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NAVAL PROPULSION MACHINERY

THE AUTHORS

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Editor's Note: This paper carries the subject from the beginning up to the early days of Naval Engineering renaissance. This rebirth began at about the time of foundation of ASNE in 1888. Another paper by these authors to be included in the August issue, will carry the story forward, through two world wars and into the predictable future.

INTRODUCTION

VOLUME I of the Journal of the ASNE, 1889, carries in its Notes on British Manoeuvres an item we have taken the liberty to excerpt as follows:

"The Saturday Review in an excellent article on The Naval Manoeuvres emphasises the opinion expressed by one of the 'Times' correspondents that the real cause of so many breakdowns in the machinery of modern ships is to be found in the persistent endeavor of naval architects to cram three horses into a stable with stalls for two. The result is that engines and boilers cannot be made heavy enough—which is synonymous to strong enough—to withstand the strains to which they are subject nowadays. . . . It will hardly be believed to what absurd lengths this saving of weight in machinery has been carried of late. We are ourselves acquainted with a ship, one of the belted cruisers, in which it was proposed by the Chief Engineer to fit a small piece of piping with the object of improving her feed arrangements; the length of the new fitting was, say, 3 feet, and the weight of it 20 pounds. Not long ago it would have been objected to on account of cost, but in this case it was refused on the score of the extra weight that would be involved, although its extreme usefulness was readily admitted by the authorities. This same vessel has been supplied with a bell which is big enough for a cathedral, and is hung from a bracket heavy enough to serve as a derrick for hoisting out her steam cutter.—Army & Navy Gazette, Sept. 1, 1888."

To the above, we can only add that the problem is still with us in the U. S. Navy. It has changed only in scope and in the magnitude of the shaft powers involved. We are still under pressure to provide more and more power in less and less space and with less and less weight of machinery. We must allow more and more room for the constantly increasing electronics and weapons systems, for which we must continually provide more and more kilowatts of electricity. In addition we are asked to design our machinery as simple as possible to be operated and maintained by as few men as possible; because of the increasing demands for skilled manpower for the so called "Sophisticated" weapons and electronics systems.

This continuing pressure, we believe, has served, and will continue to serve the most useful purpose of improving the state of the art of naval ship machinery. Given sufficient time and necessary funds for development, as well as the cooperation of the ship designers (apparently improved much since 1888), we can foresee in the next decades improvements in naval machinery even more remarkable than has occurred between the time of Newcomen's pumping engine to the present day. In this presentation and the ones that will follow, we will trace this development with emphasis on naval applications and, finally will attempt to predict what may be in store for the future.

EARLY STEAM ENGINES

The idea of obtaining motive power from boiling water is very old. It had been attempted by ingenious men for many centuries before it finally came into being. The fascinating early history of the steam engine has been detailed by many skilled writers, [1, 2] and no purpose would be served to repeat it here. We will instead, concentrate on the early successful working units and their development to a form and capability for ship application.

Thomas Newcomen built the first successful steam engine in England probably in 1712 for pumping water out of coal mines. See Figure 1. It was very successful for its time and purpose, and many such engines (over 100) were built in England and on the continent of Europe. It was reciprocating, with a large hinged beam actuating the pumps. Steam pressure was slightly above atmospheric. The cylinder acted as a jet condenser, and the power stroke occurred on condensation. In making the valves automatically operated by pins suitably placed in the plug rod, Newcomen and his associates had designed the first self-acting mechanism since the invention of the clock. By trial and error, they apparently found that the steam must be injected for a sufficient time to blow out the air accumulated

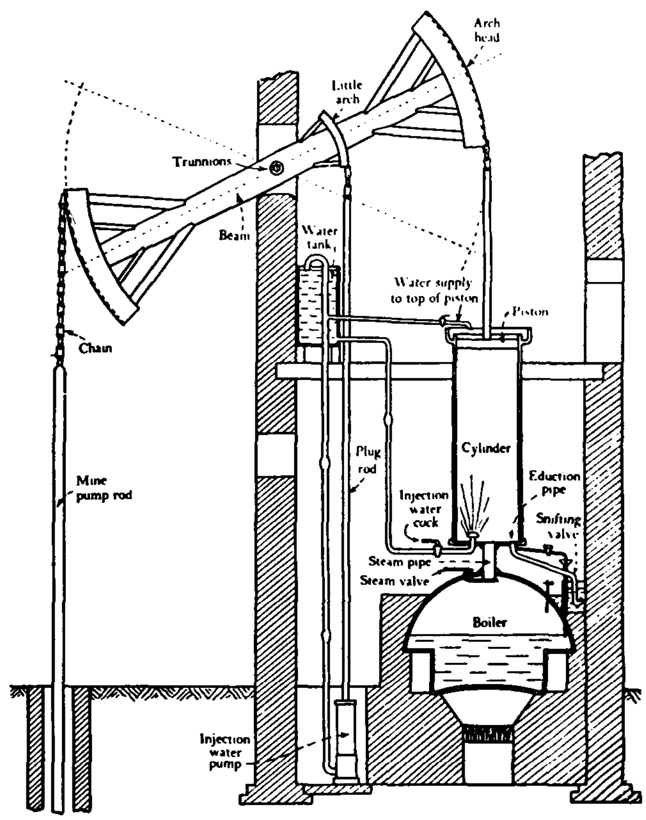

Figure 1. Sketch of Newcomen Engine.

in the cylinder. The snifter valve was provided for this purpose.

Newcomen's engine vibrated about 12 times a minute and produced about 5½ HP of output. Its size was monumental. A scaled engraving, made in 1719, shows approximate overall dimensions of 44 ft. high by 33 ft. wide by at least 12 ft. depth. This includes the boiler, engine, beam and brick supports. John Smeaton, in 1769, averaged the performance of 15 such units of varying size with cylinders up to 72 inches in diameter, and estimated a duty of 5.59 million ft. lbs. per bushel (then 84 lbs.) of coal [1]. This corresponds to a specific fuel rate of 29.8 lbs. per HP-hr. and a plant thermal efficiency of about 0.5 per cent, with pump included.

Starting in 1772, James Watt of Glasgow introduced a separate jet condenser with an air pump. See Figure 2. He pioneered improved valves and linkages, the rotating engine, the flyball governor, a form of engine indicator, and many other refinements including the use of oil and tallow for piston lubrication. By providing the separate condenser and keeping the cylinder hot, Watt decreased the fuel rate by about 75 per cent to about 7.2 lbs. of coal per HP-hr. of useful work. The corresponding thermal efficiency was about 2.5 per cent. He built the first double-acting, rotative engine, with flywheel, in 1783. Reversing was accomplished by stopping the engine and starting the flywheel going the other way. Watt also experimented with expansion of steam in the cylinder, but avoided its use because of the little benefits accruing with the low steam pressures then available with the copper pot type of boiler. Watt was ably supported by

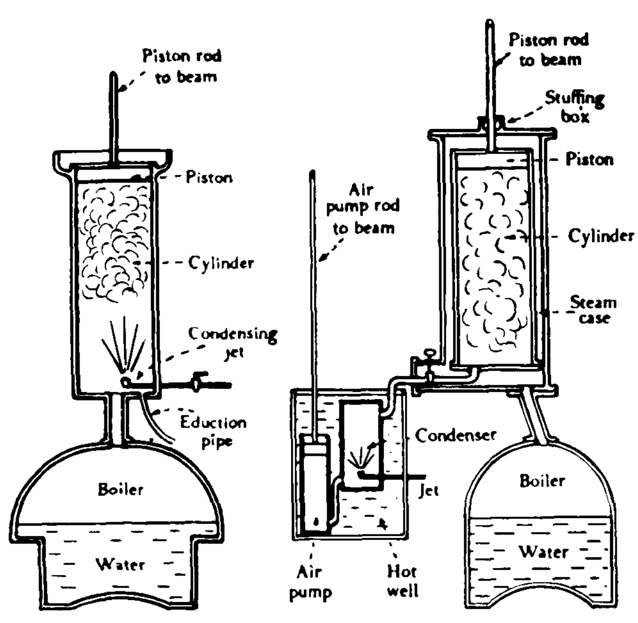

Figure 2. Sketch of Walt Engine compared with Newcomen Engine.

Matthew Boulton, his partner and business advisor. By 1800, when the business was taken over by their respective sons, the firm of Boulton and Watts had built about 500 engines of which 62 per cent were the rotative type [1].

It remains for Oliver Evans, of the U. S. in 1804, and Richard Trevethick of England to build "high" pressure engines using steam pressures of several atmospheres. Each introduced early versions of fire tube boilers to produce the steam. Both engines exhausted to the atmosphere. Trevethick actually built and operated a steam carriage in 1801, and finally built a successful passenger locomotive to run in London. Evans' engine was direct, double-acting, with vertical cylinder. His boiler was of copper reinforced by iron bands.

Arthur Woolf of England, brought out his 2 cylinder compound engine in 1811 with a significant improvement over the Watt engine. In 1812 Trevethick modified Watt's condensing engine for higher pressure and for steam expansion to approximate the performance of the Woolf engine.

From this point on steam pressures increased by small increments and improvements came in rapid succession, from contributors too numerous to mention here. Boilers, engines, valves, packing, governors, reversing gear were all improved in the next 30 years. Performance of stationary steam engines in lbs. of coal, per HP-hr. of output improved from 6.9 in 1814 to 3.4 in 1835 to 1.8 in 1842. The approximate corresponding increases in plant efficiency were from 2.7 per cent to 5.5 per cent to 10.6 per cent. The early engines were at first too cumbersome to be successfully accommodated for ship propulsion. However, the refinement of Watt's atmospheric engine and its subsequent replacement by the higher pressure engines made possible for the first time, the practical application of steam power for marine propulsion. Here we leave the stationary engine and examine the beginnings of ship steam propulsion especially in connection with the development of our steam Navy.

EARLY STEAM BOATS

The idea of moving a boat by steam is probably as old as the idea of a steam engine, since most of the early thought on the use of steam was aimed at such an application. Though a most interesting subject, we will skip over this early history [3, 4, 5], and start with the first successful applications.

It is probable that the first technically successful steamboat was built by the Marquis de Jouffroy in 1781 in France. What is known in this case is that his boat was 140 feet long by 20 feet wide; that his early tests on the Seine River were sufficiently successful so that a favorable report was made by two of its members to the French Academy of Sciences. Unfortunately the French Revolution *interrupted* his work and it was never continued.

