for resistance to corrosion and cavitation erosion in sea water; to be readily repaired, including by welding. It was realized that there would be difficulty in finding a stainless steel to meet all these criteria as well as a copper-based alloy might meet them.

Additionally, the expertise in design and manufacture of the propeller manufacturers had been developed and gained with copper-based alloys; their extensive heavily capitalized specialist plants were suited to the manufacture of propellers in copper-based alloys rather than stainless steel.

Both companies had maintained well equipped metallurgical laboratories and manganese bronzes had been exhaustively researched during the period since they had been introduced. Those alpha-beta alloys with the highest tensile properties, useful in general engineering, were not suitable for marine propellers. So a different copper-based alloy was urgently required - the obvious choice, an alloy with suitable properties, might have appeared to be aluminium bronze, save for the necessity that it should be suitable for the manufacture of large castings, which it was considered not to be, at that time.

When the J. Stone metallurgical laboratories had been set up in the early years of the century, as many other laboratories at the time, it had been involved in work on new alloys using the newly (commercially) available aluminium with copper. It was in 1912 that a laboratory melt was made of the alloy to be known forty years later as BS1400 AB2. In the years between the wars they and a few other specialist foundries sought markets for this type of alloy, in the cast and wrought forms, to take advantage of its high strength and resistance to corrosion. They also had to develop techniques in the foundry to handle this alloy which so readily absorbed gas during melting and formed oxide films during melting and pouring. By war-time in 1939 a casting weighing a ton was still exceptional, so the Stone organization considered there would be small probability of success in endeavouring to develop techniques to make possible the casting of large propellers in this alloy: they preferred to endeavour to develop a totally new copper-based alloy for this purpose. Their competitors took the opposite view. Work was put in hand and as it happened eventually both were to be successful. However,in the meantime, when the first ships built post-war had been in service for a few months, a number suffered propeller failures.

Single screw ships were affected, and if one ship of a series of sister ships was affected, all would be. No particular manufacturer was involved, most were. Blade fractures had the appearance characteristic of fatigue. Propellers sectioned for thorough metallurgical examination were found to be up to the expected standards of quality and free from significant defects. There was no doubt that all the failures had been caused by corrosion-fatigue.

In the normal course of events a screw rotating in the variable wake behind a hull might have been expected to be subjected to cyclic stresses, but in these cases there would appear to have been factors at work which had caused accentuation of these stresses sufficiently to cause failure.

However many people at the time, some 40 years ago, found it difficult to accept that fatigue failure could occur under conditions of cyclic stress other than about a mean-stress of zero, while in propellers clearly the mean-stress would be highly positive. In a similar way there were those who did not recognise that the tensile properties disclosed by test-pieces taken from sound material in heavy sections, could reasonably be expected to be lower than those in lighter sections, or in the test bar cast for inspection purposes.

With the return to peace-time conditions, and to competition in the commercial world it was clear there would be a demand for larger and faster ships. Twin-screw ships not only cost more than single-screw ships but are less efficient, so single-screw ships would be favoured. Cyclic stresses would be increased with more heavily loaded propellers, so resistance to corrosion-fatigue would in the future be a crucial factor. This effectively ruled out any consideration of stainless steel, for the resistance to corrosion-fatigue of the types of stainless steel which might have been considered, was no better than that of manganese bronze, which was relatively poor.

When the work had been started to find a new copper-based alloy, a number of families of alloys had been examined and concentration became centred upon alloys of copper and aluminium, finally with manganese. Comparative tests were conducted between these alloys, the established alloys, and the complex aluminium bronze: the determination of properties in light and slowly cooled sections; resistance to corrosion in the sea, and using spinning discs in the laboratory; resistance to cavitation-erosion, by loss of weight, using magneto-striction equipment; resistance to fatigue and corrosion fatigue, using the Wöhler equipment, long established for this purpose in the laboratory, with single point loading, 0.375in. diameter specimens, at 3000rpm, with of course zero mean stress. In later years equipment was to be devised to fatigue test specimens 3 in. diameter, cast so as to have structures simulating those in the heavy sections of propellers, and operating under a high mean stress, as does a propeller in service. The resulting alloy, called "Novoston", was considered to be superior to aluminium bronze for making propeller castings; it had a liquidus 100°C lower than the aluminium bronze and was less susceptible to the absorption of gas when melted in reverberatory furnaces, and to the formation of oxide films.

In the development work in handling the aluminium bronze, it was the melting in large reverberatory furnaces that was the major problem. As the metal absorbed gas so readily a technique was developed for degassing the alloy by bubbling nitrogen through it until the gas content had been reduced to a critical level, assessed by studying the solidification of a sample under reduced pressure.[7] An important step forward became possible when the Junkers furnace manufacturers, who had developed small mains frequency furnaces for the cast-iron industry, made a unit suitable for melting aluminium bronze. A method was contrived to attach the small melting unit to a large tilting refractory-lined bath capable of holding 18 tons of metal. The first furnace to this design was installed in 1956. With two of them, 36 tons of metal could be melted electrically. The alloy had all the other desired properties, and the alloy "Nikalium" was established.

After 1945, with the dawn of the era of air travel, while there were to continue to be luxurious cruise ships, the era of international competition in the building of large, fast passenger ships had passed. It was foreseen that future developments would be related to larger and faster merchant ships. There would continue to be smaller ships and ships of modest performance for which there would remain a market for manganese bronze propellers. But the demand for larger and faster ships for handling bulk cargoes, containers, liquid gas, and oil, grew at a surprising, even phenomenal, rate. With the new high strength alloys, research and development using increasingly powerful computers, tank testing, and work at the universities, designers were able to produce the highly developed designs required for maximum possible performance. These developments were given impetus when in 1963 the two original specialist companies merged, and putting together the wealth of experience each had acquired over the years, and taking the best features from each of the "Heliston" and "Scimitar" designs, introduced the "Meridian" design.

An important conclusion reached by the designers was that for very large ships, for maximum propulsive efficiency, the propeller should be as large as permissible and revolve at slow speed. In anticipation of requirements during the seventies the largest and most well equipped specialist manufacturing plant in the world was set up. Importantly a mains-frequency electric furnace of 40 tons capacity by Birlec was introduced to bring the capacity for electrically melted metal up to 100 tons, with a considerable capacity in reverberatory furnaces in reserve. At the time the 40 ton furnace was the largest mains-frequency furnace in the world for melting non-ferrous metal: 2700 kw, capable of melting 4 tons per hour.

Developments in many aspects of foundry technology were introduced into production methods. For example the designs of running systems and feeding heads were no longer based on experience; expanding running systems were introduced and all dimensions could now be calculated. In the laboratory X-ray spectrography was

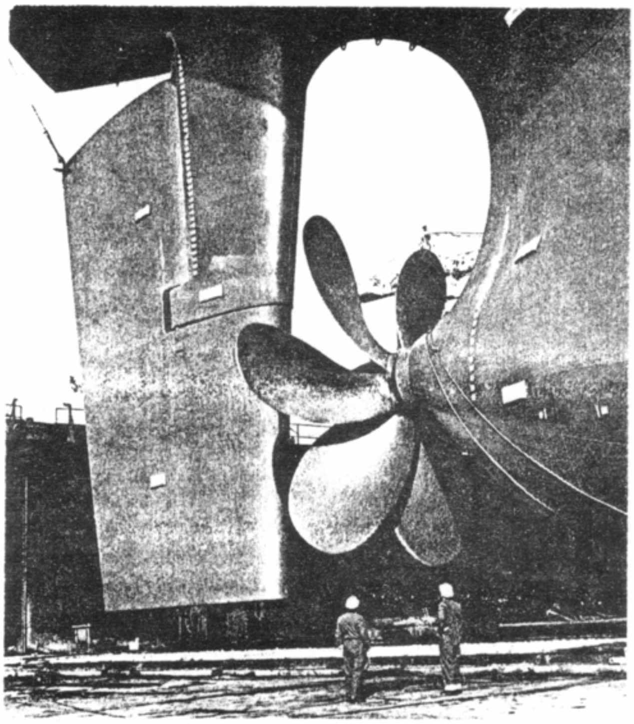


Fig. 6 The then largest propeller in the world, cast in Nikalium for the *Joannis Coloctronis,* in 1975.

introduced to replace the earlier tests for the speedy analysis of the melts before casting.

