ENABLING TECHNOLOGY AND THE NAVAL ARCHITECT 1860-2010

I Buxton BSc, PhD, CEng, FRINA

SUMMARY

(DOI No: 10.3940/rina.ijme.2010.a2.171)

Enabling technology permits the naval architect to do more with fewer resources, increasing output, decreasing cost and improving productivity, with the resulting benefits being widely distributed in a worldwide economy. For example a bulk carrier's energy consumption per ton-mile today is less than 3% of what it was a century and half ago – due to more efficient machinery, larger hulls with lower resistance per ton and improved propulsive efficiency, yet with higher speed and shorter port times

1. THE FIRST HALF CENTURY

The state of the art in naval architecture in the 1860s was well described by John Scott Russell, one of the founders of the Institution of Naval Architects (INA, later to become The Royal Institution of Naval Architects – RINA), in his "A Modern System of Naval Architecture", published in 1865. These massive tomes weighing 50 kg together and costing £42 then (about £3000 in today's money) consist of one volume of text and two of plates, the latter illustrating such vessels as the *Great Eastern* built by Russell himself. The 1860s were still a period of transition, from sail to steam and wood to iron. Although steam propulsion dated back half a century for small wooden paddle steamers, 45% of the 500 ships over 100 tons built a year from 1859 to 1861 in the British Isles were wood (43% by tonnage, 250,000 including naval vessels). Sail was still a significant part of output, 60% by number, 45% by tonnage. Of the 180 steamers built each year over 100 tons, 55 were paddle (30% by number, 21% by tonnage). Cunard's latest passenger liners *Persia* and *Scotia* were still paddle propelled, albeit with iron hulls.

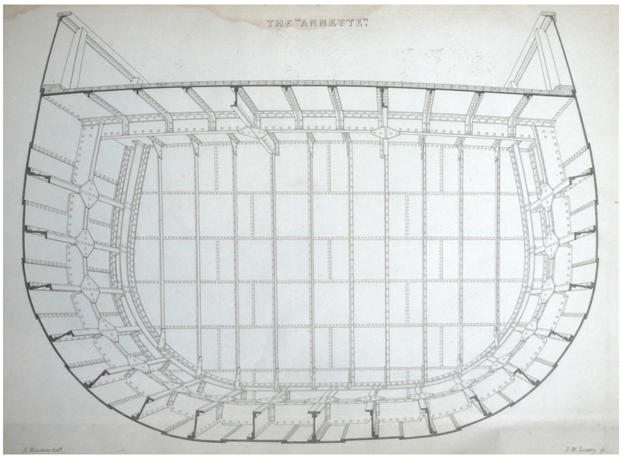

Figure 1. John Scott Russell's magnum opus "A Modern System of Naval Architecture" of 1865 included many illustration of contemporary ships and structures, some of them his own design. His 190ft (58m) 750grt passenger cargo vessel Annette was framed longitudinally, and illustrated in his 1862 INA paper. But it was nearly fifty years later before such framing came into wider use, as transverse framing was easier build in riveted construction. Isherwood's system was widely used for tankers from 1908.

The thermal efficiency of most steam reciprocating engine was low at about 8% (2.5 lb coal/hp-h specific fuel consumption - SFC) which limited endurance as well as increasing fuel cost. Although a handful of screw steamers had been built in the mid 1850s with compound engines (one high pressure cylinder and one low), most were two cylinder simple expansion engines with boiler pressures of around 20 lb/sq in (1.3 bar).

Britain at that time built the vast majority of the world's steamships and British shipowners had by far the largest fleet of steamships, so its experience and statistics give a good overall picture of developments. Of the steamship types, the greatest number were colliers, ferries and tugs, although the liner companies like Cunard and P&O were expanding their fleets of long distance passenger-cargo vessels. The largest vessels (excluding the unique *Great Eastern*) were around 3000tons gross, carrying around 800 passengers at speeds of around 12 knots with engines of about 3000 ihp (2250kW) (indicated horsepower, the measure of steam reciprocating engine power, about 80% of shaft power).

Figure 2. The steam paddle tug was developed from the 1820s and by 1860 not only assisted ships in harbour or distress but enabled sailing vessels to get in and out of harbour when winds were adverse. Flying Irishman of 1885 was typical, 120ft long (36m) and engines of about 400 ihp.

On the theoretical side, Scott Russell had expounded his wave-line principle for hull forms, William Rankine had established the basics of ship strength (important for large iron hulls – the largest wooden hull was no more than about 360ft long (110m) owing to the difficulty of making strong tensile joints in timber), while William Froude was working out his theories on ship resistance and rolling. Hull form was very much an empirical process based on previous vessels regarded as ‘successful’ and on concepts we now know to be flawed, e.g. minimising midship section area, as the hull was deemed to ‘plough a furrow through the sea’.

Iron beams were used in the construction of decks of wooden sailing ships, which allowed a simpler stronger structure. The same concept was applied to some hulls, where composite construction used wood planking on iron frames. This had the added advantage of permitting thin copper sheathing to be added to reduce fouling and worm attack in tropical waters (as in tea clipper *Cutty Sark* preserved at Greenwich). As such sheathing could not be used on iron hulls owing to electrolytic corrosion, new copper-based anti-fouling paints were developed in the 1860s. Sailing vessels started to use wire rigging – stronger and longer life than fibre ropes. Wire ropes were also being used in cargo handling appliances such as hydraulic dockside cranes, pioneered by William Armstrong, a lawyer turned engineer, an unlikely transition today!