Technically successful steam boat design was initiated in the U. S. about 1785 almost simultaneously by both John Fitch in Philadelphia and James Rumsey in Virginia. Both built several steamboats between 1787 and 1793. Fitch's last boat, the *Experiment*, built in 1789, was the most successful up to that date. See Figure 3. It is said to have made up to 6 knots and ran regularly as a packet from Philadelphia to cities on the Delaware River. It logged at least 2000 miles during the first summer, but was then laid up permanently because the operating cost exceeded the income from transportation. Both Rumsey and Fitch apparently used locally-built atmospheric engines with water jet condensers. Fitch used an oscillating steam engine with a ratchet device to chain drive a set of vertical oars arranged to simulate rowing motion. Rumsey used a steam driven pump to draw water in at the bow and eject it at the stern; an early form of jet propulsion.

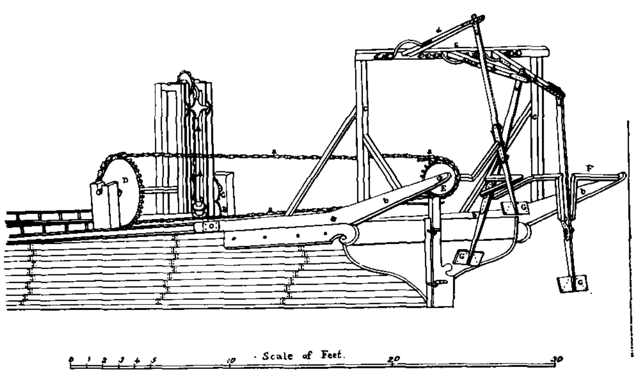

Figure 3. Sketch of John Fitch's *Experiment*.

In addition to Rumsey and Fitch, operative steam boats were built in the same general period by the following:

1788—by Miller, Taylor and Symington, in Scotland
1791—by John C. Stevens, in Hoboken, New Jersey
1794—by Elijah Ormsbee, in Rhode Island
1794—by Samuel Morey, in Connecticut
1801—by Hunter and Dickinson, in England

Many others investigated steam propulsion during this period, including Benjamin Franklin and Nicholas Roosevelt.

Various unique types of propelling devices were tried on these early steam boats. In addition to Fitch's vertical oars, and Rumsey's water jet, there were helical propeller-like devices, oscillating goose feet, the endless chain (operating like present date amphibious tracked vehicles), and the fixed paddle wheel; the latter was the device which finally caught on.

Robert Fulton's *Clermont* completed in New York City, in 1807, was the first financially successful steamboat to be built. Fulton had the advantages

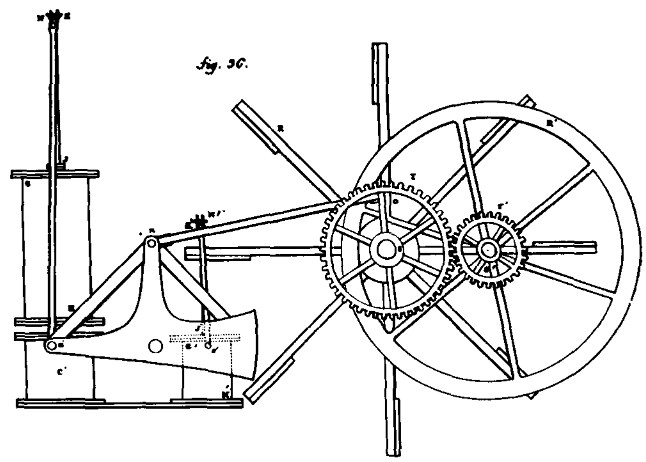

Figure 4. *Clermont* Engine from Sketch by J. B. Marestier.

of financial support from his friend and partner, Chancellor Livingston of New York. He also had the exclusive rights for 20 years for the operation of steamboats in New York State waters, awarded by an act of the legislature in 1803. He had experimented with steam propulsion in Paris in 1803 and 1804, and had studied the designs of other steamboat builders. While he can not be strictly called the inventor of the steamboat, he did assemble a design that led to the widespread use of steamboats on the rivers and inland waterways of the U. S. and to the early pioneering of oceangoing steam vessels. He used a Boulton and Watt side lever engine, with 24″ bore by 4′ stroke, a typical copper low pressure boiler set in masonry, an air pump, and jet con-condenser. (See Figure 4.) The engine drove two side wheels, 15 feet in diameter with 4 feet wide fixed buckets with about 2 feet of water immersion. The engine output was about 24 HP and the plant efficiency probably less than the Watt and Boulton stationary plant of that period because of the necessity of blowing down the saline Hudson River water. Steam pressure was about 5 psi, saturated. The engine alone weighed about 20 tons. Figure 5 shows

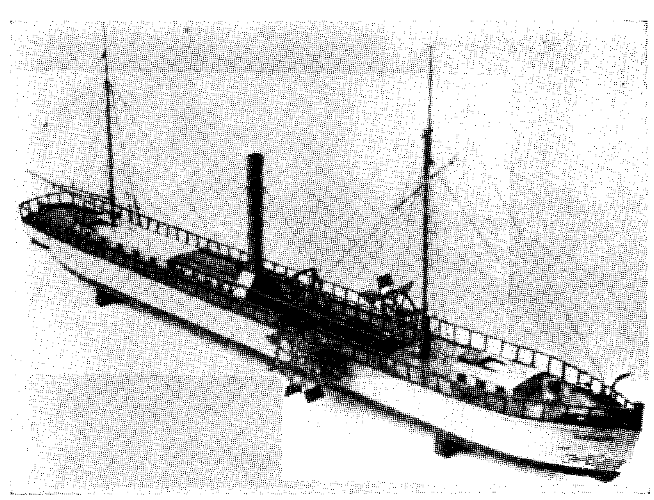

Figure 5. *Clermont* Model of National Museum.

a scale model of the *Clermont*, on view at the National Museum of the Smithsonian Institute.

The first trip of the *Clermont* was 150 miles from New York to Albany and was made in August 1807 at an average speed of 5 statute miles per hour. When completed and enlarged during the following winter, the ship, actually registered as the *North River* was about 160 tons displacement, 160 feet long by 18 feet beam by 7 feet depth with 52 sleeping berths and accommodations for a total of 100 passengers. Because of its success, Fulton and his associates built 5 more such passenger steamboats by 1812, and continued to build more. The *Chancellor Livingston*, designed by Fulton but built in 1816, after his death, had a 60 HP engine at 17 RPM.

It is interesting to note that the *Phoenix* of John C. Stevens and his son Robert, made its first successful trip out of Hoboken just a few days after the *Clermont's* first trip. Fulton's monopoly on the Hudson kept the *Phoenix* operating on less lucrative runs. In 1809 it made the first steamboat voyage into the open sea, from Hoboken around Cape May to Philadelphia.

One should also mention Oliver Evans of Philadelphia who in 1816, provided high pressure engines, over 100 psi, with cut-off and expansion to two successful steamboats, the *Aetna,* and the *Pennsylvania*. However, higher pressures were generally feared and avoided by builders of that day and pressures increased very gradually with time, even though the potential weight and space saving was great.

The success of Fulton and others led to the rapid construction of steamboats both here and abroad. By 1819, 100 steam vessels had been built in the United States, and 43 had been built by the British. By 1830 the speed of our river and bay steamers had been increased from 7 to as much as 20 statute miles per hour. By 1839, the total steam vessel tonnage of the U.S. was about 200,000 tons while that of Great Britain was about half that amount. However, the U. S. vessels were built mainly for use on inland waterways [2]. There were several reasons for this. This country already possessed an efficient and numerous sailing ship merchant marine, while the rapid westward expansion of the country created a great demand for river steamboats where wood and often coal, were very available for fuel. Sails were cheap; coal was dear in coastal cities. Cast and wrought iron was expensive. Furthermore, the strong East to West winds of the Atlantic Ocean required too much fuel consumption for the heavily laden bound vessels.

The first oceangoing ship using steam was the New York built *Savannah* in 1819, which made the passage from Savannah, Georgia to Liverpool in 25 days, using sails assisted by steam. The engine, rated at 90 HP at about 5 psi, was not used continually to prevent the fuel from giving out. With engine alone, it probably made about 5 knots. When not under sail the paddle wheel could be unshipped and folded up on deck. This ship created a sensation coming into Liverpool harbor with sails furled and smoke belching from the stack. However, the owner and conceiver of the vessel, William Scarborough of Savannah, Georgia, was much ahead of his time. Failing to sell the ship to the government for use as a warship he was forced to sell it at auction. It was converted to a sailing packet and spent the rest of its days operating between east coast cities of the U. S. The National Museum, (Smithsonian Institution) after much research, has recently undertaken the construction of an authentic scale model of the *Savannah,* which should be on exhibition this June [7].

No discussion of oceangoing steamships would be complete without mention of the British built *Great Western,* which inaugurated a regular steamship passenger service from England to the United States in 1838 [2]. The first voyage from Bristol to New York took eight days. The ship was 236 feet long with a displacement of 1320 tons. It was powered by 200 HP side lever engines and four 5 psi boilers, which used about thirty tons of coal per day, for a plant efficiency of about 5.6 per cent. The *Great Western* made 74 round trips before she was disposed of, in 1846.

Sailing ships predominated for many decades in the merchant marine of all countries. It wasn't until the invention of the open hearth process for making steel, and the adoption of the compound engine and the screw propeller, that the steam vessel could compete with the sailing vessel in carrying large cargoes long distances. And, it was not until late in the 19th century that the steam tonnage began to overtake the sailing ship tonnage, in this country and in the British empire. For many years, therefore, oceangoing steam propulsion was more the concern of the U. S. Navy than of the merchant marine. It is to steam warships of the United States that we now transfer our attention.

EARLY STEAM NAVY OF THE UNITED STATES

The *Demologos* (voice of the people) or *Fulton* as it was later named, was the first war steamer ever built by any Navy of the world [4, 6]. It was authorized in 1814 and completed in New York in May, 1815. Unfortunately Fulton died before its completion. This ship was completed shortly after peace was concluded with England. Had it been used successfully against the British blockade, there is no telling what impact this would have had on accelerating the use of steam in the Navies of the world. It was a formidable ship for its day. Figure 6 is from drawings recently discovered by the National Museum, (Smithsonian Institution) in the Danish National Archives. Figure 7 shows the *Fulton* boiler as sketched in 1823 [3]. *Fulton's* displacement was 2475 tons. It had a single vertical

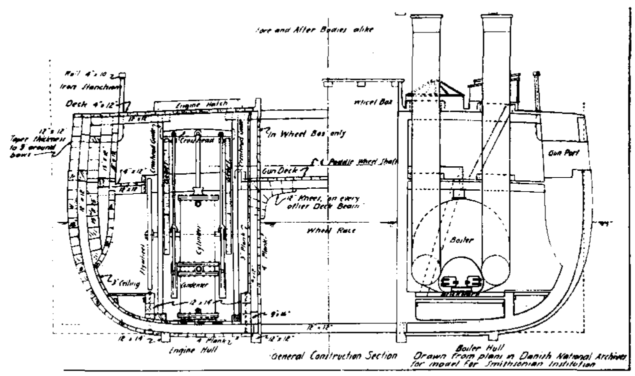

Figure 6. Section of *Fulton* 1st, showing machinery plant.