For a long period during the seventies the regular production of propellers of finished weight around 70 tons, cast weight 100 tons, was maintained. Among these the largest in the world at the time 72.4 tons, 9.4m. diameter, for an oil tanker of 386,000 tons dw (fig.6) and another 70 tons, 11m diameter for a vessel of 352,000 tons dw. In 1970 current trends at the time led to speculation about the possibility that one day a tanker of 500,000 tons or even 1m. tons dw might be built and a study was made of possible methods of propulsion. Serious thought was given at one time as to how a propeller of finished weight 100 tons, cast 140 tons, might be made.

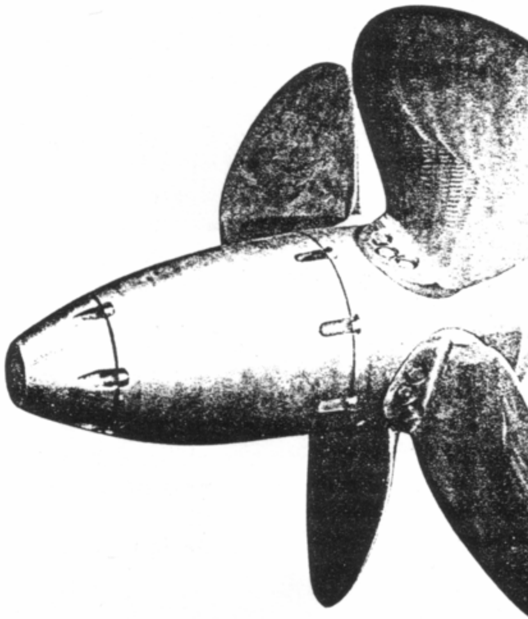


Fig. 7 A controllable pitch propellor (1968).

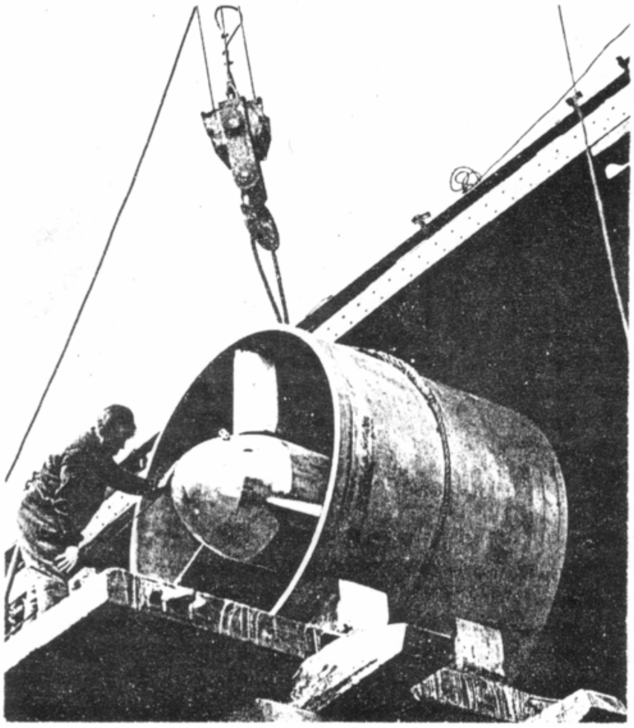


Fig. 8 A bow-thruster for the *Queen Elizabeth* (1969).

An interesting development which took place at this time arose from a problem with the development of fatigue cracks initiated at the corners of key-ways in the shafts of high powered single-screw ships. It was overcome by the introduction of new techniques for fitting propellers to shafts: the key and key-ways were omitted and a greatly improved interference fit achieved using hydraulic pressure to force the boss sufficiently on the the shaft.

As early as in 1845 the idea of a propeller working in a tube had been conceived and various experiments based on the principle followed. However it was not until 1925 that Kort revived it by developing a propeller working in a short nozzle, to channel the varying wake behind the ship and thereby to improve efficiency. The principle worked particularly well with tugs and trawlers, vessels which had to tow heavy loads. Similarities in the conditions have more recently been seen in some large single-screw ships with large heavily loaded propellers and a number of these have been fitted with nozzles to improve efficiency in propulsion.

Probably the most important type of propeller for special application today is the Controllable Pitch Propeller, the C.P.P. (fig.7). It is one in which the blades can be rotated about their axes to change the pitch, so that with the engine at constant speed, from full-ahead to full-astern can be achieved with instant control, from the bridge. Applications for this type of propeller can be found on ships which are required to operate under two different sets of conditions, for which propellers of different pitches ideally would be selected. For example, a tug to proceed at a good speed to an emergency and then to tow a heavy load; a trawler to go to and from the fishing grounds at speed and when there to tow a heavy trawl; a submarine submerged and on the surface. Probably to assist in manoeuvrability, is the main use today. With a single screw it serves this purpose but with twin screws, as on a cross-channel ferry, which spends a high proportion of its time manoeuvering in confined spaces, the C.P.Ps. are invaluable.

Related to this is the "Bow-thruster" (fig.8). Two ordinary small propellers or one C.P.P. set to operate athwart ships in the bows facilitates nudging into, or away from, the quay; useful for the cross-channel ferry, or for docking a very large ship.

Of course propellers were developed in countries other than Britain. In the U.S.A. for example considerable progress was made during the early decades of the last century, and commercially successful small screw driven steamers were in operation there in 1836. However the outstanding achievement of the period was that in Britain by F.P. Smith. During the latter half of the century the Germans were prominent in their success with transatlantic liners.

As the years went by propeller manufacturing industries were set up in many countries. Companies in N. America supplied the domestic market. But the centre of the shipbuilding industry was Europe, particularly Britain, by far the largest shipbuilding nation in the world. British propeller manufacturers supplied most of the propellers, although there were two other major companies in Holland and Germany.

British influence spread world wide into many countries, with manufacturing companies in some; leading manufacturers from the Eastern Bloc countries, Russia and Poland, came for know-how and expertise.

However even though during the seventies with the rapid growth of the shipbuilding industry in the Far East, and the corresponding decline in Europe, there was inevitably a reduction in demand for propellers for "new building", and the investment of over a century in research and development, in design, metallurgy, manufacturing techniques, with a modern plant continued to prove invaluable as new markets were developed.

ACKNOWLEDGEMENTS

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APPENDIX - Typical Propeller Alloys

Composition	1	2	3	4	5	6	7
Cu	56	60.9	61.1	62.5	75	79.75	
Zn	41.5	35	34.5	32.4			
Sn	1.0	0.5		0.5			
Al	1.4	2	2	8	9.5		
Fe	1.0	1.0	1.2	1.2	3	5.0	
Ni					2	4.5	
Mn	*	1.2	1.2	1.4	12	1.25	
Zn equiv.	45	43	44	43	-	-	
Typical Mechanical Properties							
0.1% P.S.S						[*0.2% P.S.]	
t.s.i.	14	12	15	16.5	20	17.5	29*
TS t.s.i.	34	33	34	36	44	43.5	44
El.%	25	28	25	28	28	25	20
Melting Range:							
	All between		860- 880°C	950- 990	1055- 1030		
Typical Microstructure							
alpha %	15	35	25	35			
Fatigue in 3% NaCl							
10^8 revs	5.4	5.4	5.4	5.4	8.0	9.1	5.0
Cavitation rate of loss							
mm^8 /hr	3.2	3.2	3.2	3.2	1.4	1.1	2.6

* originally permitted, but used in practice only as a deoxidant.