The 1860s also saw steam applied to auxiliary machinery. The massive *Great Eastern* was found soon after completion to need steam steering gear, progressively extended to the larger steamships, although hand operated gear continued to be used in smaller coastal vessels into the 20th century. Steam powered deck winches with derricks were introduced (and even a few steam deck cranes), with steam for anchor windlasses and bilge pumps. Salt water ballast had long been recognised as more efficient and cheaper than sand or shingle which had to be laboriously loaded and discharged from wooden sailing vessels. Early designs included canvas bags in the bottom of the holds. But water ballast tanks integral with the ship’s structure were the way ahead, which were developed from about 1854. Coupled with steam driven pumps and piping systems, ballast handling time was greatly reduced, and seaworthiness improved, although there was usually insufficient capacity in double bottoms and peak tanks to fully immerse the large diameter slow revving propeller.

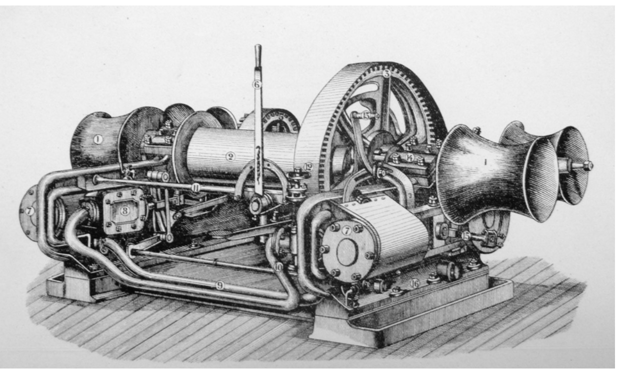

Figure 3. Steam powered auxiliary machinery enabled bigger ships to be built, by mechanising the steering gear, anchor windlass and deck winches. The latter (illustrated) speeded up cargo handling in conjunction with derricks. Captain Paasch’s “Illustrated Marine Encyclopedia” not only illustrated ships and their fittings from the late 19th century, but his dictionary “From Keel to Truck” also gave translations in English, French, German, Spanish and Italian.

Separate condensers had been introduced in the 1850s, whose vacuum not only improved efficiency but reduced the need for salt water feed in the boilers, which caused problems with deposits and corrosion. Steam evaporators did not become common until later, so that all the fresh water for boilers, passengers and crew had to be carried, and topped up on port calls.

The 1860s saw the first underwater telegraph cables laid (including some by *Great Eastern*) which greatly improved commercial communications and operating efficiency, as shipowners, agents and masters could be advised of available cargoes and market opportunities. Equally important was the opening of the Suez Canal in 1869, which gave a boost to long distance trade to the eastern hemisphere, significantly reducing transit times to India, Australia and the Far East, and putting another nail in the coffin of sailing ships. Although some continued to be built right up to 1905, they were increasingly displaced to secondary trades with long port times.

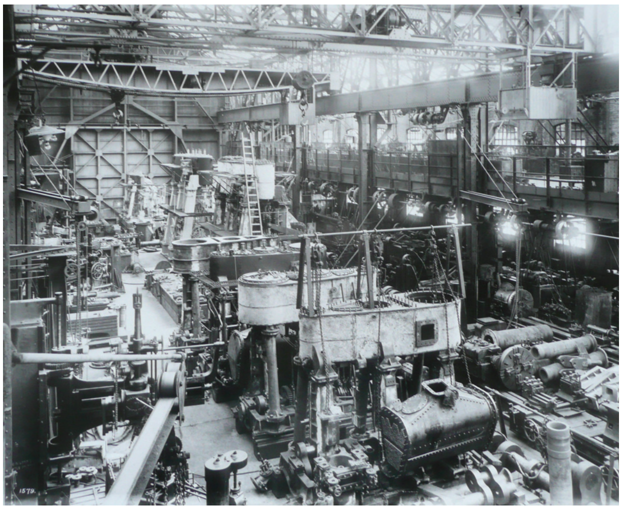

Figure 4. The steam reciprocating engine had developed to power most deep sea ships by 1860, but nearly all with low pressure boilers and single expansion. The 1870s saw the compound engine, and the 1880s the triple expansion, with high, intermediate and low pressure cylinders. That became the mainstay propulsion of most lower powered ships for the next half century. New engine works sprang up to produce fifty or more such engines a year. The photo shows Smith’s Dock erecting shop on the Tees, building triples for their cargo and fishing vessels.

In the late 1860s, the compound steam engine was widely adopted with a higher steam pressure of around 60 lb/sq in (4 bar) and more reliable boilers. SFC was reduced to around 2 lb coal/hp-h, which translated into more cargo for the same fuel, or less fuel with the same cargo, or longer voyages, as well as reduced fuel cost and fewer bunkering calls. A lot of bunkering coal exported from Britain was carried in sailing ships to areas where there was none or the local coal was of poor quality. The high freight costs of 20-40 shillings per ton (£1.00-2.00) resulted in the price of coal in say Indian Ocean ports being three or four times the UK price of under 10 shillings (50p) per ton. The plethora of previous boiler designs, box, haystack, locomotive etc, gave way to the cylindrical ‘fire-tube’ boiler, often called a Scotch boiler. New stronger designs of furnace in which the coal was burned reduced the risk of collapse and scalding of the stokers.

The compound engine soon gave way to the more efficient triple expansion engine in bigger ships from about 1880. With higher pressures of about 150 lb/sq in (10 bar) expanding through a high, intermediate and a low pressure cylinder, SFCs were reduced to about 1.5 lb coal/hp-h (13% efficiency). Such higher pressures required very thick iron plates in large boilers, so boilers began to be built in steel from that same date, requiring plates about 20% thinner. Siemens-Martin open hearth steel of consistent quality became available from about 1878, with production rapidly expanding. The transition from iron to steel hulls took only ten years. Small quantities of cast steel had been available from the late 1850s but its high price of around £20 per ton compared with £9 for wrought iron limited its use to lightweight vessels like river steamers and blockade runners for the American Civil War, although it had been used to build masts and spars of lighter topweight. But bulk manufacture in Scotland and north-east England soon reduced the price of steel to about £6 per ton, even below that of iron. Its greater strength reduced steelweights by around 15% and its greater ductility improved survivability in the event of grounding or collision, while the larger size of plates possible (up to 8ft wide in place of 4ft) reduced riveted joint length and construction cost.