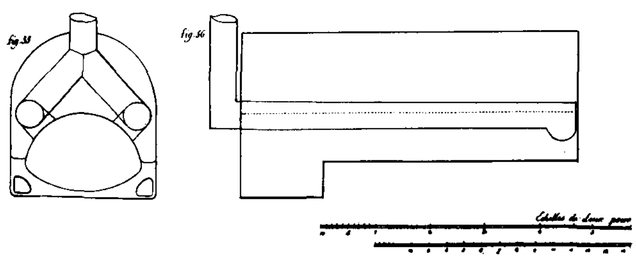

Figure 7. Sketch of *Fulton* 1st boiler, by J. B. Marestier.

cylinder low pressure condensing engine, with 48" bore by 5 feet stroke and was fitted with two 22 feet long return flue copper boilers operating at about 5 psi. It consisted of two keels, decked over with a protected 16 feet diameter paddle wheel in the tunnel. It had four rudders, two at each end, and could make an average speed of about 5½ knots in either direction. For armament it carried 20 thirty-two pounders, and it had sides of solid protective timber 4 feet, 10 inches thick. Its Commander, Captain David Porter, added two masts for sails and increased the height of the sides for added protection. It made several successful trips on engines alone in the open sea and then was used in the Brooklyn Navy Yard as a receiving ship. It was destroyed by a magazine explosion in 1829.

The second large U. S. Naval vessel was the "*Fulton, 2nd*" built in the Brooklyn Navy Yard in 1837. The engines were manufactured by the West Point Foundry Association, of New York. Displacement was about 1400 tons, with a length of 180 feet, an extreme beam of 34 foot-8 inches, and a mean draft of 10½ feet. It was fitted with three masts, and was rigged as a topsail schooner. There were two horizontal condensing engines on the spar deck, each operating one 22 foot-10 inch side paddle wheel. Buckets were fixed, and were 11 feet-6 inches long by 3 feet wide. The engines had an early type cut-off and were operated on 11 psi pressure from 4 copper double return flue boilers supplying each engine. Estimated HP was 625, and the total weight of machinery was about 241 tons. Specific weight was then about 860 lbs. per horsepower. From a copy of her weekly log we have computed her plant efficiency to be about 3 per cent. Its maximum speed approached 15 knots. This vessel could carry fuel for only two days steaming and was intended as a floating battery in defense of New York Harbor. The armament consisted of 8 forty-two pounders and 1 twenty pounder.

In 1852, *Fulton 2nd* was rebuilt as *Fulton 3rd*, but still with sailing rig. The machinery was replaced by a single inclined condensing engine with Sickles cut-off, and two wrought iron circular double drop return flue 30 psi boilers. Feathering paddle wheels were substituted for the original fixed wheels. Developed IHP was 899. SHP was about 760. Fuel was about 6 pounds per SHP hour for a plant efficiency of 3.4 per cent. Maximum speed was said to be about 14 knots. Specific machinery weight was about 450 lbs. per SHP. This ship was employed on general cruising duty at home and in the West Indies. It was taken over by the Confederates in Pensacola, Florida at the outbreak of the Civil War and was burned by them on evacuating that port in 1862.

Our seagoing steam Navy can be said to have really begun in 1842 with the wooden hulled side wheelers, *Mississippi* and *Missouri*. Each was sail-rigged, and was of 3200 tons displacement. They were identical except for the engines. The *Mississippi* had two side lever engines, 75" bore by 7 foot stroke. The *Missouri* had two inclined engines of the same displacement. Each had three copper boilers with steam pressures of about 15 psi. Their SHP is estimated as 300 per ship. The *Missouri* was destroyed by fire in 1843. The *Mississippi* was the flagship of Commodore Perry in the Mexican War and on his expedition to Japan. It cruised thousands of miles under steam, twice circumnavigating the earth, and finally was destroyed by Confederate gunfire in the river whose name it bore.

The *Michigan* was built for the Navy in Erie, Pennsylvania, about 1843, for operation on the Great Lakes. It is noteworthy for its iron hull and boilers and its relatively high steam pressure of 29 psi. The boilers were not replaced for 50 years. The vessel was still in operation in 1896. Its fuel rate was about 6 lbs. of coal per SHP per hour, for an overall efficiency of about 3.4 per cent.

The *Princeton*, completed in 1844 and designed almost exclusively by John Ericsson, was the first Naval warship of any country to have screw propellers. It was also the first warship with machinery placed entirely below the water-line, the first to use blowers discharging to the fireroom and to burn (smokeless) anthracite coal. Her engine was a unique oscillating rectangular piston type, ably described by Bennet in The Steam Navy of the U. S. [4] This ship was also rigged for sail. The *Susquehanna* and *Powhattan* built in 1851 were modeled after the *Mississippi*.

Wooden ships and sails combined with steam were still the order of the day, with screw propellers replacing side wheels. The period 1854-1858 saw the construction of the *Merrimac* of subsequent Civil War fame, and 10 additional ships, *Wabash, Minnesota, Roanoke, Colorado, Niagara, Pensacola, Lancaster, Hartford, Richmond*, and *Brooklyn*. Displacements (loaded) varied from 2600 tons (*Brooklyn*) to 5500 tons (*Niagara*). These ships generally had two large single expansion horizontal cylinders, slide valves with cutoff at about 0.3 stroke, and steam pressures of 12-18 psi. Vacuum was maintained at about 20-24 inches Hg. by jet condensers. Boilers were of the Martin, water tube type, with iron shell and copper tubes and with one large telescopic smoke stack per ship. A form of feed preheating was provided by means of the hot salt water boiler blowdown. Horsepower varied from 800 to 1300 per ship. Maximum performance of the *Merrimac* is said to have been 8.9 knots, 46.7 RPM, 1294 HP, and 3.28 lbs. of coal per IHP-hr. The efficiencies of the best of these plants was about 5 per cent. Specific machinery weight was about 900 lbs. per HP.

The *Pensacola* machinery was an exception to the above. Its machinery, though considered quite unreliable and eventually changed, incorporated many new ideas that came into common use many years later. These included pressurized firerooms, surface condensers, and scoops to assist the circulating water pumps. The surface condenser, first patented by Samuel Hall, in England in 1834, did not come into general Navy use until near the end of the Civil War. It was at this time that oil replaced tallow as an engine lubricant. The tallow had tended to clog the early types of surface condensers.

The *Niagara* achieved fame by laying the first Atlantic cable, together with HMS *Agamemnon*.

Seven screw sloops of 1200 to 1400 tons were built in 1858-60. Their machinery showed little innovation. The *Wyoming* had a closed surface condenser. The *Dacotah* had step-up gears to drive an 81 RPM screw with two 36 RPM engines. The *Pawnee* was the first screw ship to have twin screws.

CIVIL WAR STEAM NAVY

With the outbreak of the Civil War, Naval steam ship construction was rapidly accelerated. It began with wooden steam sloops, steam gunboats, and double-ended gunboats for narrow shallow rivers, and ended with the construction of iron-clads, of which John Ericsson's *Monitor* was the first to gain worldwide attention. By the end of 1864, the size of the federal Navy had increased from 26 steamers and 49,700 aggregate tons, at the outbreak of the war, to 558 steamers and 408,000 total tonnage; with about one-half of the new construction accomplished by the Navy Department [8].

The *Monitor* was one of three early ironclad designs contracted for by the Navy. The other two were the *Galena* and *New Ironsides* both of which saw much service during the Civil War. A number of more conventional ironclads were also built for the Army for use on the Mississippi, but it was the *Monitor* in her stand-off battle with the *Merrimac* that spelled the end of the construction of wooden ships. As is well known the *Monitor* was unorthodox and unique in its almost completely submerged hull which offered a very small target and permitted heavy (8 inch) wrought iron armor on a midships circular gun turret that could be rotated by steam power. The only other protrusions on its flat, almost awash deck was a much smaller, heavily armored pilot house and small removable stacks over its boiler discharge gratings [6, 11]. It was of about 1200 tons displacement, carried no sails and masts and could make about 9 knots. The engines were Ericsson's vibrating lever type [6, 10], and the boilers were wrought iron fire tube types of his design. It had a jet condenser, and one 9 foot diameter screw propeller. Steam pressure was about 18 psi. Two blowers took air through gratings in the main deck and discharged it into the boiler room. This ship was completed 100 days after the date of contract, and as is known to every school boy, arrived off Newport News, on March 9, 1862, a day after the *Merrimac*, and just in time to prevent the complete destruction of the blockading fleet of federal warships.

Over 70 ironclad ships were subsequently ordered, most of them larger versions of the *Monitor* with more speed, more seaworthiness; some with double turrets. The early monitor types were towed during long voyages. However they all could withstand the most powerful artillery at close range and were exceptionally useful at coming in very close to the opponents naval guns or fortifications. The U. S. Navy was not the first to use armored warships. The French Navy claims that distinction [2], in their Black Sea Campaign in 1855. However, the principle of the *Monitor*, especially that of fewer larger guns in heavily armored turrets, was immediately copied by other Navies. Some of the larger *Monitors* remained in the Navy for many years. Several double-turreted *Monitors* built in 1874, were not decommissioned until 1900, and were still on the Navy list in 1915. *Monitor* type warships continued to be built up to 1898. Many were used as submarine tenders during World War I.

CIVIL WAR STEAM MACHINERY

With the impetus given to shipbuilding during the Civil War, and with the rapid changes in warship design, one might be led to believe that there was a comparable amount of improvement in steam machinery. This is far from true. Steam pressures went up to 30 psi and stayed there. Engines remained single cylinder types, often with two cylinders in parallel. Boilers had been changed from copper to iron. Engine designs were refined. Valve gear was improved to provide variable cut-off and higher efficiency of operation. Surface condensers were introduced, and various types of water tube and fire tube boilers were compared. There are indications of much experimenting and study by the U. S. Navy, Bureau of Steam Engineering [8]. Steam superheat, and even the use of petroleum as a fuel, were investigated during this period. But two improvements that could have had the greatest impact, high pressure steam and compound engines, were apparently never seriously considered by any of the world's Navies at that time.

This may seem surprising in view of the fact that steam pressures on our western rivers had reached 135-150 psi by 1860 [9], and there were even several steamboats on these rivers with compound engines. Compound engines in mills and factories had been used in England since 1845. They had been introduced into British oceangoing merchant ships [2] in the middle 1850's with about 30 psi steam, mainly to reduce coal consumption. The British Navy followed in the early 1860's, but they, too, stayed with 30 psi steam. In the case of the U. S. river steamboats however, the more compact, high pressure engines were a necessity in the often shallow and fast running rivers. Moreover with wood as readily available fuel along the shores of the rivers, efficiency was often secondary to compactness, so that it was very common to provide single cylinder high pressure expansion engines exhausting to the atmosphere.