Manganese Bronzes - High Tensile Brasses
1. Original Parsons alloy
2. Stone's bronze
3. Early alloy for higher strength
4. More recent alloy for higher strength
5. Novoston
6. Nikalumin
7. 13% Stainless steel

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TECHNICAL STUDIES OF IRON ARTIFACTS FROM DWARKA (MAHABHARTA PERIOD) INDIA

O.P. Agrawal, Hari Narain, Jai Prakash, G.P. Joshi

Abstract: The metallographic and other scientific studies conducted on three completely mineralised iron nails indicate that the Dwarka (Gujarat State) artisans were familiar with the smelting of iron ore, and able to produce impure wrought iron in the Mahabharta period, possibly around 1500 - 1200 B.C. Investigation of these artifacts, however, indicates that their technology was in the preliminary stage and they did not know how to carburise and purify wrought iron. It is also revealed that the smiths did not use meteoric iron for these nails.

INTRODUCTION

The archival records of the sunken ships or submerged ports indicate that the the world's earliest tidal dock was built at Iothal during 2300 B.C.[1] Although India played a vital role in the Indian Ocean very little is known about the adventures on the sea and in shipbuilding. The National Institute of Oceanography, Goa undertook the marine archaeology project to investigate the history of maritime trade, shipbuilding and cultural migration in India. Under this project the marine archaeological investigation and the survey of the submerged port of Dwarka (N.W. Coast, Gujrat State), (figs. 4, 5) indicated that the famous city of Dwarka, which was once the capital of Lord Krishna, submerged in the Indian sea many centuries ago. The recent on-shore and off-shore exploration at Dwarka and Bat Dwarka, conducted by the teams of marine archaeologists from the National Institute of Oceanography, Goa, have found archaeological remains dating possibly around 1500 - 1200 B.C.[2], roughly the time when the battle of Mahabharta is supposed to have taken place.

Some iron nails were found along with a conch shell seal, black and red ware, and red lustre ware. Three iron nails (fig 1) were received by the National Research Laboratory for Conservation of Cultural Property, Lucknow for preservation and technical studies. The details of these nails are given in the Table.

These nails were examined with the following main objectives:

i) To know their fabrication techniques
ii) To know whether meteoric or smelted iron was used for their fabrication.

METALLOGRAPHIC EXAMINATION

Two nails, Nos. Fe 179 and Fe 180 had less deposition, nail No. Fe 180 was complete in shape but No. Fe 179 had been reduced to half the length. The nail No. Fe 181 was almost completely covered with silicious materials and small shells etc. As it was difficult to take a sample at this stage, all the nails were mechanically cleaned and the deposition layer was scraped with fine chisels and watchmaker's tools to the level of the bare mineralized metal. (fig 2, Table). Very small sections were cut from these nails with a Buehler Low Speed Isomet saw and embedded in a thermoplastic resin and prepared by following the standard metallographic procedures. Details of these cut sections are given in the Table, below. The depth of the cuts was not more than 10mm. Samples from the core and the corrosion products were also taken for analysis by emission spectrograph and X-ray diffraction. After cutting it was revealed that all the objects were completely mineralized (mainly iron oxide) and cut sections after polishing revealed the presence of one or two tiny metallic crystals. It is difficult to make sound scientific observations on such corroded materials, but a study at higher magnification can help in detecting the carbide structure.[3,4,5] This technique was utilised for the studies of these corroded objects. Etching was done with 2% and 5% Nital (nitric acid in alcohol) and acid mixture

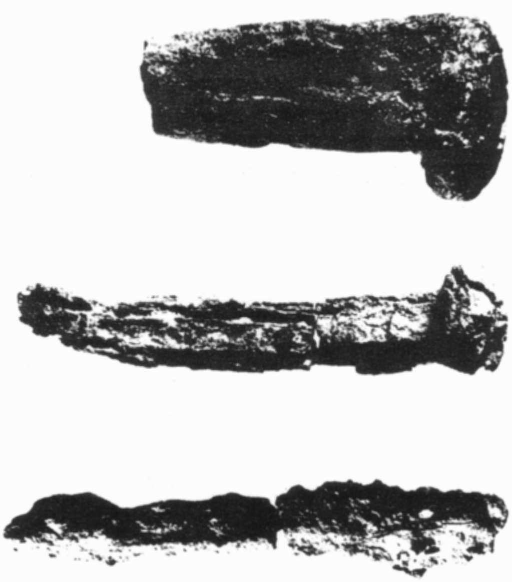


Fig 1. Nails 179, 180, 181 - as received

Fig 2. With metal bared.

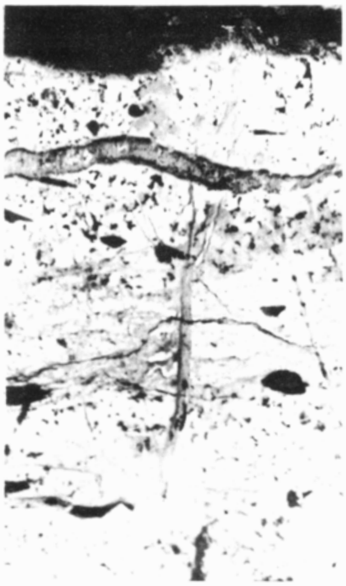
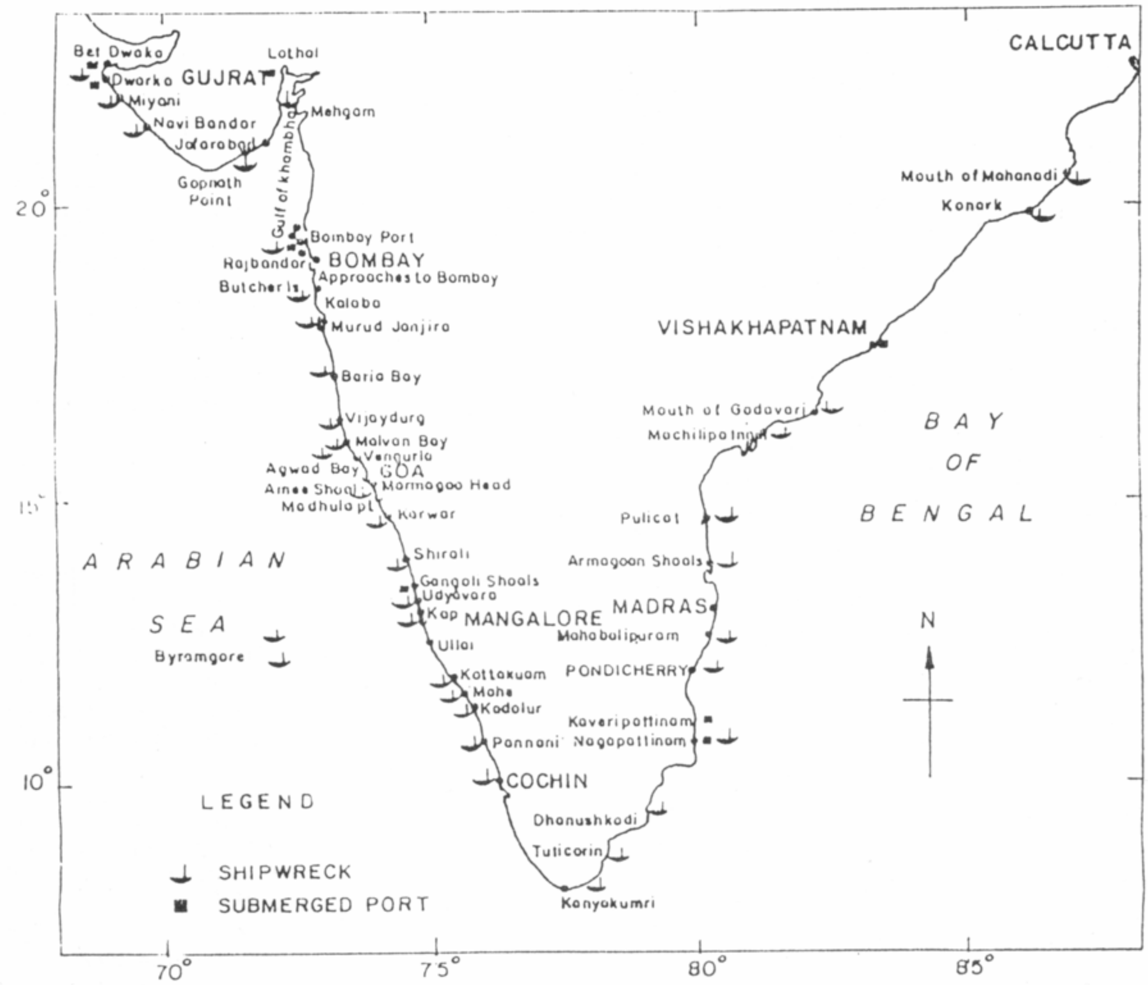