Figure 5. The first oil tanker to have all the features that would become standard – cargo contained in the main hull by longitudinal and transverse bulkheads and engine aft - was built on the Tyne in 1886. Armstrong, Mitchell (later Armstrong, Whitworth) was the major builder of early tankers: 4000dwt Minister Maybach was built by them in 1887.

The 1880s also saw the birth of two specialist ship types, a trend which continues to this day – the tanker and the refrigerated ship. Previously oil had been carried in wooden barrels or metal cases, prone to leakage and slow to load and discharge. The 3200ton deadweight 8knot *Gluckauf* built on Tyneside in 1886 was the first successful bulk oil carrier, stowing cargo within the hull itself, with longitudinal and transverse bulkheads, and with machinery aft, and its own pumping and piping system, a concept that endures to this day, although the ships are one hundred times larger and double the speed. Although there had been a few experimental refrigerated installations in sailing ships (surely not the ideal carrier), the first steam propelled fully refrigerated ships based on CO_2 arrived in the early 1880s. These permitted the export of cheap frozen meat from countries like New Zealand and Australia, to feed the increasing urban populations of Europe as industrialization gathered pace. By the turn of the century, the steam trawler and ore carrier had been added, the latter especially on the Great Lakes.

Figure 6. The steam trawler was introduced in the late 1870s, enabling large quantities of fish to be landed and transported in ice by rail to the growing urban populations. By 1900 the UK was building about 200 such vessels a year. Smiths Dock then on the Tyne specialised in building fishing vessels – their Hawk of 1897 has bridge aft of the funnel.

Although the basic concepts of buoyancy and initial stability were well known in 1860, the calculation of large angle stability was onerous, yet capsizes of ships such as the ironclad *Captain* in 1870 had shown the need to do so. Fortunately Amsler came up with his mechanical integrator in 1878, a concept later extended to the integraph, which allowed bending moments and shear forces to be calculated for demanding vessels like large passenger vessels or warships. Previously calculations of midship section modulus had been based on approximations like Max bending moment = k x Displacement x Length, although for most ships, scantlings were based purely on tables related to tonnage or main dimensions in Classification Society rules. It then became possible to evaluate the benefits of for example higher tensile steel, e.g. in destroyers and torpedo boats, and of longitudinal framing, e.g. Isherwood's system of 1908. Simple beam theory applied to the midship section had been shown by experience to produce scantlings of adequate strength for seagoing ships in association with nominal stresses.

Froude's towing tank first at Torquay (in 1872) and then at Haslar near Portsmouth, based on his law of comparison between model and ship resistance, provided the means to explore a great variety of hull forms as well as predict power with greater confidence. It was this latter advantage that persuaded shipbuilder Denny of Dumbarton to build the first commercial towing tank in 1883. The company built many high speed and shallow draft ships, so a more accurate prediction of power enabled them to determine dimensions and hull form and to size the machinery with greater confidence and lower margins when tendering.

By this time, the major Classification Societies had become well established, Lloyds Register starting in 1760 (100 years before RINA), Bureau Veritas in 1828, American Bureau of Shipping in 1862, Norske Veritas in 1864 and Germanischer Lloyd in 1867, to be followed by a British (or rather Scottish) rival to LR in 1890, the British Corporation, and Nippon Kaiji Kyokai in 1899. These societies also assigned freeboards, statutory in British registered ships from 1890, but not agreed internationally until 1930 – one of many steps towards the level playing field so necessary to an industry like shipping. Indeed such subjects were regularly discussed in the various technical forums such as (R)INA or North East Coast Institution of Engineers & Shipbuilders (1884) or Society of Naval Architects & Marine Engineers (1893). With its large merchant fleet, Britain often took the lead in establishing new safety legislation covering matters such as life saving appliances, tonnage rules, subdivision, crew qualifications and provision of navigational aids, enshrined in major legislation like the Merchant Shipping Act of 1894.

Other late 19th century technical developments which enabled bigger, better and faster ships to be built included forced draft for boilers (increasing power output and reducing fuel consumption) and electrical generators (including some early steam turbines) permitting electric lighting. This was particularly useful in larger ships with extensive accommodation like passenger ships and battleships and in engine rooms where guttering oil lamps or candles were the only alternatives if no natural light could be arranged. Electrically driven machinery began to make an appearance both on board ship and on docksides, simplifying power transmission. Manganese bronze propellers (usually then blades bolted to the boss) reduced erosion and corrosion as well as improving efficiency in high powered vessels, albeit at higher cost than cast iron.

2. INTO THE TWENTIETH CENTURY

The most significant enabling technology at the start of the 20th century was the introduction of the steam turbine. Although Charles Parsons is regarded as the pioneer, there were also designs prepared in the USA, Germany and Sweden. The turbine offered almost unlimited power compared with the steam reciprocator, and in a smaller engine room and with less vibration, although initially fuel consumption and cost were much the same. Following Parsons' experiments with *Turbinia* in 1894-97 (now on display in Newcastle's Discovery Museum) Royal Navy applications progressed rapidly from destroyers to cruisers, and then to the battleship *Dreadnought* ordered in 1905. In parallel, merchant ships moved from the 3000-shp Clyde ferry *King Edward* in 1901 to the momentous decision by Cunard in 1904 to order 70,000-shp turbines for their 25-knot transatlantic liners *Mauretania* and *Lusitania.* This sixfold increase in power from destroyer *Viper*'s 11000-shp in 1900 was just as bold as Brunel's step from the 3000grt (gross registered ton, a measure of volume not weight) iron steamer in the mid 1850s to his 18915grt *Great Eastern*. But unlike the latter, the Cunard liners were a great commercial as well as technical success. What modern engineer would make a six fold jump in capability in only four years?