The Navy was, first of all, worried about the effects of a shell passing through a high pressure boiler. The Navy also had its sails; and so long as sails were available, steam was only needed during the period of battle, or when becalmed. Traditions die hard in the Navies of the world. Stubborn John Ericsson refused to put sailing masts on his *Monitor*, but it had to be towed from New York to Hampton Roads. What was lacking was another stubborn, inventive type, who could combine the higher pressures of the river steamboats with the compound engine designs of the British. This would truly have caused a revolution in naval designs.

However, we must remember that this was the age of the inventor, rather than of the scientist. The works of Carnot, Joule, Lord Kelvin, Clausius, Rankine and others were only beginning to be known outside of scientific societies, even though the Carnot theory of heat engines dates from 1824. It was not until 1859 that Rankine in his "Steam Engine and Other Prime Movers" first made clear to engineers the implications of the new science of thermodynamics on the design of a steam engine cycle. It is not too surprising, therefore, that burdened with the task of carrying on the bloodiest war of the century, the U. S. Navy did not make, what we can now see, would have been a very important improvement in steam plant design; one which would have eliminated sails in the Navy at a much earlier date. As it was, the sails plus screw combination continued to be the general rule in the Navy until the acceptance of the triple expansion engine, in the 1880's.

POST CIVIL WAR PERIOD, 1865-1898

For some time after the close of the Civil War, no money was made available for new construction. The first new development in machinery, was the installation in 1871, of compound engines in the *Tennessee*, started during the war and completed 1867. These engines, and almost all those designed during the next two decades, were designed by the Bureau of Steam Engineering.

In 1871, the Navy circumvented this lack of funds by applying maintenance funds to "rebuild" existing ships by replacing them by ships of the same name. Six such ships, dating back to 1828 were replaced by wooden screw sloops of about 2000 tons. Five iron hulled *Monitor* types, *Miantonomah, Amphitrite, Terror, Monodnock*, and *Puritan*, were replaced in the same way, starting in 1874. These were all fitted with compound engines. Steam pressures were 70 to 80 psi. The *Miantonomah* engine is shown in Figure 8.

Eight gunboats were authorized in 1873, varying from 1000 to 1400 tons and from 560 to 800 HP, again with compound engines. Also authorized was the wooden frigate *Trenton* at 3900 tons displacements and 3100 HP. Her engines were compound back-acting type, each consisting of one high pressure and two low pressure cylinders. Steam pressure was 70 psi and fuel rate about 3 lbs./SHP-hr. with a thermal efficiency of about 6 per cent. The *Trenton* was the first ship to be electrically equipped [12].

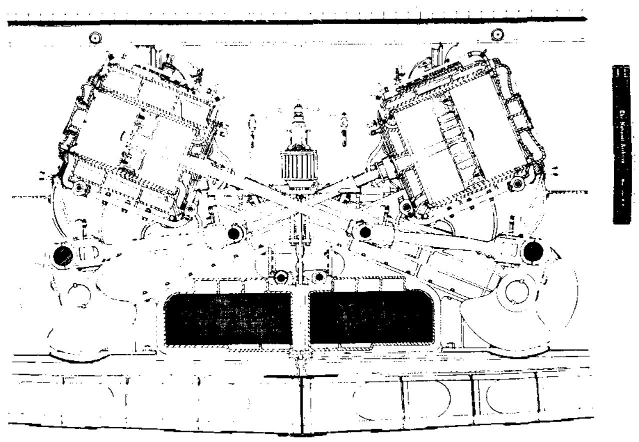

Figure 8. Compound engine of rebuilt *Miantonomah*.

By 1880, the Navy was hopelessly outclassed in comparison to foreign powers, and was quoted as being "one cylinder behind the practice of the rest of the world." In 1882, construction was authorized for four steel cruisers of from 1500 to 2500 tons, the *Atlanta, Boston, Chicago,* and *Dolphin.* There was nothing novel in their machinery. They were single screw as was the practice, with compound engines and fire tube boilers. The speeds of these ships were about 16 knots.

In 1885, the English belted cruisers of the *Orlando* Class were fitted with triple expansion engines. By improving the fuel rates to about 2 lbs. of coal per HP-hr. and decreasing the specific machinery weight to about 190 lbs. per SHP, it caused a revolution in ship design. Speeds were eventually increased from 16 to over 20 knots; and sails, previously a must for long hauls, were finally on their way out on naval ships. With the development of the Bessemer and the open hearth process, steel started gradually to replace cast and wrought iron for machinery.

This country soon followed the lead of the British with the cruisers *Newark* at 4000 tons and 8500 HP, *Charleston* at 3700 tons and 7000 HP, and the *Yorktown* at 1700 tons and 3400 HP. All except *Charleston* had triple expansion engines. Steam pressures were up to 160 psi and ship speeds up to 18 knots. Fuel rate for the *Yorktown* was 2.3 lbs./IHP-hr. for a plant efficiency of about 7.8 per cent. Twin screw design was now the standard practice, giving added impetus to the elimination of sails. The *Rochester,* authorized about this time, was the first major war vessel without sails [12]. At this time also the Navy began again to accept and encourage shipbuilder and engine manufacturer designs for steam machinery and to encourage competition in this regard.

In 1885, construction was initiated for the battleship *Texas* of 6000 tons and 8600 HP, and the cruisers *Baltimore, Maine* and *Vesuvius.* The *Baltimore* was the fastest of these, making 20 knots on 9100 HP and about 4400 tons displacement. The torpedo boat, *Cushing,* with 250 psi steam and quadruple expansion engines was designed for 22 knots.

From this point on, this country was well on its way to become a naval power. The period 1887 to 1898 was one of accelerated shipbuilding. Only the larger or more significant naval vessels will be mentioned here.

In 1887, construction was authorized for the gunboats *Philadelphia, San Francisco, Concord* and *Bennington,* and the monitor, *Monterey,* with 3400 to 5400 HP requirements. The years that followed saw the construction of the cruisers *New York, Olympia, Columbia, Minneapolis, Brooklyn, Cincinnati, Detroit, Marblehead, Montgomery* and *Raleigh,* and the 10,000 ton battleships *Indiana, Massachusetts,* and *Oregon.* Typical engines were triple expansion and were now vertical instead of horizontal. Typical performance was that of the *Olympia* which burned 2.1 lbs. of coal per IHP-hr. with 164 psi steam and a plant efficiency of 8.5 per cent. The *Columbia* and *Minneapolis* were triple screw ships and made 23 knots on 20,000 HP and 7000 tons displacement. Battleship speeds were 16 to 17 knots.

These were followed by contracts for the 11,000 ton battleships *Iowa, Alabama, Kearsage, Illinois, Alabama* and *Wisconsin,* by more gunboats and 26 knot torpedo boats. The *Wisconsin,* completed in 1900, used 187 psi steam and 26 inch condenser vacuum and showed a trial fuel rate of 1.7 lbs. of coal per IHP-hr. and a plant efficiency of 10.6 per cent.

A large number of the ships of this new fleet was available by 1898. For that year the Secretary of the Navy could report that the fighting fleet included 5 battleships, 18 cruisers of various types, 18 gunboats, 11 torpedo boats, 6 coast-defense monitors, 14 vessels of the old Navy and various auxiliary ships. The Navy had come of age in quality and quantity of equipment. However, much more development remained in the field of steam machinery. The development of the marine steam turbine by Rateau in England in 1896 and subsequently by Parsons in this country was the beginning of a new wave of development, that would lead to the desirability of higher pressures and highly superheated steam. In 1898, also, the Navy began to award contracts leading to the adoption of water-tube boilers, already in use in some foreign Navies. An experimental ship was being fitted for oil fuel. Another new Navy would have to be built. These and other subsequent developments will be the subject of another paper.

Figures 9 through 12 show the change in steam conditions, plant efficiency and specific machinery weight through the years, starting with Newcomen's pumping engine.

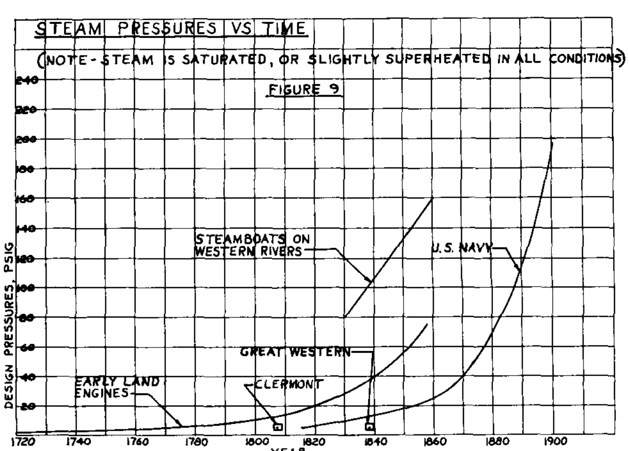

Figure 9. Plot of Steam Pressures and Temperatures versus Year, for Navy and other designs.

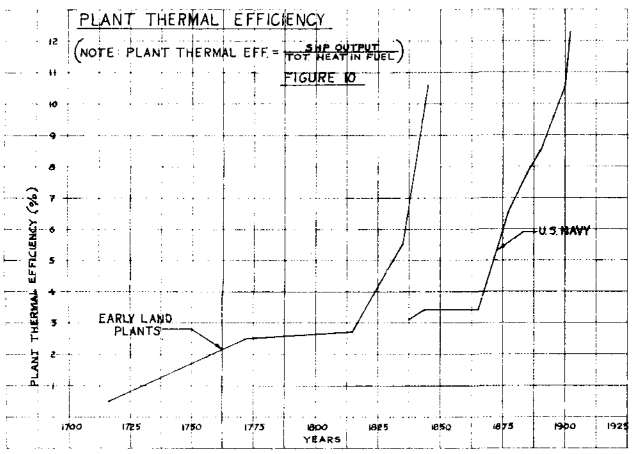

Figure 10. Plot of Steam Plant Thermal Efficiencies and Specific Fuel Rates versus Year, for Navy and other designs.