Fig 3. Relic carbide.



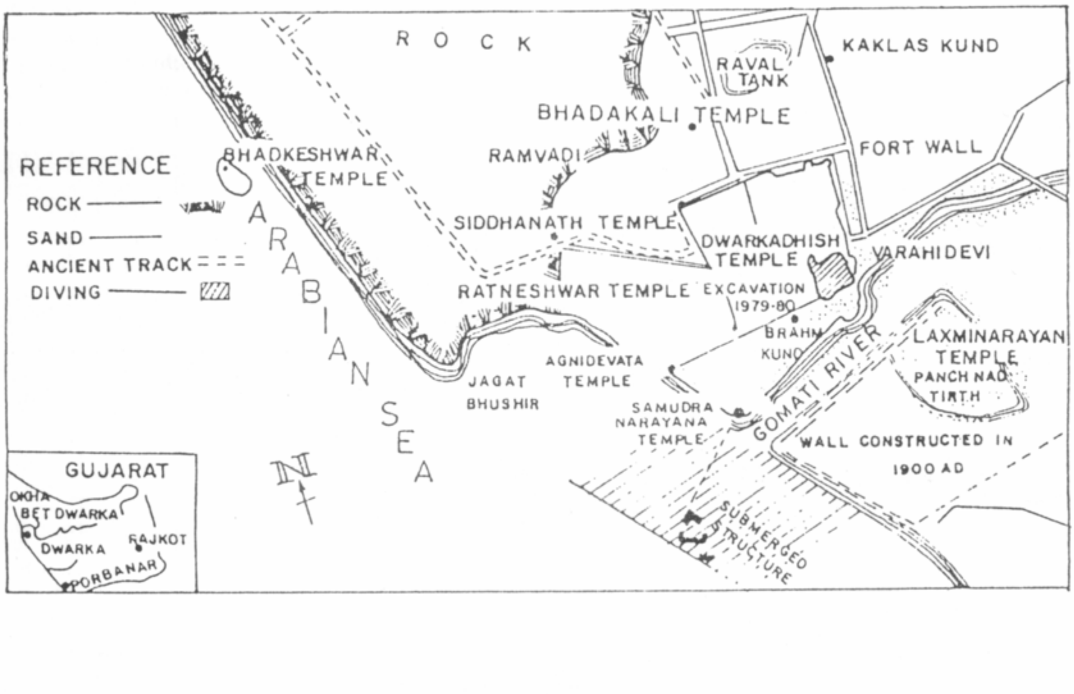


Fig 4. (above) India Survey of wrecks and ports. **Fig 5. (bottom) The port of Dwarka.**

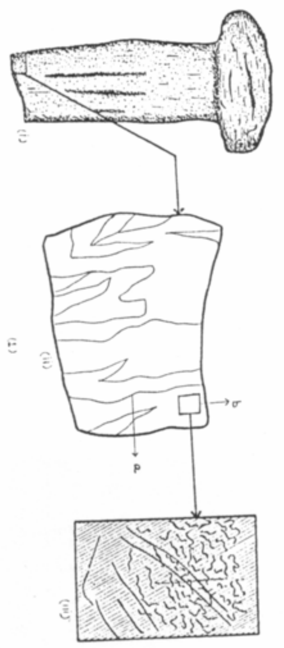


Fig 6. Nail 179.

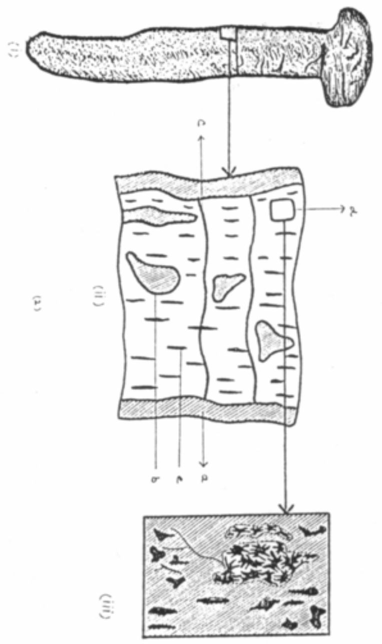


Fig 7. Nail 180.

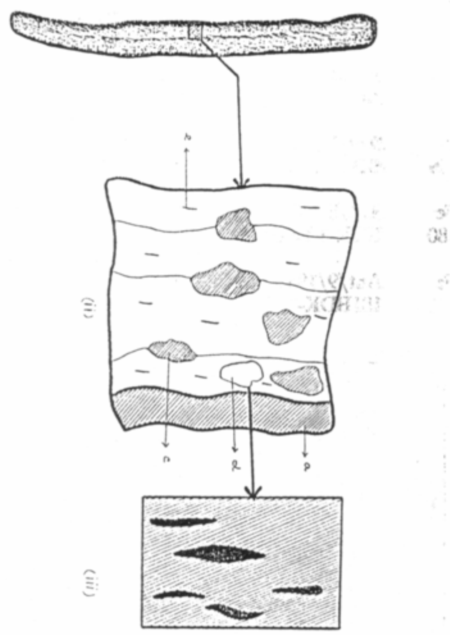


Fig 8. Nail 181.

(nitric, sulphuric and hydrcholoric acids in distilled water).[6]

INTERPRETATION OF MICROSTRUCTURES

Iron Nail Lab. No. Fe 179

Examination of section at 125x (fig 6) revealed neither metal core nor any metal but it revealed few cracks in mineralized metal (fig 6, I-III). The section was free from slag impurities. Etching with acid mixture revealed (at 500x) relict carbide structures near the periphery in only one area (fig 3) and it was not traceable in the other parts of the section.

Iron Nail No. Fe 180

The section was examined after fine polishing at 315x, which revealed mineralized metal having one tiny metal crystal and a few elongated slag inclusions (fig 7. I,II,III). The metal crystal was present near the periphery. Upon etching with 2% nital for 15-20 sec. the crystal revealed the ferritic structure with pearlite nodules at the grain boundary (fig 9). The direction of elongated slag inclusions was towards the tapering end of the nail. Further etching of the section with the acid mixture did not reveal any relic carbide structure near the periphery or away from the periphery.