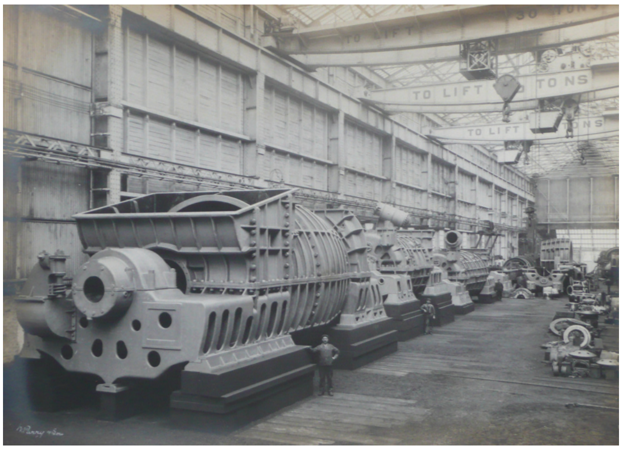

Figure 7. The decision in 1904 to use steam turbines in Cunard's express Atlantic liners Mauretania and Lusitania was a momentous one, coming only ten years after Parsons had installed his first experimental turbine in Turbinia. The 70000 shp developed on four screws enabled them to maintain 25 knots with ease; they were a great technical and commercial success. The photo shows Mauretania's direct drive turbines in the erecting shop at Wallsend Slipway & Engineering company's works in 1906.

The early steam turbines were coal fired, so boiler capacity and firing rate were limitations on sustained power. Many new designs of watertube boiler were developed offering greater steam raising capacity, but few survived more than a few years, Babcock & Wilcox being one the most successful. But experiments with oil fired boilers had started in the 1880s, so by the early

1900s, successful designs of burner had been developed. From about 1914 all the major vessels of the Royal Navy used oil fuel, not just the newly developed submarine with its internal combustion engines. Although more expensive than coal either on a weight or calorific value basis, the weight of fuel was less, it could be stowed in awkward compartments like double bottoms, it greatly reduced the number of stokers to be carried, and it did away with the slow and dirty business of coaling ship. Higher powers also required improvements such as the compact reliable Michell thrust block.

The same decade (1900) saw the application of the oil engine to marine propulsion, initially only in small vessels. Its greatly increased thermal efficiency (32%) – hence lesser fuel load – quick starting and compact space and uptakes spawned many designs. After Burmeister & Wain had developed the directly reversible diesel, the way was clear to use them in deep sea ships, resulting in the Danish *Selandia* of 1912. Take-up of the diesel was delayed by the First World War, where maximising production from existing manufacturing facilities was paramount. Between the wars, different shipowners took different views on the potential problems of lower reliability, more expensive distillate fuel, greater maintenance and repair bills, more skilled operators and modest power per cylinder. Thus steam reciprocators retained a significant share of the marine propulsion market into the 1940s, indeed the 2648 Second World War Liberty ships all used a British design of triple expansion engine.

Figure 8. Burmeister & Wain in Copenhagen produced the first diesel engine for deep sea ships for cargo vessel Selandia in 1912, offering much lower fuel consumption than steamships, albeit at higher construction cost. Over the next decade, many designs appeared but few were successful. The Doxford opposed piston engine with good balancing characteristics went to sea in 1921 and remained a popular engine for the next 40 years. Here one of their 6 cylinder 6600bhp engines for the twin screw Portuguese liner Angola is in Hawthorn Leslie's erecting shop in 1948.

There was little evolution of ship types between the two world wars, not so much due to lack of technology but due to economic stagnation and little growth in world trade. Apart from transatlantic liners reaching 80,000grt and 30knots (*Queen Mary, Normandie*), cargo ships and tankers remained around the 8000grt mark, whose speeds had barely increased either, with around 11 knots. Progress was more in refinement of designs, with tank testing producing better hull forms (including the Maierform), streamlined aft ends and rudders, exhaust turbines added to steam reciprocators, e.g. Bauer-Wach. The first steel hatch covers appeared, offering greater strength, safety and quicker opening and closing – a boon to coastal colliers with their short voyages and low freeboards. But the traditional steel beams, wooden boards and tarpaulins were not completely replaced by designs like MacGregor covers until the 1950s. Wireless became mandatory on ships over 1600grt in 1919 which not only reduced casualties but improved commercial efficiency. Electrical generating capacity increased, so electric motors started to replace steam driven auxiliaries, especially on diesel ships.

Higher standards of subdivision in passenger ships were introduced in 1930. Particularly in passenger carrying ships (there was as yet little challenge from air transport) innovations were introduced such as partial air conditioning (first class passengers only!), fin stabilisers, gyro compasses and echo sounders. Nozzle propellers were installed in tugs to increase thrust, while the first controllable pitch propellers appeared in a few smaller ships. Crew accommodation slowly improved. Seamen moved from forecastle to poop (more space, lesser motions, drier), separate eating and washing places (with hot water!) were introduced, and refrigerators allowed a wider range of food to be stored – no more coops for live chickens or sheep! As yet number of crew remained high at 40-60 on a typical deep sea cargo ship, only showing a reduction in ships where oil replaced coal.

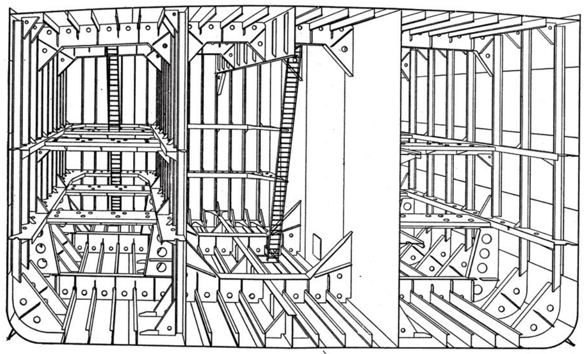

Figure 9. Welding technology, although developed in the 1900s, became more widely used in the 1930s, especially for tankers. Making really oil tight riveting was difficult, so it was no surprise that they were the first ship type to make wide use of welding. In Second World War, welding was used for American mass production of Liberty cargo ships. Full scale structural tests were made on welded and riveted ships in Britain; the cross section

shows one of the tankers so tested. By the 1960s, the transition from riveting was complete. Lighter smoother hulls paved the way for ever larger ships.