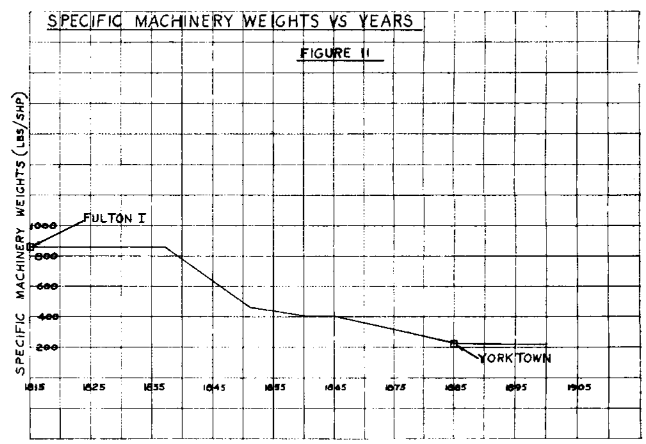

Figure 11. Plot of Steam Plant Specific Machinery Weights versus Years for Navy designs.

ACKNOWLEDGMENTS

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To Mr. Howard I. Chapelle, Curator of water transportation in the United States National Museum, Smithsonian Institution, for his assistance in connection with early steamboat history.

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G. M. BOATWRIGHT, M. WELLING AND M. R. HAUSCHILDT

Naval Propulsion Machinery—Part II

THE AUTHORS

Editor's Note: This paper, Part II of a three part paper, is continued from page 348 of the May 1963 issue. It covers the period from 1900 to the end of the second world war. Post war developments will be described in the final part which will appear in a later issue.

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1900 TO 1915

A NUMBER OF CRUCIAL technical battles and new developments were taking place in the field of naval machinery at the turn of the Century, stimulated by the Spanish American War in 1898. Steam conditions typical of 1900 were 187 psi saturated used on the battleship *Wisconsin.* Plant thermal efficiency was 10.6 per cent and the machinery weighed 300 lbs/SHP. The reciprocating steam engine was still king, but the steam turbine was ready to make its challenge. The British quickly built the torpedo boats, the *Cobra* and the *Viper*, after the success of Sir Charles Parsons *Turbinia* [1]. The *Viper* was the first turbine driven war vessel. Steam engine design reached its ultimate in the American Navy in the *Kentucky* and *Kearsarge* which were placed on trials in late 1899. These engines featured turned steel columns tied together and braced with steel tie rods. The same type of engine was also employed on the last reciprocating engine ship, the battleship *Oklahoma.* Later design modifications included designing each cylinder to produce the same power thereby reducing vibration. Piston speed was raised up to 1000 feet per minute and 50°F of superheat temperature was added to the new 265 psi steam pressure. Forced lubrication, which had been tried out originally by the British on their steam turbines, was also added in 1906 to the reciprocating engine driven *Delaware.*

The Spanish American War taught many valuable lessons of the importance of good boiler maintenance, the need for improvements in boiler design, the need for good clean feed water, the important tactical advantage of water tube boilers, and the need for better location of blowers and other auxiliaries in fire rooms, where men could reach them for maintenance.

In 1898 solid or seamless drawn steel boiler tubes were brought to the attention of the Navy. Their advantage was apparent and they were adopted almost immediately but problems of pitting and corrosion developed which required much investigation before they were considered satisfactory. In 1899 and 1900 a series of experiments to solve the corrosion problem were conducted by Lt. Comdr. Worthington in which the effects of oil, oxygen, acid, salt water and other likely contaminants were investigated.

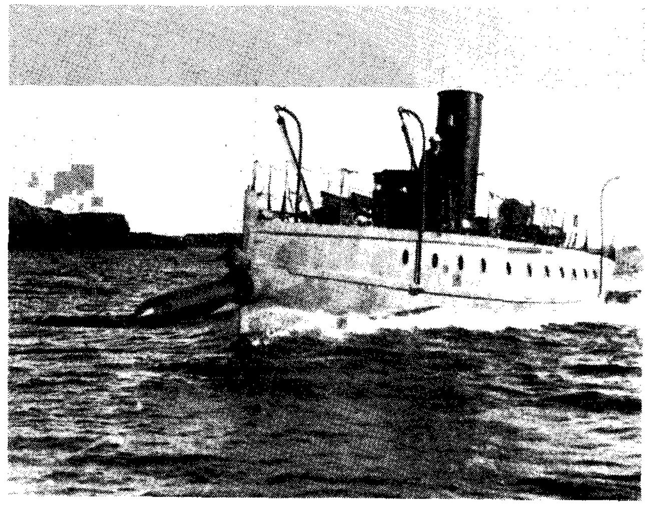


Figure 1. USS *Stiletto.*

The first ship to use caustic soda to counteract oil and acid effects was the *Marietta.* A turbine tube cleaner was also developed in 1902 which made the cleaning of boiler tubes a much easier job.

The first fuel oil experiments at sea were conducted on the torpedo boat *Stiletto,* Figure 1, conversion in 1897, but were considered a failure. Also in 1902 tests were conducted on the Hohenstein boiler to determine the feasibility of burning fuel oil as compared to the burning of coal. The report which appears in Volume 16 of the JOURNAL and the success of these tests led to installation of oil burning boilers in future Naval ships and led the way

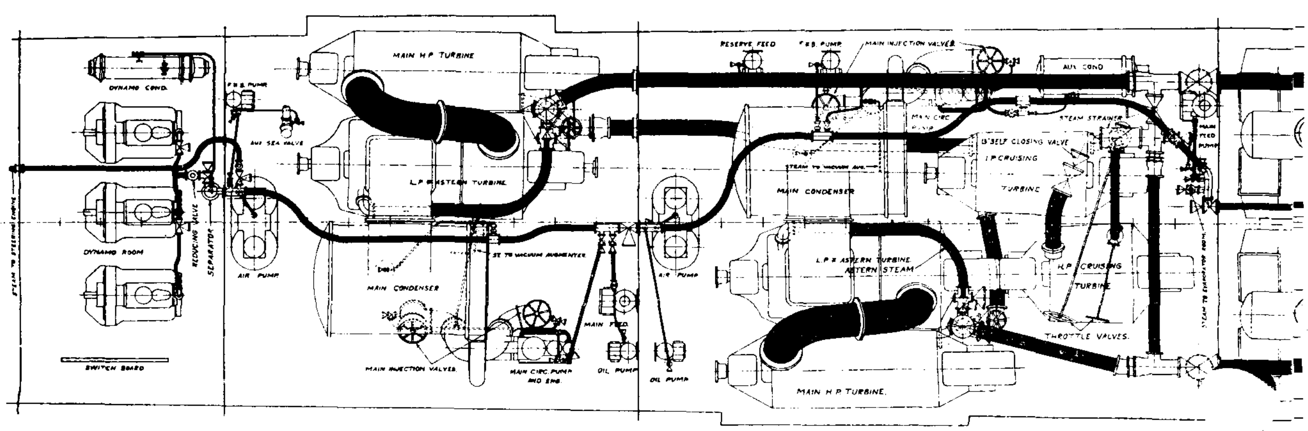


Figure 2. Machinery Arrangement of USS *Chester.*

for the rest of the World in this area. The discovery of the Spindletop Oil Field in Texas at about the same time also answered the question of adequate oil supply for the Navy. One item of interest is that most of the tests were carried out with compressed air or steam with only a few tests with mechanical atomization. This report served as a standard of excellence and a model for future reports of this type throughout the World.

Parts of the report are included here to show the advanced thinking displayed by this group of engineering investigators.

"5. That the evaporative efficiency of crude and refined oil is practically the same, no matter from what locality the oil may come. The danger of using crude oil, however, is much greater. As it should not be an expensive matter to build refineries near one of the terminal points of a pipe line, the expense of such refining should not increase to a perceptible degree the cost of such fuel, since the sale of the by-products of crude oil would often pay in great part the expense of distillation."

"13. That no design of oil fuel installation should be permitted for marine purposes which would not permit renewal within twenty-four hours of all grate and bearing bars, so that a return to coal could be accomplished within a reasonable time in case of failure of oil supply."

"19. That in the stowing of liquid fuel on board vessels whether taken on board for fuel purposes or for transportation in bulk, the compartments containing the crude product should be as few as possible, both for reasons of safety and for facility of delivery and discharge."

"20. That with the use of oil the forcing of a marine boiler should be much more readily accomplished than with the use of coal."

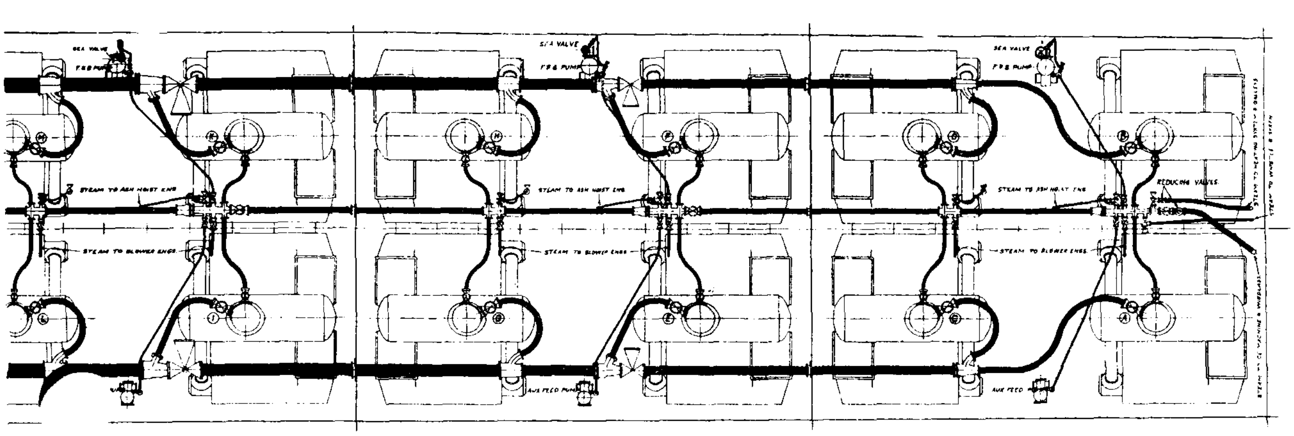
"31. The Board regards the engineering or mechanical feature of the liquid fuel problem as having been practically and satisfactorily solved. For mercantile purposes the commercial and transportation features of the problem are existing bars which limit the use of oil fuel in merchant ships. For Naval purposes there is the additional and serious difficulty to be overcome of providing a satisfactory and safe structural arrangement for carrying an adequate supply."

As is often the case in tests of this type today the original allowance of \$20,000 for these tests was inadequate. The total cost was about \$250.000, but well worth it to the Navy.

The use of mechanical atomizing fuel oil burners in new ships was first specified in the *North Dakota* and *Delaware,* which were contracted for in 1907. Also tests of mechanical vs. steam and air atomization in 1907 clearly showed mechanical atomization to be the best from the viewpoint of efficiency and good clean combustion.

In the year 1907 the United States fleet made its historic around the World tour. This provided the first fleet-wide engineering competition. Much valuable information was obtained on the speed, the amount of fuel consumed, hours under forced and natural draft, the total cruising radius, and on performance of various types of boilers and auxiliaries on ships that took part in the exercise.