Iron Nail Lab.No. Fe 181

Macro study of the section revealed that it was completely mineralized and the metal had had a few stress cracks. The study at 125x revealed plenty of slag inclusions spread all over the mineralized section (fig 8. I,II,III). Examination at higher magnification (250x) revealed only one tiny metal crystal near the periphery, which upon etching with 2% nital revealed, at 315x, ferrite with pearlite nodules near the boundary (fig. 10). Further etching with acid mixture for 5-10 seconds did not reveal the presence of any relic carbide structure near the periphery or in the core.

SPECTROGRAPHIC EXAMINATION

Samples from the above nails were also analysed by emission spectrograph. It was found that the main constituent of the nails was iron with silica, manganese and magnesium as minor constituents and titanium as a trace element. Details of the corroded metal analysis are given in the Table: nickel and cobalt were not reported by the analyst in any sample drawn from these nails.[7,8,9,] X-ray diffraction of the outer encrustation revealed the presence of magnetite and quartz.

INTERPRETATION AND DISCUSSION

Examination of the three nails from Dwarka showed that they were fabricated by forging from the impure wrought iron bloom. It appeared from the above studies that these nails absorbed some carbon accidentally while the smiths were repeatedly forging them to give the final shape. The presence of relatively more amounts of silicate impurities indicates that perhaps the smiths were not much aware of the harmful effects of its presence. Spectrographic analysis indicated the presence of titanium in these nails in trace amounts. It is reported in the literature that titanium makes an alloy with iron which has excellent resistance to atmospheric and sea water environment.[10,11] The smith might have found that nails prepared from the iron ore rich in titanium content proved harder and capable of withstanding a longer period in the marine environment than the nails prepared from the other ores. Perhaps the smith deliberately or unknowingly exploited this property in preparing bigger sized and more durable nails in the Mahabharta period.

CONCLUSION

The above investigations point out that the Dwarka artisan exploited the available iron ores which contained some titanium, extracted the metal after roasting it and varied the content of silicate impurities in wrought iron, knowingly or unknowingly, according to the need. Studies also revealed that the iron technology was in the preliminary stage and had not reached the stage of deliberate carburisation. It is

Table: Details of Iron Nails Subjected to Metallurgical Study from Dwarka

Lab. No.	Accession No	Cultural Association	Sample size mm.	Length cm	Diameter max cm.	Weight g.	Element composition present		
							major	minor	trace
Fe 179	Ant/7/1983 BDK-1, 1Z	Mahabharata 1500-1200 BC.	8 x 10	5.7	top 3.0 body 1.6	63.0	Fe	Si,Mn,Mg,Al,Ca	Ti
Fe 180	Ant/8/1983 BDK-1,Beach	-do-	8 x 6	7.3	top 3.0 body 1.4	80.0	Fe	Si,Mn,Mg,Al,Ca	Ti
Fe 181	Ant/9/1983 181BDK-1, 1Z	-do-	10 x 10	21.0	3.0	351.0	Fe	Si,Mg,Al,Ca	Ti

Fig 9.

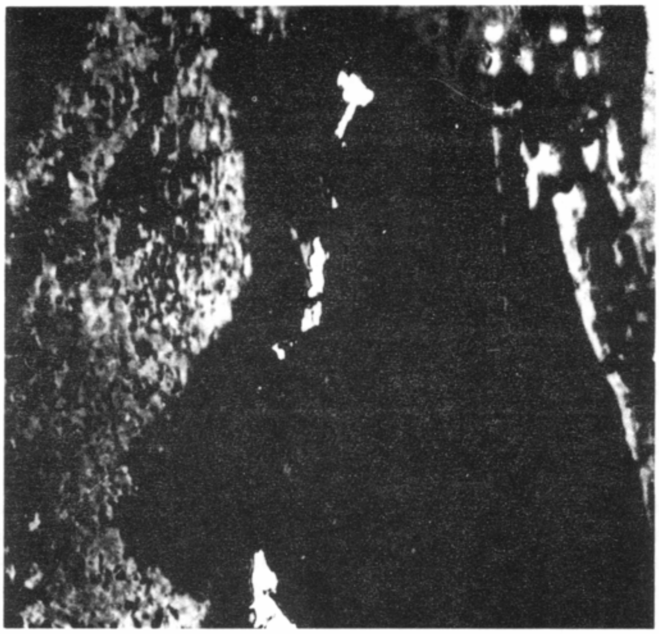


Fig 10.

also noticed that the smiths did not use meteoric iron for the nails. But the smiths prepared the nails to be used in the sea environment from the ore having some titanium content. The study of more iron artifacts from this marine site may throw more light on the utility of iron in this region during the period of Mahabharta.

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The authors are grateful to Shri Anil Risal Singh for photographic work and Dr K.K. Jain for analysing the corrosion products. We wish to thank Dr S.R. Rao, Emeritus Scientist, Principal Investigator, Marine Archaeology Project, National Institute of Oceanography, Goa, for kindly providing the specimens, maps and other relevant information.

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EXAMINATION OF SOME OBJECTS FROM EARLY WRECKS

J. Lang, S. La Niece, P.T. Craddock, M. Cowell and W.A. Oddy

In the 1970s a number of objects from recently discovered wrecks at Kyrenia, Marsala and Torre Sgaratta in the Mediterranean were examined in the British Museum Research Laboratory. A few of the results have been reported (Frost 1974; 1981) but it seemed appropriate, in view of the conference theme "Metals in Shipbuilding", to outline the results.

The objects examined were
(i) Nails, tacks and lead sheet from the Kyrenia wreck of the 4th century BC (Katzev 1969; 1970).
(ii) Fragments of nail, tack and lead from a Punic wreck off Marsala, 3rd century BC (Frost 1972; 1973; 1974; 1981).
(iii) Nail from the Torre Sgaratta wreck, off the coast of southern Italy, 1st century AD.
(iv) Prow from a Roman galley, found near the site of the battle of Actium.

EXAMINATION AND RESULTS

(i) Four nails from the Kyrenia wreck were examined. Two were completely concreted, the head of the third was partly exposed, while concretions had been completely removed from the fourth. A cross section was taken from the broken end of one of the concreted nails. The polished mounted section showed a worked and annealed structure with a little lead, present in the grain boundaries. X-ray Fluorescence spectrometry (XRF) analysis of the metal showed that it contained 99% copper and less than 1% lead. X-ray diffraction (XRD) analysis of the corrosion products identified the following minerals: on the exposed nail, cuprite (Cu_2O), paratacamite ($Cu_4(OH)_2Cl_2$), djurlite ($Cu_{1.93}S$); on the cross section, chalcocite (Cu_2S); and on the surfaces of the concreted nails, paratacamite ($Cu_2(OH)_3Cl$), djurlite.

Fig. 1 Kyrenia wreck nails.

Two tacks were cross sectioned. One (a) had some metal left while the other (b) was completely corroded.
(a) The metal of the head of the tack contained some elongated inclusions of copper sulphide and lead and was very heavily worked, with no sign of recrystallisation. XRF analysis showed a composition of 97-98% Cu and 2-3% Pb. No other elements were detected. The corrosion products on the surface of the metal were cuprite and paratacamite, while the black iridescent outer layer was covellite (CuS). Soft black patches on the outer surface were found to be galena (PbS).

(b) XRD analysis of the completely corroded tack (fig. 2) showed that the outer layer consisted mainly of covellite whilst the material at the centre consisted of djurlite with some aragonite ($CaCO_3$); the latter must represent an initial deposit, through which the copper corrosion products diffused.

XRF analysis of the surfaces and body of the tack only showed lead in one area (arrowed in fig. 2) presumably part of the lead sheathing still adhering to the shank.