Welding came of age in the 1930s. Introduced in the 1900s using gas, the shielded electric arc was developed in time for WW1, where it proved useful in awkward repairs. The first all-welded seagoing ship was the coaster *Fullagar* built by Cammell Laird in 1920 (at a loss!). But welding was regarded as expensive, unproven and less reliable than riveting, especially for main hull structures. So it tended to be used where there were clear advantages such as oil tight bulkheads in tankers or oil fuel bunkers, where really oil tight riveting was difficult to achieve. It took the high production demands of WW2 to bring about the widespread use of welding. The huge emergency shipyards in the USA were laid out for all welded prefabricated construction, with large welding bays, heavier cranage and ample storage space for units – and needing less skilled labour. Without welding, the US would not have been able to build the 5000 ships that the Maritime Commission produced between 1941 and 1945. But there were still problems to be solved with brittle fracture, requiring the development of notch tough steels in the late 1940s, and the need to integrate design and construction more closely, both in terms of detail design to remove stress concentrations and in block assembly methods. But welding brought significant performance advantages in terms of lower structural weight (typically about 15% by removing overlapped riveted joints, flanges and connecting angles) and in smoother hulls, typically about 20% less resistance. Ramsay Gebbie of Doxford made a careful comparison of an all-riveted and an all-welded cargo ship of equal cargo deadweight (9515 tons) and speed (14 knots) in his 1958 Amos Ayre INA lecture. He concluded that owing to the lighter, smaller and smoother hull, power and fuel consumption were reduced by about 20%, and building cost by about 12%, while the profitability of the riveted ship was at best 90% of the welded ship, and could be as low as 52% depending on freight rate, fuel price and port time. By 1960 the transition was complete.

Figure 10. The submarine enabled smaller navies to strike at larger navies using the torpedo. Airless underwater propulsion (electric motors and batteries for the first half century), safe submergence and surfacing, and control in three dimensions were demanding technologies. Medium speed diesels were the prime mover of choice for surface propulsion and battery charging until nuclear power arrived in the 1960s. The shape of the British Uther of 1943 shows to advantage in drydock, with the prominent ballast tanks.

3. POST WORLD WAR TWO

The last half of the 20th century saw the fastest ever evolution in ship development, with size increasing tenfold, more new ship types and the container revolutionising general cargo transport. On the naval side, the nuclear propelled submarine changed warfare for ever, both strategically and tactically. Postwar recovery saw a booming world economy, with oil replacing coal as the primary energy source. Tankers increased dramatically from the 'three twelves' of prewar (12,000dwt at 12knots on 12tons oil per day) to the first 50,000dwt in 1956 to the 200,000dwt *Idemitsu Maru* in 1962 culminating in the 550,000dwt giants of 1976 like Shell's *Batillus* with a draft of around 28m – although the latter class proved too large and inflexible in service, and none remained in service long. Nearly all such vessels were built in building docks, some spanned by gantry cranes of up to 1000tonnes lifting capacity, enabling very large blocks and complete superstructures to be lifted. Ports expanded continually to accept such large vessels, with a corresponding demand for dredgers, usually suction, capable of as much as 30m (100ft) depth.

A particular enabling technology was computer aided design (CAD), initially used to mechanise tedious naval architectural hand calculations from the late 1950s, but soon applied to structural analysis where finite element methods allowed ever larger tankers to be designed with greater confidence. In due course CAD was linked with computer aided production methods with full product models associated with numerically controlled machine tools.

The fourfold increase in oil prices in 1974 not only halted the growth of tankers but encouraged the search for offshore oil. While jack-ups were adequate in shallower waters, drilling in deeper waters required semi-submersibles. Motion analysis programs were essential, and coupled with dynamic positioning using thrusters, resulted in increased operability in all manner of offshore vessels. Many of these vessels had helicopter landing decks, as did most major warships from the 1960s.

The bulk carrier concept of a single deck vessel with hoppered holds was not new, as it had been used in short sea gas and electricity colliers for decades. But it was not applied to deep sea ships until the late 1950s, although deep sea iron ore carriers with their small central cargo holds dated from the 1920s. The bulk carrier design was ideal for grain and ore cargoes, which hitherto had been mostly carried in tween-deck cargo vessels. Size grew steadily from the initial 15,000dwt to over 100,000dwt by 1968 although the 60-70,000dwt Panamax proved popular with a breadth of 104ft, later 106ft (32.2m), to get through the locks. The development of the combined carrier (ore/oil or ore/bulk/oil) in the late 1960s proved popular initially, offering the ability to switch cargoes between voyages, either to reduce ballast steaming or to take advantage of higher freight rates in the other market. But by the 1990s disadvantages outweighed advantages, with requirements for double hulls and high standards of hold cleaning between oil and dry bulk cargoes, so that few have been built since then. Although the smaller bulk carriers had their own cargo handling gear to enhance their 'go anywhere' capability, initially derricks then cranes, the bigger ships carried no gear, trading as they did between relatively few ports handling iron ore and coal, so relied on shore gear.