By 1902, a new type of turbine design was challenging the Parson turbine monopoly. Charles Curtis invented the velocity compounded impulse turbine in 1895 and turned over his rights to The General Electric Company, which developed the design further. Naval officers observed tests of this turbine on the yacht *Revolution* in 1903. The Navy after hearing many good reports of European turbine success decided to compare the reciprocating engine and direct drive steam turbine in three scout cruisers in 1905. The original design plans were for reciprocating engines with a speed of 24 knots. The *Chester* was built by Bath Iron Works with Parson turbines. See Machinery Arrangements, Figure 2. Steam condition was 225 psi saturated steam. The *Birmingham* with a Navy Department reciprocating engine design was built by Fore River Company



and the *Salem* with Curtis turbines was also built by Fore River Company. The reciprocating engine was found to be the winner in nearly all areas. For speeds up to 20 knots the reciprocating engine was superior to the Parsons turbine. It was superior also to the Curtis turbine up to a speed of 21 knots. However, the turbines had a much greater overload capacity than the steam engine. The *Chester* had four shafts and made 26.22 knots on her trials, the highest speed made by a cruiser up to that time. An unusual feature of the *Salem* was the reversing end for end of the position of the duplicate turbines to provide for opposite direction of rotation of propellers.

One of the early concerns about turbines was the problem of reversing which was solved by use of the astern turbine.

As a result of the poorer overall performance of the turbines on these Cruisers and also on the battleship *North Dakota* (Parsons turbines) turbine application in the Navy received a temporary setback.

A milestone was reached in 1904 when this item appeared in the Annual Report of the Secretary of the Navy "The water tube boiler having fully established its superiority over the Scotch boiler for Naval use, it remains to discover the best form of this boiler." The transition from Scotch to water tube boilers took place between 1883 and 1903. Thereafter, a series of boiler tests were carried out to determine which boiler was to serve the Navy of the future. The Niclausse Boiler, Figure 3, was tested under forced draft at the Stirling Company plant of Barberton, Ohio, and a very favorable report of the test was made; but operation in the fleet often turned up many difficulties with this and other water tube boiler designs.

The results of the investigation by the British Admiralty Committee on Naval Boilers in 1904 had quite an effect on the future course of boiler installations. This report eliminated the Belleville boiler and also indicated preference for the Babcock and Wilcox, and Yarrow type boilers over Niclausse and Durr type boilers.

The following tabulation [2] shows the status of the water tube boiler in United States naval vessels in 1903, excluding those installed in torpedo craft.

Battleships and Armored Cruisers	**No. of Ships**
Niclausse design	5
Thornycroft design	2
Babcock and Wilcox design	14
Protected Cruisers and Gunboats	
Babcock and Wilcox design	11
Monitors and Auxiliary Vessels	
Babcock and Wilcox design	6
Hohenstein design	2
Thornycroft, Niclausse and Mosher designs	1 each
Combined Watertube and Scotch Installations	
Babcock and Wilcox and cylindrical design	2
Ward and cylindrical design	1
Yarrow and cylindrical design	1

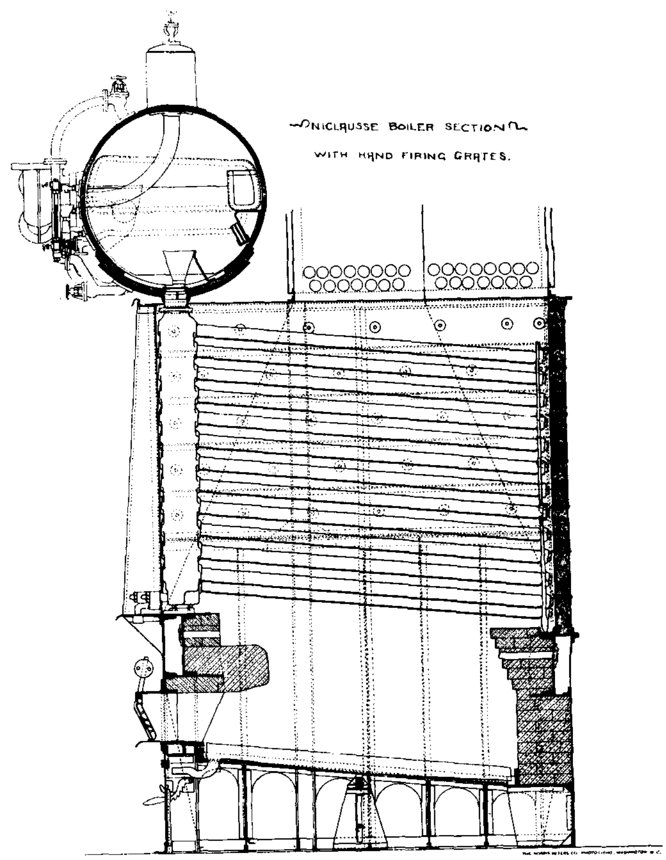


Figure 3. Niclausse Boiler.

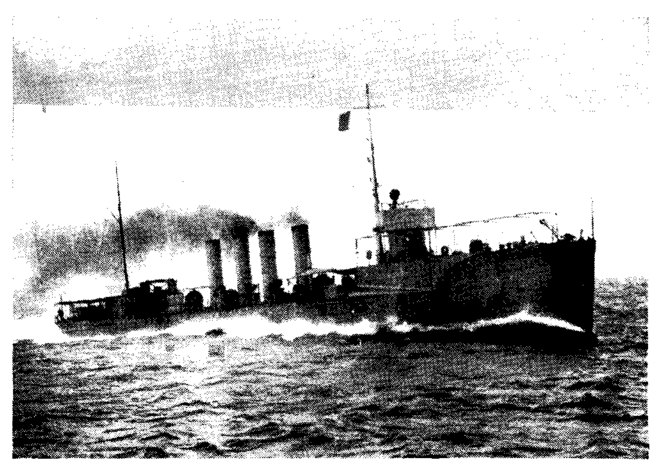


Figure 4. USS *Beale* 3 Shaft Destroyer.

The first turbine driven destroyers, *Mayrant* and *Warrington,* were authorized in 1906. They were three shaft designs with Parsons turbines. Later destroyers were two shaft designs using Curtis and Zoelly turbines. Two shafts were adopted for all later destroyer designs because of their better maneuvering qualities. Figure 4, USS *Beale* was typical three shaft DD.

With the advent of turbine driven main shafts came also turbine driven auxiliaries. First, however, the reciprocating engine blower was replaced by the Sirocco motor driven blower, which was lighter and smaller. In 1905 turbine driven blowers were installed on the *Salem* and in 1906 turbine driven blowers were specified for destroyers. Even though some shipbuilders objected because of the poor economy of turbine driven auxiliaries they were here to stay because of their reliability considering the electric plants of those days.

The state of the art was demonstrated by the *Viper*, burning 2.49 pounds of coal per IHP per hour and making 33.8 knots with a turbine drive, showing a superiority of turbines for high speed vessels. By 1908 the rapid engineering developments in the Navy and the historic trip of the Great White Fleet around the World had served to demonstrate to the public that the United States Navy was the "first line of defense."

In 1909 the destroyer *Roe* was fitted with oil burners under all four of its boilers and the curtain came down on the coal burning age of naval propulsion. In 1910 the battleships *Kearsarge*, *Kentucky*, and *Illinois* had their Scotch boilers replaced by Mosher water tube boilers. Foster Wheeler Company developed the "U" shape fin tube superheater with radial fins on the tubes also in 1910. Yarrow had also developed the "U" type superheater for the express type boiler. The Engineering Experiment Station began a series of tests in 1910 to determine what could be done about water side deposits in boilers. This resulted in the development of the first boiler compound. New fuel oil and lube oil specifications were established in 1915, which helped to clear up a very confused situation in the boiler area.

Neuhaus [1] reported that a 300 ton reduction in fireroom weights resulted from the use of oil burners instead of coal in the design of the *Nevada*, and that fuel required for cruising radius was decreased in the proportion of nine to seven. The high and low pressure turbines were tandem connected to the same shaft, with each turbine in a separate compartment. A double reduction gear cruising turbine was also fitted capable of being disconnected at high powers by means of a "jaw" clutch. Most remarkable was the reduction of the fireroom force by 50 per cent and a reduction of boiler room space from 128 feet in overall length to 66 feet in this design compared to previous designs.

In 1909, both merchant and naval ships were still being built with direct drive turbines. The battleship *Arkansas* contracted for in 1909 was designed with a high pressure turbine and an astern turbine coupled to one propeller, and a low pressure, a cruising turbine and an astern turbine coupled to the other propeller. In the same year Parsons installed the first helical single reduction gear in a large ship called the *Vespasian*. The increased turbine speed of 1500 RPM and reduced propeller speed made possible new lows in fuel consumption. Not long afterwards, the United States Navy made an experimental gear installation on the Collier *Neptune*. This proved successful and the battleship *Nevada* was designed in 1912 with high pressure and low pressure turbine pinions each mating with a low speed, single reduction gear driving a propeller. By 1915, turbine drive single reduction gears were being installed in cruisers and destroyers, while turbo-electric drive was being installed in the new battleships.

This basic approach in the selection of machinery continued for some time, with the electric drive being fitted for easier control in the higher powered ships, where the reliability of reduction gears had not been established, because of many problems of pitting and tooth breakage in early gears. Single reduction gears were fitted in destroyers and cruisers because of their lighter weight, better efficiency and smaller horsepower requirements.

In 1912, the then Capt. Dyson [3] reported:

"In the use of superheated steam, the Bureau of Steam Engineering has been rather conservative; at present there are seven vessels in naval service fitted for superheat, the maximum degree of superheat obtained at the boilers being 85°F which reduces to about 60°F at the engines." An increase in full power economy of 6 per cent and 12Kt cruising speed economy of 3 per cent was obtained on battleships with both reciprocating engines and turbines using superheated steam.

The most famous auxiliary ship of 1912 was the *Jupiter* by reason of her successful experimental electric drive machinery, which was used for many tests and which led the way to Admiral Griffin's decision to install electric drive in battleships and battle cruisers against considerable opposition. The *Jupiter* as described by Emmet [4] was equipped with one turbo-generator unit and two induction motors, one driving each of the propeller shafts. Steam consumption was 11.2 lbs per SHP-Hr, and the machinery weighed 156 tons for a developed total of 5000 KW or 6705 IHP. The *Tennessee* machinery built by Westinghouse was a typical turbo-electric plant. Four motors were installed, one on each shaft, each rated at 8375 horsepower continuous overload and two generators supplied power for the ship. Steam was supplied by eight boilers, each in a separate compartment lying outboard of the machinery spaces.