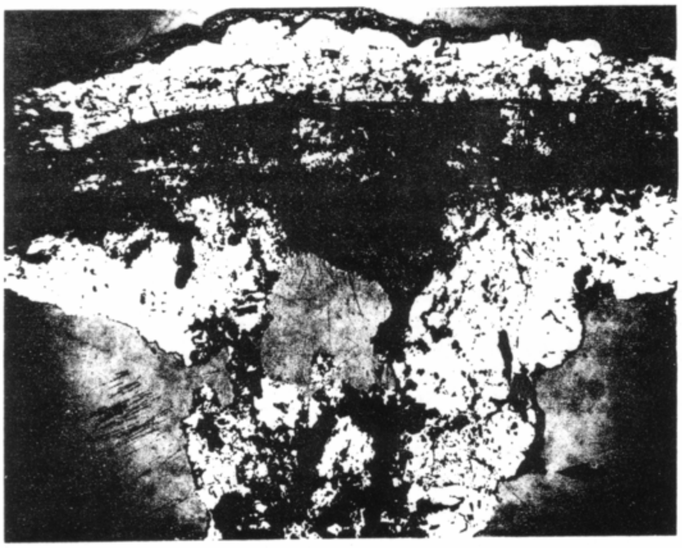

Fig. 2 The completely corroded tack.

Three samples were taken from the corroded surfaces of lead from the Kyrenia. Black material was identified as galena (PbS), while white crystalline material was phosgenite ($PbCO_3.PbCl_2$) and hydrocerussite ($2PbCO_3.Pb(OH)_2$).

(ii) A tack from the sheathing on the Punic wreck was analysed by emission spectrometry and was found to be essentially copper not bronze. Frost (1981) and Tylecote (1977) report that the nails and brads from the Punic wreck and her sister ship were bronzes containing more than 7% tin and 7% lead.

A nail from the Punic wreck examined was completely corroded to copper sulphides. The lead sheathing contained trace silver and copper (emission spectrometry).

(iii) A nail from the Torre Sgaratta wreck was sectioned and found to be completely corroded (fig. 3). The structure was layered and followed a square pattern, resembling a nail from a 1st century BC wreck at Palanos (Laures 1983) which was similar in appearance; both nails were clearly originally square sectioned. A radiocarbon date of 170 cal BC to 65 cal AD (at 95% confidence level by intercept method) (Lawn 1970; Stuiver 1986) for the timbers of the Torre Sgaratta wreck suggests that the ship was old when she sank at some time after AD 192, (indicated by a coin of the emperor Commodus). Copper or bronze nails were used in the original construction while later repairs used iron ones (Throckmorton 1987).

Qualitative emission spectrometry of the corroded material showed that the elements present were typical of a Roman bronze (copper with tin, lead, silver, nickel with traces of gold, antimony, zinc, arsenic, manganese and bismuth). The corrosion product was covellite.

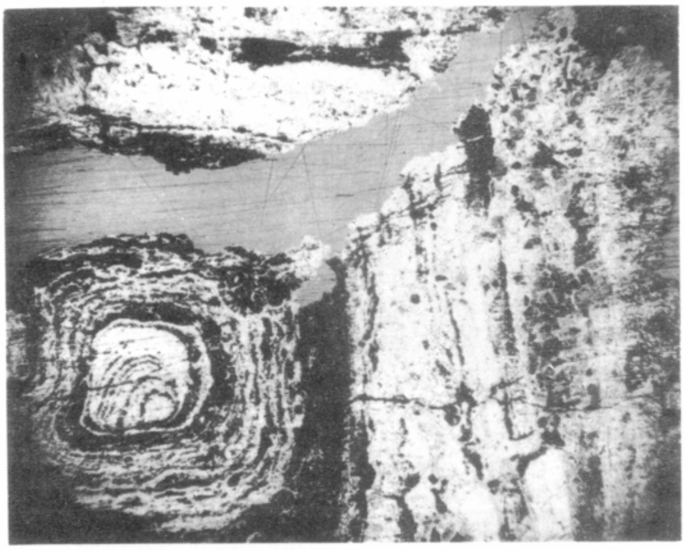

Fig. 3 Nail from the Torre Sgaratta wreck.

(iv) The prow, a figurehead of Romana, from a Roman galley was clearly cast (fig. 4). The composition is typical for a cast Roman bronze (atomic absorption analysis and polarography with typical error limits of 1-2% for major elements and 5% minor elements).

copper	79.8%	lead	16.8%
tin	1.8%	silver	0.04%
iron	0.25%	zinc	0.23%
cadmium	0.1%	antimony	0.14%
nickel	0.03%		

The corrosion products are mainly paratacamite and cerussite ($PbCO_3$).

COMMENT

The use of copper rather than bronze nails in shipbuilding might at first appear surprising but when it is observed that the nails often protruded through the timbers and the ends were knocked down, the use of a softer metal is more understandable. The composition of the later nail and the prow is typical of a Roman bronze.

Lead sheathing was apparently used from at least the 4th century BC to protect the hulls of merchant vessels from the depredations of the teredos worm, which is very active in warm Mediterranean waters. The Kyrenia was the first example found with a pre-Imperial date, although the technique is known from literary sources to have been used in the Roman Imperial period (Athenaeus ca.200 AD).

The analysis of the tacks shows that they were also soft and with their large heads, they would secure lead to the timbers without tearing holes in it. It is interesting to note that spare rolls of lead sheet were carried for repairs, and unused nails were also found.

It is clear from the results of the present analysis of the Punic tack and those on nails and brads reported by Frost (1981), carried out on sound metal, that both bronze and copper were used for making nails (including tacks and brads) in the Punic vessels.

Marine corrosion products have been discussed by MacLeod (1982) and those found in the present study are not unusual in anaerobically formed concretions. These are formed, according to MacLeod, either as a result of being buried in the marine sediment and the action of sulphate reducing bacteria or in a polluted environment; the latter situation might include shipwrecks, especially in coastal waters.

Fig. 4 The Figurehead of Romana.

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Historical Metallurgy Society Conference: Metals in Shipbuilding. March 1990.

CORNISH COPPER AND NAVAL SHEATHING NEW EVIDENCE FOR AN OLD STORY

P.T. Craddock and D.R. Hook

The adoption of copper sheathing by ships from the mid 18th century is well known (Knight 1973), as is the epic struggle between Thomas Williams of the Angelsey Mines and the Cornish copper producers at the end of the same century (Harris 1964). Recent analyses of some contemporary ingots of Cornish copper show that at least some of Cornwall's problems may have been inherent in the metal they were producing (see table).

Copper sheathing on the hull of a ship prevented worm attack into the timbers and fouling by barnacles and weed, the combined effects of which had hitherto shortened the life of a ship and very greatly reduced its performance. However where the copper sheathing came into contact with the iron bolts and fastenings holding the ship together, an electrochemical reaction was set up causing the very rapid corrosion of the more electronegative iron with catastrophic results, such that there was serious talk of abandoning copper sheathing altogether. An obvious solution was to make the bolts of copper as well, but the metal was judged to be too soft. Alternatives such as copper alloys which were hard enough were tried but with no great success as they too were liable to corrode. Finally ways of cold working the copper to harden it sufficiently for use as naval bolts were perfected.

Thomas Williams had been closely involved with the copper sheathing of ships since the start and the Angelsey mines provided almost all the copper used (Knight 1973). Thus in order to protect a very valuable and growing market for his copper he had been very active in promoting the research and development of the wrought copper bolts. The manufacturing process involved a complex series of rolling and drawing operations, using grooved rolls then recently introduced by Henry Cort for the puddling process of making wrought iron. Such was the success of the bolts that from the 1780's all new British naval vessels were fitted with William's patented wrought copper bolts, and the iron bolts in existing naval vessels were to be replaced as soon as possible.