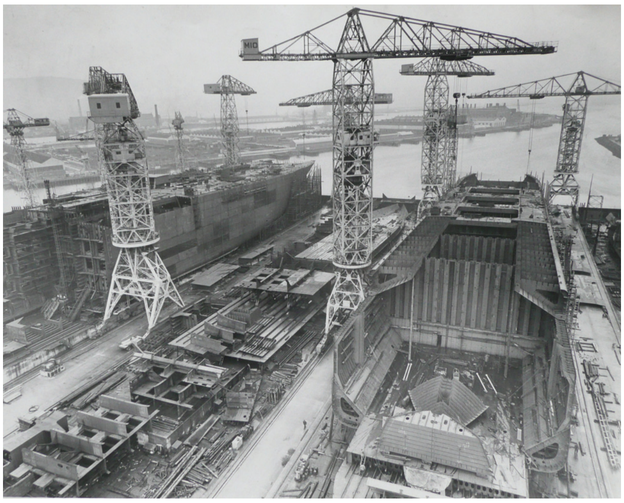

Figure 11. The single deck bulk carrier developed quickly in the 1960s as far more suited to cargoes like ore, coal and grain than tween-deckers. This view of 76000dwt Essi Kristine under construction at Harland & Wolff's Belfast shipyard in 1967 shows the now classic hoppered hold shape with topside wing tanks. To the left is an early VLCC, Shell's Myrina of 190000dwt. Such vessels were difficult to build on conventional slipways, so shortly afterwards H&W built their 556m x 93m building dock in the Musgrave Channel, immediately behind the tanker, with one (later two) 840ton goliath crane spanning the dock, permitting much larger prefabricated units than was possible with the berth cranes seen. Such building docks were widely constructed from the mid 1960s, usually in 'greenfield' shipyards – but often actually land reclaimed from the sea.

The late 1950s and 1960s saw a great increase in specialist ship types, as demand for large volumes of cargoes like export motor cars justified a tailor-made design rather than a general purpose ship. The growth in car exports initially from Europe, later from the Far East, brought about the pure car carrier, a floating multi-storey car park initially capable of carrying about 1000 cars, but around 8000 today. The first purpose-built chemical (parcels) carrier was *Marine Dow-Chem* built in 1954. Chemical resistant tank coatings such as epoxies and zinc silicate and some tanks built of stainless steel allowed a huge range of chemicals to be carried in bulk in a single ship. That also required the development of segregated pumping and piping systems, so that the submerged (deepwell) pump was born, hydraulically driven from the deck.

Liquefied Petroleum Gas (LPG) carriers were another 1950s development, where cargoes like propane could be liquefied either by cooling to about -48^{o}C, or in smaller tanks by pressure alone. A more demanding technology was required for Liquefied Natural Gas (LNG) which liquefies at -163^{o}C, so having heavily insulated tanks separate from the main hull structure. The first purpose built LNG ship was *Methane Progress* of 27,400m^3 with aluminium alloy tanks in 1964. Spherical tanks were developed by Moss-Rosenberg, but the most popular design proved to be the membrane tank, a prismatic tank with a thin cryogenic lining supported all around by insulation and a secondary barrier (in case of LNG leakage causing brittle fracture). LNG carriers plateaued in size at around 130,000m^3 for over two decades, but in recent years have broken the 200,000m^3 barrier. Such vessels were for long the last outpost of steam turbine technology as the boil-off gas could be readily burned in the boilers. More recently diesel-electric machinery plus reliquefaction plant has been used.

The impetus for specialist ships comes when the volume of a particular trade expands to a level sufficient to support a custom-built fleet. Although specialist port facilities are also required, the increased efficiency and improved quality of cargo outturn outweigh the lack of flexibility for alternative cargoes. Flexibility was the key attribute of the general purpose (multi-deck general cargo) ship, which dominated such trades for over a century. It was the inefficiencies of the latter that spurred the development of the container ship to speed up general cargo handling, eliminate labour intensive methods and reduce port time from a week or so to a day or so. Although early vessels developed for Sea-Land's US coastal trades were based on road trailer dimensions (but using the cellular stowage principle), standardisation of container dimensions by ISO in 1965 paved the way for its widespread adoption. The now ubiquitous 20ft and 40ft boxes (no-one talks of 6.1 or 12.2metre containers) allowed mechanised handling and stowage processes and equipment to be developed, ranging from gantry cranes to container spreaders to straddle carriers to lashing mechanisms, as well as intermodal transfers to road and rail vehicles. Steel hatch covers were designed to take containers stacked on them; today up to half the container load can be stowed on deck, the rest in cell-guides in the holds.

Such was the increase in productivity from larger faster container ships that one vessel replaced five or six break-bulk vessels, so all the main trade routes had been containerised by the mid 1970s. Since then the 3000 TEU (twenty foot equivalent unit) ship has grown to 14,000TEU, although speeds have remained in the mid 20s knots. Following oil price increases, the steam turbine container ships of around 80,000shp (60MW) of the early 1970s gave way to slow speed diesel ships, with engines now available with up to 115,000bhp (85MW) with 14 cylinders on a single screw of around 10m diameter.

Figure 12. Standardisation of container dimensions and fittings in 1965 enabled the widespread adoption of containerisation, slashing port time for general cargo ships so permitting much larger ships. The deck stow roughly doubled the number of containers carried in the holds. Until the 1980s, such ships were designed to the limits of the locks of the Panama Canal (built in 1914), corresponding to about 4600TEU (twenty foot equivalent units), the size of Dusseldorf Express seen leaving Miraflores Locks. Ships of three times that capacity are now in service, which will be able to transit the third set of locks due to open in 2014.

It was in the 1950s that the use of turbocharging in 2-stroke diesels (previously in 4-strokes), heavy fuel oil and cylinder bores approaching 1000mm enabled the slow speed direct drive engine to challenge the steam turbine in bigger ships. That remains the prime mover of choice today, although the emphasis is now on reducing emissions which require higher quality fuel. Medium speed diesels had been developed between the wars (sometimes based on submarine or locomotive diesels), and post-war were widely favoured in smaller vessels and in low headroom ships like ferries, usually geared rather than direct drive.