At this time the United States fleet was rated second in strength to the British having recently passed a number of other naval powers. One very important reason for this standing was the continual and rapid improvement in naval propulsion machinery in the period from 1900 to 1915, as well as the willingness to experiment with new designs, and investigate the causes of failure.

In this period were a number of shafting failures in which both the propellers and main propulsion machinery were suspected as the cause. A full investigation was started in 1916. The propellers were absolved of the blame, when it was determined by means of a special torsionmeter test that a critical speed of synchronous torsional vibration was the cause of shaft failure.

WORLD WAR I PERIOD

The battle of Jutland between the British and the Germans taught many valuable lessons on ship protection and interior arrangement, which influenced propulsion design. Just before the entry of the United States into World War I, a tremendous shipbuilding program was launched to build four 32,600 ton turbine electric drive battleships, the *Colorado*, (Figure 5), *Maryland*, *Washington* and *West Virginia*. A typical machinery arrangement for this class is shown in Figure 6. These were four screw ships with a total SHP of 28,900 and a speed of 21 knots. Electric drive provided improved ship compartmentation, good maneuverability and an easier method of reducing speed than single reduction gears.

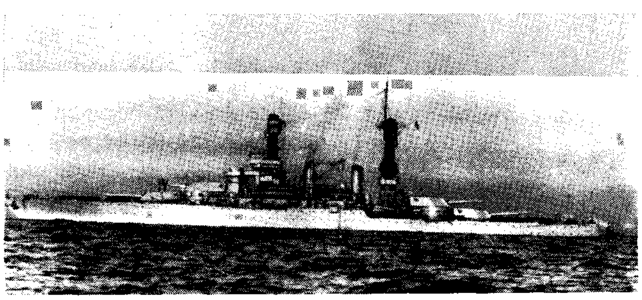


Figure 5. Battleship USS *Colorado* BB 45.

All used 280 psi—50°F superheated steam supplied by eight Babcock and Wilcox boilers. A typical propulsion plant was the *Maryland* with two 10 stage Curtis main turbines rated at 11,000 KW each driving individual AC generators rated at 13,400 KVA. Provision was made so that one generator could drive all four main motors. The main motors had a nominal rating of 7,225 SHP each at 170 shaft RPM and were of the induction type. The motors were wound for 72 poles but could be operated with 36 or 24 pole combinations on three phase current. Speed changes were made by changing poles or varying the speed and frequency of the main generators. The controls of the main drive units were centralized in one compartment or control room located alongside of the after machinery space. This was one of the first applications of a central control station as we now consider this feature in modern ship design. Reversing of propellers was accomplished by reversing one set of leads to the 3 phase power supply. Another feature of this design was a direct exhausting condenser which was located directly under the turbo-generators. This was an entirely new idea at this time. The trend to electric main propulsion also continued with a majority of air compressors, pumps and other auxiliaries supplied with electric drive.

Destroyer numbers 75 to 347 were authorized and all except 18 built during World War I. These ships were affectionately known as the "Four Pipers" because of their four stacks as illustrated by the USS *Fairfax*, Figure 7. Design SHP ranged from 24,200 to 27,000 SHP. The types of propulsion machinery installed were: Fore River-Curtis geared turbine, General Electric-Curtis geared turbine, Newport News-Curtis direct drive turbine with one geared cruising turbine. Four water-tube express type boilers, two per fireroom supplied 250 to 265 psi saturated steam. Three blowers were supplied for each boiler. Firerooms were closed and each

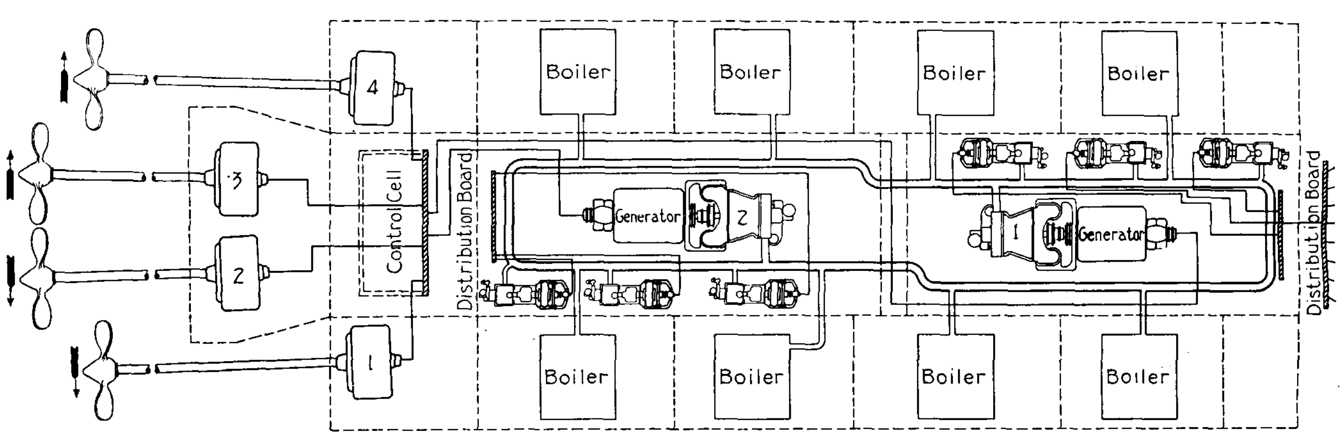


Figure 6. Machinery Arrangement *Colorado* Class Battleship.

boiler had its own uptake and smokepipe.

The following table compiled by Neuhaus [1] ists the horsepower constructed during the two years of United States participation in World War I, a total of 9,501,440 horsepower:

Destroyers	6,578,000
Battle Cruisers (6 ships)	1,080,000
Battleships	480,000
Scout Cruisers	630,000
200-Foot Patrol Boats	280,000
Mine Sweepers	75,600
Seagoing Tugs	48,600
Submarines	41,640
Emergency Fleet Corp. Oil Tankers	31,800
Harbor Tugs	12,000
Fuel Ships	10,400

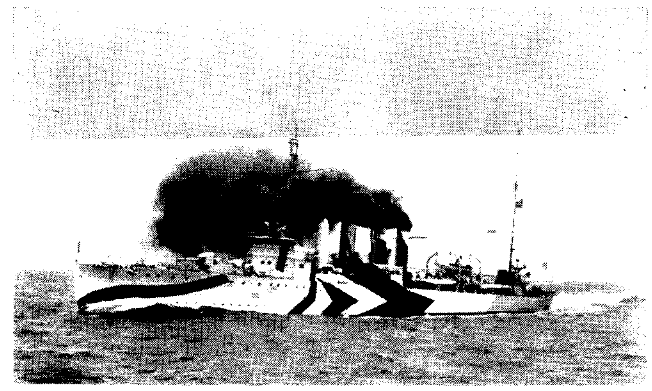


Figure 7. USS *Fairfax* (DD93) "Four Piper" Destroyer.

1922 TO 1932

A definite limit of what could be built was placed on the United States by the Washington Naval Treaty of 1922. Many ships were marked for disposal as a result of this conference, however, there was a saving clause which provided for retention of two battle cruisers provided they were converted into aircraft carriers. By this time the airplane was making itself felt in the United States Navy. The battle cruisers designated by the United States were of 180,000 SHP design and were converted to the aircraft carriers *Lexington* and *Saratoga*. This decision was a vindication of the General Board's recommendation of 1915 that we should begin to develop and build aircraft carriers. In 1919 the Collier *Jupiter* was determined to be the ship which should be converted into the first experimental carrier. Along with the *Jupiter's* conversion, its name was changed to the carrier *Langley* and certain changes made, not only in the flying deck structure, but also in the machinery plant. (See Figure 8.) The regular Scotch boilers were retained, but converted to oil burning. Another unusual feature was the change in the stack and uptakes and smokepipes which were led off to the side of the ship. Stack control dampers were installed so that either one of the smokepipes could be used. The results of *Langley* tests were used to determine the turbo-electric machinery designs for *Lexington* and *Saratoga*. The *Lexington* had General Electric turbo-generators installed rated 32,500 KW at 1755 RPM. Steam conditions were 265 psi and 50° superheat throttle. (Arrangement of *Lexington* machinery is shown in Figure 9.) Turbines were directly connected to main generators rated at 40,000 KVA of 3 phase 5000 volt design. Six geared turbines ship service generators rated at 750 KW each supplied the excitation for main generators. Each turbo-generator was installed in a separate machinery space with total of 4 machinery spaces. Two motors in tandem were directly connected with each of the 4 shafts. Each motor was of the induction type and

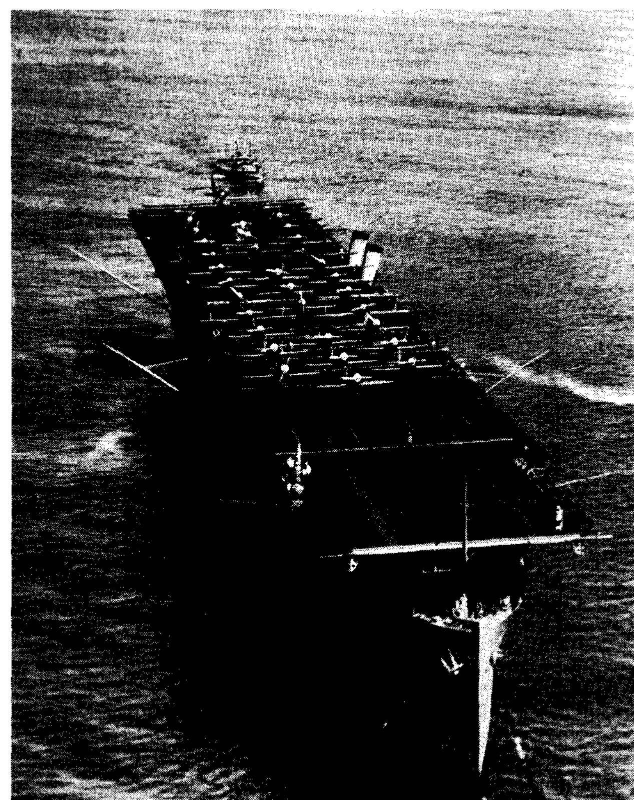


Figure 8. Carrier *Langley* After Conversion from Collier *Jupiter*.

was rated at 22,500 SHP. The 8 motors installed provided a total of 180,000 SHP per ship. On trials they developed 200,000 SHP at a speed of 33 knots. Both of these carriers were destined to become famous ships. The *Lexington* made a 2128 mile run from San Pedro, California to Honolulu in 1928 and broke all sustained speed records. Average speed of 30.7 knots was maintained for a period of 72 hours 34 minutes.