Williams' bolts and sheathing of Angelsey copper proved popular on the continent and soon the Spanish, Dutch and French navies were also being supplied. Thus copper for naval requirements provided a considerable market for the copper from Angelsey, and played no small part in the great competion in the 1780s and 1790s between Angelsey and Cornwall, the traditional supplier up to that date of most of Britain's copper. Whilst the supplies of easily mined, high grade ore held out from the mines on Pary's Mountain and Mona, Williams was able to undercut Cornish prices and generally out-manoeuvre the Cornish producers. The low mining costs coupled with Williams' undoubted business acumen and drive have always been assumed to be the reasons for his success, but there may be another factor - the inherent inferiority of the Cornish copper. This would have been especially serious for applications where good working properties were essential, such as on the rolled sheathing and wrought copper bolts, unless the metal had been carefully refined.

A hint of these problems is given in some of the surviving documentation of the period; Matthew Boulton, the Birmingham manufacturer, for example complained of the quality of Cornish copper and Williams himself gave a more specific example. As part of an agreement, the "Great Treaty", drawn up in 1785 between Williams and the Cornish producers to limit competition between them, Williams had in 1786 handed over an order from the Navy for two hundred tons of copper sheathing to the Cornish suppliers, which previously had been handled almost exclusively by the Angelsey mines.

They, however, had taken so long to deliver it and the metal was of such bad quality that "We as contractors have been disgraced by them at the Navy Board insomuch it will be difficult for us ever to retrieve our character there" (Harris 1964 p.80). Admittedly Williams was hardly an unbiased observer, but it does seem that something was seriously wrong. Under the terms of the Treaty both sides were to sell their copper on equal terms, but right from the start of the agreement Boulton noted "I observe Angelsey hath been selling and continues to sell large quantities of copper, as well as manufacturing very large quantities whilst Cornwall is not selling an ounce" (Harris 1964 p.70).

The British Museum has recently acquired some early 19th century copper ingots from shipwrecks, including material form the EIC *Hindostan* lost on the Wedge Sand, Margate in 1803, the EIC *Earl of Abergavenny* lost off Weymouth in 1805, and the EIC *Brittania* lost on the Goodwin Sands in 1809 (Hook and Craddock 1987). The ingots are all of Cornish copper, including a battery plate from the *Brittania* carrying the stamp of the Rose Copper Company. Analyses of these ingots (Table) and of some early 19th century cast brasses made in Bristol, which always used Cornish copper ores to make the copper, has revealed an unusually high bismuth content. Even small quantities of bismuth as low as 0.01% in copper cause serious embrittlement and although the presence of arsenic would ameliorate the situation slightly, the Cornish copper with the level of bismuth recorded here would be unworkable (Gowland and Bannister 1930 p60). The contemporary hammered sheet brass made in Bristol had to be made from copper from which the bismuth content had been reduced, and this is confirmed by analysis (Hook and Craddock 1988). Cornish copper, again smelted locally near the brassworks, was used showing that the problem was appreciated, in Bristol at least, even if the cause was unknown. However bismuth

Table

Wreck	BM Reg	Cu	As	Bi	Zn	Fe	Pb	Ag	Sb	Ni
EIC *Hindostan* 1803	1985, 7-5,1	98.5	0.58	0.25	0.01	0.02	<0.01	0.08	0.03	0.03
EIC *Earl of* 1805 *Abergavenny*	1985, 7-5,2	96.7	1.4	0.17	0.01	0.03	0.01	0.06	0.04	0.13
EIC *Brittania** 1809	1985, 7-4,8	100 100	0.31 0.34	0.15 0.17	0.05 0.06	0.02 0.04	0.02 0.02	0.07 0.07	<0.03 0.03	0.02 0.02

*Sampled at either end.

Notes:

1. The analyses were obtained using atomic absorption spectrophotometry following the procedure of Hughes *et al* (1976).
2. The following elements were sought but not found to be present above their respective detection limits:
   Sn 0.15, Mn 0.001, Au 0.005, Cd 0.0006, and Co 0.003.
3. The figures in the table have a precision of approximately ±2% for copper and better than ±30% for the remaining elements, the precision deteriorating as the detection limit for a particular element is reached.

was notoriously difficult to remove from copper by fire refining as recorded in the early 20th century when the traditional method was still practised (Bailey 1967 p278), and the suspicion lingers that the one reason for the poor performance of the heavily rolled and worked copper made elsewhere from ore supplied from Cornwall was the presence of traces of bismuth which had survived the usual purification processes. It is possible that in the confused conditions surrounding the Great Treaty quality control suffered.

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METALS AT SEA - AN OVERVIEW

David Lyon

Over the centuries the increasing use of metals is a success story which has its reflection in the volume of metal objects found by diving on shipwreck sites. In themselves these artifacts are sometimes the only and usually the most visible items on these sites. This is a summary of documents, pictures and artifacts which illumine and illustrate this story.

The success story of metals at sea had its setbacks; the changing fortunes of metal sheathing, the French abandonment of iron knees after their initial experiments in the mid- 18th century (why did they do this?) and the Royal Navy's temporary abandonment of iron hulls in the 1840s, being cases in point. However they do not obscure the general upwards trend. Copper nails used for fastening, bronze rams and lead sheathing all antedate the Christian era. Caesar describes the iron fastenings and chain rigging of the ships of the Veneti. Archaeological evidence confirms the importance of iron nails in Scandanavian shipbuilding during the Dark Ages - indeed the main evidence for the shape of the Sutton Hoo ship is the stained sand from the corrosion products of the clench nails. The use of guns at sea, first wrought iron, then bronze and finally cast iron made for a vast increase in the amount of worked metal aboard ships - and has made wrecks of the period after 1500 much easier to find than earlier ones - guns being relatively indestructible and highly visible.

Let us take the example of what was raised from a pair of early 18th century British warship wrecks (the *Stirling Castle* and another site tentatively identified as the *Northumberland* - both casualties of the "Great Gale" of 1703 on the Goodwin Sands, investigated in 1979-1980 by the Thanet Archaeological Unit) to show the sort of metal objects present as part of the structure and fittings of a larger ship of the "great age of sail". There was a bronze cannon from the *Stirling Castle,* cast in the Netherlands 50 years earlier whose ordnance serial number permitted the positive identification of the site. Interestingly the identification would have been fairly clear even without the serial number as this ship was one of the only two ships of her kind at that time to carry bronze four pounders on her poop. None of the bigger iron guns, many of them still on their carriages, were raised, but some of the iron cannon balls and the lead shot for small arms were. The iron of the pistols, muskets and sword blades had gone, but brass gun plates, sword guards and the like survived, as did wooden stocks. The ships bronze bells were there, complete with "broad arrow". The feeding of the crew was represented by the riveted copper cooking "kettles" still in association with the bricks, peg tiles and stone paving slabs of the galley area, not to mention what is probably part of a copper chimney, as well as with a service of various sized pewter plates. Administration and navigation required nested weights, lead inkwell and sand-dispenser, not to mention the brass dividers that appear on any site of this period. Odd lead items have recently been identified as glue pots, whilst what appear to be cylindrical sash-weights may be just that. Lighting is represented by remains of several different forms of oil lights, hanging or adjustable. Lead scupper pipes were found in numbers. A large iron concretion appeared to be part of the chains - the supports for the shrouds - and can represent both ship structure and rigging. A large iron anchor in close association with the first hull illustrates the largest metal object aboard a ship of this period. Something similar to this listing would apply to most ships of the period from the mid-16th to the mid-18th centuries - from the *Mary Rose* to, say, the *Invincible* wrecked in 1758. One might find sheet lead and copper carried for repairs to the hull, metal navigational instruments (mariners astrolabes) and the like as well. Ships carrying metal cargo might add variety - for example the late 18th century wreck in the South Edinburgh Channel - which included stacks of copperplaten Swedish flat ingots of copper which could serve as currency, rods of iron, and a dozen anchors stacked three by three as cargo. It is no wonder that the magnetometer is a useful survey tool for locating wrecks of this date. However undoubtedly the greatest concentration of metal in ships of this period will normally be the armament - guns of iron or, less often, bronze cannon carried on the decks, or, sometimes, in the hold as ballast, together with their stores of shot. Much earlier the largest item of metal aboard a warship of the classical period had been the ram - a large and removable bronze casting - as witness the evidence of the Athlit ram. Another major concentration of metal was represented by iron anchors - the classic type of anchor usually now called "Admiralty pattern" dates back to well before the Christian era. Copper pins were often used to fasten the mortice and tenon construction which was standard in the Mediterranean up to the Dark Ages, whilst iron nails seem to have been the main method of Scandinavian construction during those same Dark Ages - probably replacing an older "sewn boat" tradition. By the 15th century wrought iron guns had begun to appear at sea followed first by cast bronze and then by an increasing flood of cheaper cast iron weapons as the 16th century wore on.