The short sea roll-on/roll-off vessel evolved from the Second World War tank landing ships in the 1950s. They offered big reductions in port time where trailers could be used, as well as providing a drive-on/drive-off facility for cars and trucks. These required innovation in cargo access equipment, with external and internal ramps and elevators. The same concept was applied to deep sea ro-ros in the late 1960s carrying cargoes such as forest products and containers, block stowed on the decks or on trailers. But after two decades of competition, the cellular container ship won out, partly by being better suited to the hub-feeder concept, with large mainline ships serving major ports like Rotterdam supplied by smaller feeder container ships from secondary ports.

There had been great expectations from barge carriers from the late 1960s, with lift-on/lift off concepts like the 380dwt LASH (Lighter Aboard SHip) barge and even a few float-on/float-off designs. While loading or discharging the mother ship could be done in hours, the cargo still needed handling to and from the barge itself, perhaps at an upriver berth. But the mainly low value commodities that could move in 380-ton parcels could not support the high costs of the operation, so by the late 1980s nearly all barge carriers had been converted or scrapped.

Post WW2 deep sea passenger vessels continued to be built in significant numbers. Innovations such as stabilisers and later bow thrusters made for a more comfortable voyage and easier manoeuvring. Bulbous bows were often fitted, tuned to their relatively high Froude number and near constant draft – later bulb shapes were developed for a much wider range of hull forms and drafts. Aluminium superstructures were introduced in the mid 1950s, which allowed an extra deck to be fitted without jeopardising stability, as well as doing away with troublesome expansion joints. But long distance passenger sea transport had been overtaken by air transport by the late 1950s, so by the late 1960s all the large liners had been scrapped or converted to cruising or become museum ships, as *Queen Mary* at Long Beach in 1968. But as that door closed, another opened, the purpose built cruise ship (not 'cruise liner', as they do not operate on a fixed route). Pioneered by Scandinavian owners, ever larger and more luxurious floating leisure centres developed into today's 150,000gt plus monsters carrying over 4000 passengers – the 200,000gt/6000-pax barrier was broken in 2009. Technical problems requiring solution included structural integrity and safety with large open spaces like atriums, hotel electrical loads comparable with propulsion loads leading to diesel-electric systems, multiple thrusters (including stern as well as bow) and podded propulsors, improved fire protection, lifesaving appliances and subdivision.

Figure 13. .Spanning almost the entire century and a half, high speed catamaran Normandie Express passes preserved ironclad Warrior (right) at Portsmouth in 2008. Both are about 6000tons gross. Warrior was built in 1860, iron hull, 5470 ihp steam reciprocating machinery with single screw, 14 knots and rendered

obsolete wooden walled battleships. Normandie Express was built in 2005, aluminium hull, 38,500shp medium speed diesels with four waterjets, 42 knots, 850 passengers, 235 cars.

Transport of passengers is today focussed on short sea and local ferries, with a huge variety of designs, usually including vehicle transport. Sizes now exceed yesteryear's deep sea liners, 50,000gt being not uncommon on some European routes, at over 20 knots. From the 1960s, high speed craft began to challenge conventional ferries on short routes, initially air cushion vehicles and hydrofoils with speeds of 35-50 knots. With their inherently low lift/drag ratio, light alloys were needed to keep hull weight down and gas turbines were often used to provide the high power. Steady growth has continued, with some craft now carrying around 1500 passengers and 400 cars at speeds of over 40 knots. But it is the catamaran concept that dominates the fleet today, where two slender hulls offer low drag while the bridging structure offers space. Medium speed diesels have often proved more economical than gas turbines, with both types of prime movers coupled to the ubiquitous waterjet (up to four). Freight-only high speed craft have yet to challenge conventional ro-ro's on short sea routes. On deep sea routes, the problems of seakeeping, large fuel load and cost, and low payloads await enabling technologies to improve lift/drag ratio and fuel consumption significantly – a problem that early aircraft also faced.

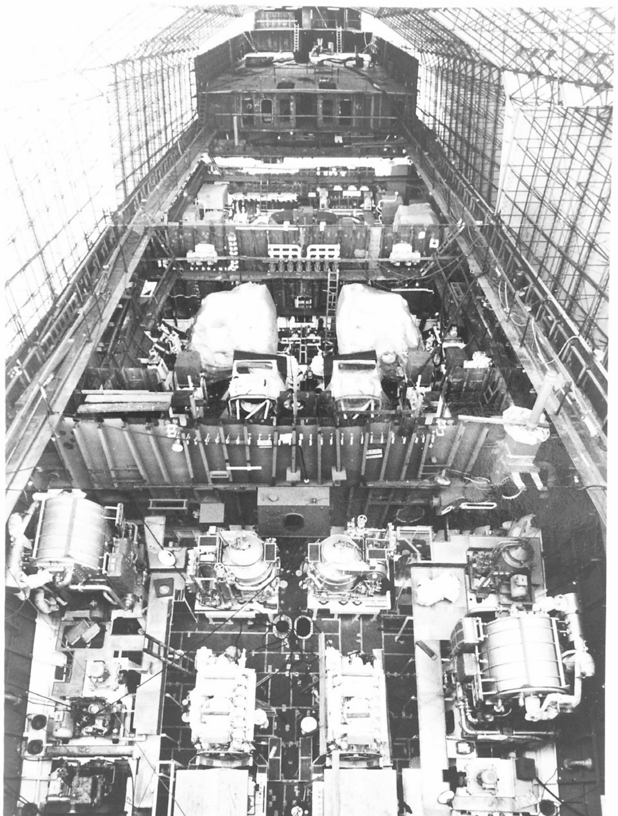

Figure 14. Gas turbines were an important enabling technology for fast warships, permitting high power in a compact space, with lesser manning and maintenance from the 1970s. With gas turbines being of lower efficiency at modest cruising powers, it was common to fit two gas turbines per shaft, one for boost to around 30 knots, and one for cruise up to about 20 knots (sometimes diesel). The frigate Sheffield has three machinery spaces. Nearest the camera is the Aft Auxiliary Machinery Room with two diesel generators in the centre, two auxiliary boilers in front of them with auxiliary machinery modules and distillation plant at each side. The middle compartment is the Aft Engine Room, showing the two 5000shp Tyne gas turbines and forward the much bigger gearboxes. The further compartment is the Forward Engine Room, although the two 25,000shp Olympus gas turbines are barely visible.