Ship historians usually dismiss the 17th and 18th centuries as a period when nothing very basic happened in ship design - the ships of Trafalgar merely represent improvements on the basic design of the Tudor galleon whilst early 19th century merchantmen are merely developments of the original Dutch "flutes". Whilst nothing so drastic as the evolution of the three masted ship at some time in the 15th century or the technological strides of the 19th century affected ship design in the intervening years, this idea of relative stagnation does not stand up to close examination. A slow but relatively steady flow of improvements, often, in themselves, fairly minor; in rig, structure,fittings, armament, hull design and so on, produced relatively enormous effects in performance and reliability that may seem small to us looking through "the wrong end of the telescope", but were, cumulatively, of enormous and lasting importance. Many of these improvements involved metallurgy - the parts of the chain pumps (actually a revival of a Roman device) in use by British (though not French) war ships by the beginning of the 18th century, for example. After 1700 the pace of development was accelerating, and increasingly involved metallurgy.

Contrary to another well-established legend the improvements most often stemmed from navies rather than merchantmen, and, in particular, from that consistently technically inclined service, the Royal Navy. Its increasing pre-eminence in action during the 18th century probably owed more to its position in the forefront of these apparently insignificant technical advances than is usually admitted. What is certain is that increasing use was made of permanent pig-iron ballast as the 18th century wore on, that in the 1740s iron galley ranges were replacing the old brick ones, and at the time of the American War of Independence two major technical developments swept in. These latter comprised the copper sheathing of the entire British fleet and the adoption of the carronade. Neither of these was satisfactory at first - the coppering programme was saved from long term disaster caused by cathodic erosion of iron fastenings only by the drastic and expensive expedient of adopting brass fastenings below the water line a few years later; in the same way, the design of both the carronades themselves and their slides had to be altered before the next round of French wars to make them satisfactory. Meanwhile the Royal Navy was completely re-equipped with Blomefield's new pattern guns before the end of the century. The metallurgical developments we associate with the beginnings of the Industrial Revolution were beginning to have their effect. New patterns of pumps and of galley stoves appeared - often making use of improved and cheaper iron.

With the new century the pace of change increased again. Seppings' improvements in construction (essentially the adoption of a semi-girder form of structure which permitted the enlargement of the limitations on the building of wooden ships and therefore produced longer and bigger vessels) relied heavily on the use of wrought iron knees and strapping. New forms of pumps, anchors, water closets, guns all required more use of metal as did chain rigging, iron water tanks and the use of iron for protection of hawse holes, brass for "racers" for the carriages of the new, larger, guns and so on. Despite the improvements of Seppings and others wood structures were being pushed to their limits in the bigger vessels despite the increasing use of iron reinforcements to permit greater length (taken to its extreme in the huge American schooners of the beginning of the 1900s with their mass of ironwork still visible in, for example, hulks still rotting into the mangrove swamps of Port Adelaide). The final strain on wooden structure came from the installation of steam engines - yet more metal and other heavy weights piled in amidships, combined with the inevitable vibration and stresses of propulsive machinery caused severe hogging and wracking to which a wooden hull made of relatively small discrete pieces of timber difficult to fix rigidly together was ill suited. Even before the extra difficulty of installing a long shaft to drive a screw propeller in an essentially non-rigid hull came to worsen things further (and at least in one case, to nearly cause the loss of a steam screw ship of the line through leaks caused by the "working" of the shaft) the adoption of metal hulls was an obvious way out of the problem. Various incidental difficulties had to be solved before iron hulled ships could be satisfactory as seagoing ships. Science solved the problems of using a magnetic compass in an iron hull. Developments in metallurgy caused the final solution to the problems of iron plates which shattered under the impact of solid shot in low temperatures (which explains why the Admiralty abandoned its initial experiment with iron hulls in the 1840s - and makes it a fortunate fact for the pioneer iron warships that they fought their first battles in warm climes - *Nemesis* in Southern China and Borneo, *Guadalupe* off Yucatan. Perhaps the most intractable of all problems was the rate at which metal hulls grew foul - not totally solved yet by anti-fouling compounds. One early answer was to use an iron skeleton and a wooden skin - the "true" composite construction. The wooden skin could then be coppered. This method of construction actually came after the first iron hulls - not as an intermediate stage between wooden and metal hulls. In the closing years of the 19th century another expedient was adopted for cruisers intended for prolonged service in tropical waters. These were "wood sheathed" - a wood lining put on an iron (or more often steel) hull which was then itself coppered.

Mild steel replaced iron for shipbuilding very rapidly after Denny's of Dunbarton showed the way with the *Rotomahana* and *Buenos Ayrean* in the early 1880's. They were building on earlier developments - mostly involving small, fast or shallow draft vessels where the need for lightness and strength in construction outweighed the higher costs. Firms of the type of Thorneycroft and Yarrow had been building torpedo boats and river craft in steel (mostly Bessemer steel) for the previous decade. It is also hardly surprising that the Admiralty had laid down a vessel of cruiser size (the despatch vessel *Iris*) of steel several years before Denny's laid down their two vessels. Not all uses of new metals in ship construction were as successful, however. Yarrow's built an aluminium hulled torpedo boat for the French which they promptly moored near a sewage outfall. They had to dispose of the badly corroded hull within the year.

Even now metal has not completely replaced wood at sea - not to mention the competition from other materials like ferro-concrete and GRP, there is the current revival of interest on wooden traditional boats to be borne in mind. Ships continued to have planked decks and panelled state rooms. In the height of the ironclad era most armoured ships had their armour-plating mounted on teak backing - the wood gave extra resilience and increased protection against the impact of shells. Indeed there is a design, contemporary with HMS *Warrior*, in the Admiralty collection of ship plans for an iron hulled ship protected with wooden armour!

ACKNOWLEDGEMENTS AND SELECT REFERENCES

This brief essay is based on a quarter of a century's investigation of technical records - especially the Admiralty and other plan collections at the National Maritime Museum - and nearly as long taking part in the development of underwater archaeology. It is also based on many hours of discussion with such friends and fellow researcher as J. Adams, T. Adams, J. Boudriot, J. Broadwater, D.K. Brown, R. Gardiner, R. Kean, A. Konstam, A. Lambert, B. Lavery, D. MacGregor, I. Morison, the late Keith Muckelroy, A. Preston, T. Roth, R. Smith, D. Syrett and many others. In these circumstances it is somewhat difficult to footnote many statements except with "personal communication" or "see the Admiralty Collection passim" and so I have taken the coward's course of eschewing footnotes altogether. For further reading the following can be particularly recommended:

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