Gas turbines have been the prime mover of choice for most high speed warships from the late 1960s, derived from aircraft jet engines, although the first seagoing (industrial) gas turbine was fitted in a British torpedo boat in 1947. High power-weight ratio, compactness, repair by replacement, reduced manning and quick starting have for military vessels outweighed the disadvantages of high fuel cost, few frame sizes, lack of reversibility (usually achieved by controllable pitch propellers), large uptakes and downtakes, and possible salt spray ingestion. Electric propulsion technology with high power density motors has increased the number of ships with full electric propulsion, especially those with a wide range of power demands, whether naval, commercial or offshore. Azimuthing thrusters have become the propulsor of choice for tugs, two giving great manoeuvrability under one-man control, hence a smaller crew.

While some high speed craft have been built of fibre reinforced plastic, a much larger market has been in mass produced leisure craft, where low maintenance has been an advantage. Its non-magnetic properties encouraged the use in mine countermeasures vessels from the mid 1970s. Fishing vessels have been built in the widest range of materials, also including timber and ferro-cement, but the stern trawler offering safer operation for the crew is usually built in steel.

Supporting technologies have had a collective impact on ship performance. Self polishing tin-based co-polymer anti-fouling coatings in the 1970s provided smoother longer life protection, a capability now offered by foul release (non-stick) coatings since the ban on TBT-based coatings in 2003. Inert gas systems for hydrocarbon cargo tanks from the 1960s improved the safety of tankers, based initially on scrubbing flue gases from boilers. Automation starting with auto-pilots has reduced crew number down to half a dozen on coastal vessels and around a dozen on some deep sea ships with dual trained deck and engine crews. Improved navigating aids have helped reduce ship casualty rates, although both the quantity and quality of experienced seafarers continues to concern ship operators – airlines do not have similar problems. Full integration of technical and commercial requirements to optimise ship voyages and port performance each day to take account of internal and external conditions (including weather and fuel prices) is now within reach.

But perhaps the most pervasive recent technical influence has been the ever increasing regulatory demands and standards. Coordinated by the International Maritime Organisation, the intent is to achieve international agreement before implementation by individual flag states, e.g. ballast water treatment. Classification societies, concerned with the integrity of hull and machinery systems, have expanded in number. The International Association of Classification Societies (IACS) tries to coordinate technical requirements through such means as Common Structural Rules for tankers. But the marine industries have for historical reasons had more fragmented regulatory regimes than land based national industries, so adoption of readily applicable best practice takes time. So perhaps what the marine industries need in the next decades is to focus enabling technologies on getting the best out of well established concepts like bulk carriers and diesel engines by improving operational efficiency and mitigating potential hazardous and environmental impacts of ships, but without jeopardising the technical and economic gains of the last 150 years, i.e. optimising benefit-cost ratios, not purely in monetary terms. The professional institutions have a continuing role in discussing and disseminating the best ways forward, largely using the English language, now universally adopted in the maritime industries.

SOURCES

Such an overview necessarily draws on a wide variety of sources, far too many to cite, but the list below was useful. Personal files started in a shipyard 50 years ago and the British Shipbuilding Database covering some 80000 British-built ships has provided much of the underlying technical data.

BIBLIOGRAPHY

1. "A Modern System of Naval Architecture". 3 vols. J Scott Russell, 1865.
2. "Ship", "Shipbuilding" chapters. P.WA (Philip Watts). Encyclopaedia Britannica Vol XXXII 1902 p.539-602.
3. "Ships and Efficiency. One Hundred and Fifty Years of Technical and Economic Developments." I L Buxton. Trans RINA 2001.
4. "The Development of the Merchant Ship 1880-1990". I L Buxton. Mariners Mirror February 1993.
5. "Steam at Sea: Two Centuries of Steam-powered Ships". Denis Griffiths. Conway Maritime Press, 1997.
6. "A Short History of Marine Engineering". E C Smith. Cambridge University Press, 1937.
7. "Warrior to Dreadnought. Warship Development 1860-1905". D K Brown. Chatham Publishing 1997.
8. "The Grand Fleet. Warship Design & Development 1906-1922". D K Brown. Chatham Publishing 1999.
9. "Nelson to Vanguard. Warship Design & development 1923-45". D K Brown. Chatham Publishing 2000.
10. "Rebuilding the Royal Navy. Warship Design since 1945". D K Brown & G Moore. Chatham Publishing 2003.
11. "The Advent of Steam. The Merchant Steamship before 1900". Conway's History of the Ship. 1993.
12. "The Golden Age of Shipping. The Classic Merchant Ship 1900-1960". Conway's History of the Ship. 1994.
13. "The Institution of Naval Architects 1860-1960". K C Barnaby. RINA 1960.
14. "Warships 1860-1960" A J Sims. Trans RINA 1960.
15. "Merchant Ships 1860-1960". J M Murray. Trans RINA 1960.
16. "Historical Transactions 1893-1943." Society of Naval Architects & Marine Engineers, 1945.
17. "A Half Century of Maritime Technology 1943-93". Eds H Benford & W A Fox. Society of Naval Architects & Marine Engineers, 1993.
18. "A Century of Service to Engineering & Shipbuilding 1884-1984". J F Clarke. North East Coast Institution of Engineers & Shipbuilders, 1984.