The Washington Naval Treaty of 1922 definitely

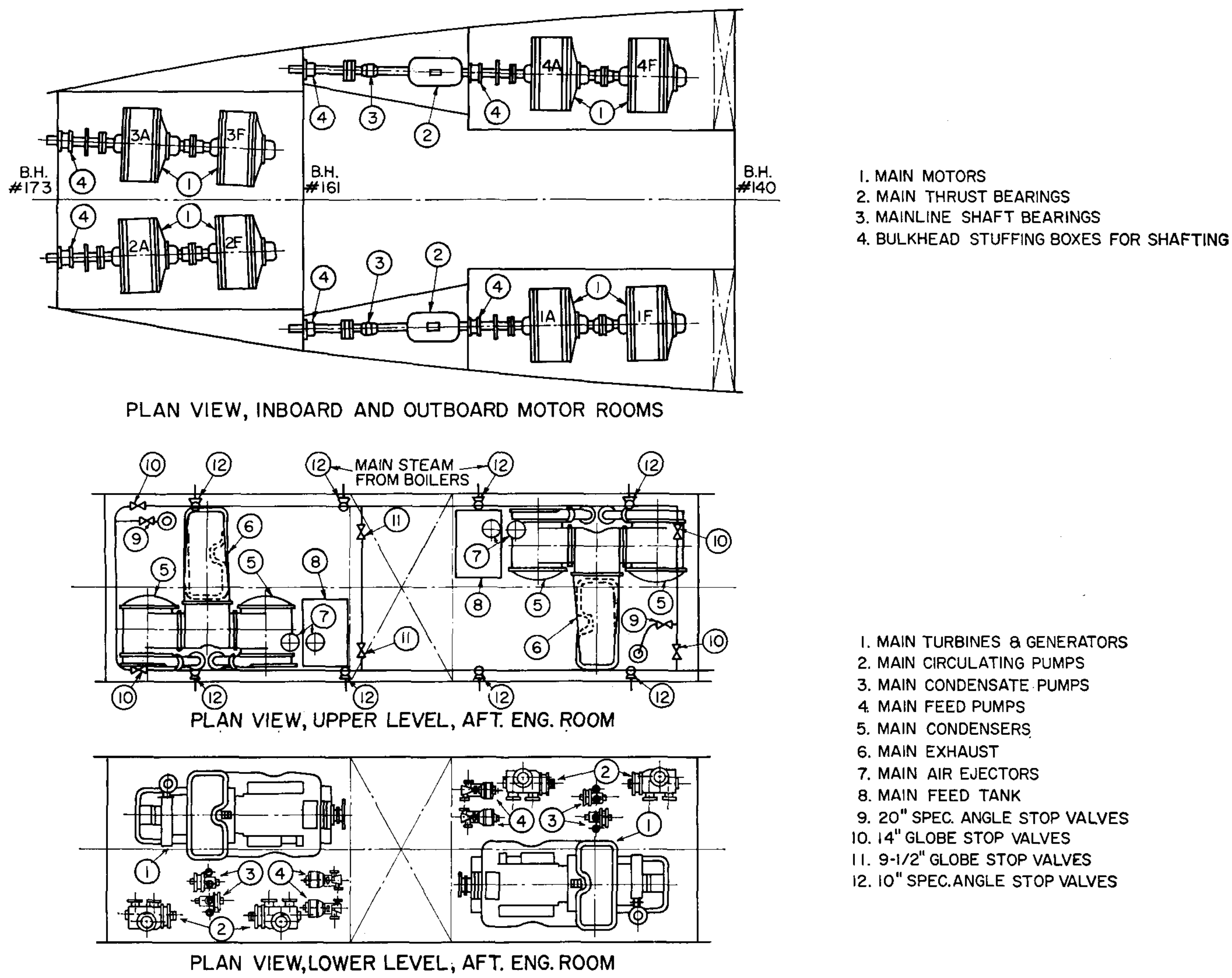


Figure 9. USS *Lexington* Machinery Arrangements.

put a damper on the building of new machinery plants during this period. One exception, however, was the 10,000 ton cruiser design which resulted from the lack of a limitation in vessels of this size.

The *Salt Lake City* was the first of a class of 8 vessels and its construction was completed in July 1926. The machinery was designed with interchangeability as a primary feature. There were some exceptions to this and all of the plans were prepared by one group called "The Marine Engineering Corporation." The first 2 ships were built using 2 firerooms with 4 Babcock and Wilcox boilers located in each fireroom arranged 2 abreast and back to back. The 6 other ships of the class had 4 firerooms with 2 boilers located in each fireroom. The main machinery was of turbo-gear propulsion with a total of 4 shafts, each shaft being rated continuously at 26,750 SHP for a total of 107,000 SHP. In addition to a high and low pressure turbine on each shaft a cruising turbine was also fitted by means of a hydraulic clutch and a single reduction gear to the high pressure turbine shaft. An unusual feature of the design was the direct drive of the main air pump, lube oil pump, drain pump and make-up feed pump from the cruising turbine shaft. While the Washington Treaty restricted a considerable amount of new naval construction, it did force a new approach to design problems in the use of alloys of high strength to reduce weight and forced the rearrangement of machinery, higher machinery speeds and more careful, coordinated designs.

Rossell [5] stated, "Among the immediate consequences of the Washington Treaty on the design of naval machinery was the general recognition of geared turbines together with small-tube oil fired boilers as the most suitable type of propulsio: machinery for all surface warships except moto! boats and other very small vessels."

1933 to 1937

By 1933, the United States realized that its example was not being followed by other powers in regard to disarmament, and a Navy building program was undertaken that was larger than any since that immediately preceding World War I. In 1933, the President allocated funds from the National Recovery Act for the construction of 32 vessels; 4 light cruisers; 20 destroyers; 4 submarines; 2 aircraft carriers and 2 gunboats.

Significant developments which occurred at this time were the specification of a high cruising radius at cruising speeds which was somewhat of a departure from naval requirements in foreign nations, and an increase in cruise speed to 15 knots. In the boiler field, Babcock and Wilcox Company developed a sectional express type boiler which was used on a number of naval vessels, but a little later the "A" type express boiler was redeveloped with superheat. Fusion welded boiler drums were first installed in the Navy in 1930.

In the combatant ships authorized in 1933, the scout cruiser boilers were designed to deliver steam at 300 psi and 572°F. The destroyer boilers were designed to deliver steam at 400 psi and 650°F with a superheater arrangement similar to Figure 10. The cruiser and aircraft carrier designs generated saturated steam at 450 psi in one set of boilers and superheated the steam to 650°F at 400 psi in separate superheater boilers. In 1934, the *Somers* Class destroyers were equipped with a divided furnace boiler with steam conditions of 565 psi and 700°F. The only substantial change in design was the addition of a division wall in the furnace making superheat control possible by varying the firing rate on the superheater side. Previously, superheat control had been accomplished by cumbersome dampers and baffles. The advantage of this design was a considerable savings in weight and space, while providing good superheat control. This was also the first design using double casing boilers, thereby eliminating the closed fireroom system. The first installations were made in the cruisers *Minneapolis, Astoria* and *New Orleans*. Another trend of the time was shown in the modernization of the battleship *New Mexico* about 1931 with the replacement of the turbo-electric plant by double reduction geared turbines.

DOUBLE REDUCTION GEARS

Double reduction gearing was first used at sea in 1917, but due to many casualties, was not accepted in the Navy until the early 1930's. The *Mahan* class destroyers, the *Brooklyn* class cruisers, and the *North Carolina* class battleships were among the earliest new ships to have double reduction gears. The compact locked train type of double reduction gear was used in the *Mahan* and later ships permitting more efficient turbine speeds. It proved much more desirable than the turbo-electric drive, both in terms of total weight of machinery and in overall efficiency of the plant.

About the same time the development of smaller and lighter weight diesel engines used on railroads made available a new type of prime mover for use in the Navy which was quickly used in submarine designs. The diesel also was now ready to compete as a prime mover for small surface ship designs. The installation of two 900 HP diesel engines on the USS *Maryland* arranged to be exhausted through a waste heat boiler marked the first use of diesels for an emergency power source.

The failure of the 1936 Naval Limitation Conference to limit new war ship construction brought about the first new shipbuilding particularly in the larger size ships. In 1937 the United States began construction of two 35,000 ton battleships; 4 additional battleships were authorized in 1938, with the

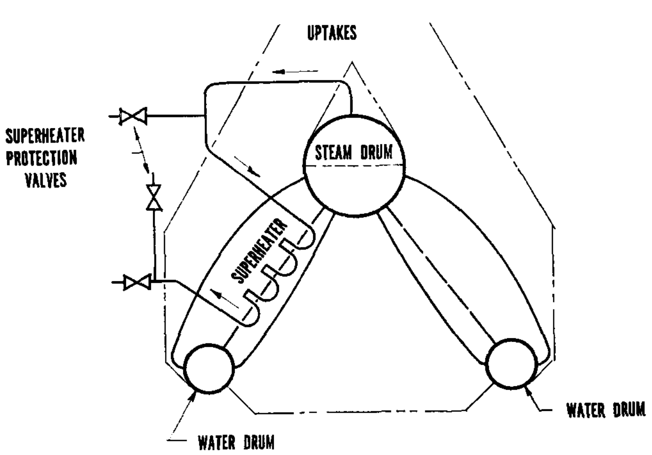


Figure 10. "A" Type Boiler with Uncontrolled Integral Super-Heater.

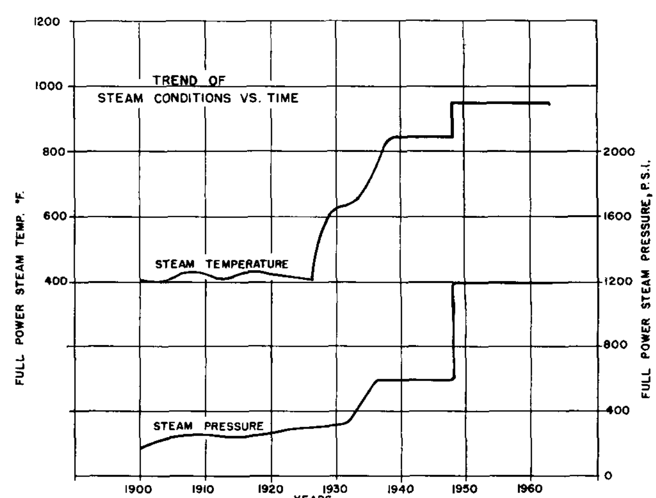


Figure 11. Trend of Steam Conditions vs Time.

possibility of moving their tonnage up to 45,000 tons standard displacement.

STEAM CONDITIONS BATTLE

The rapid development of high temperature, and high pressure power plants on land heralded the battle that was about to take place in naval circles.

Steam conditions have long been one of the most controversial items in naval machinery design. Figure 11 shows the history of steam conditions throughout the last 75 years in the Navy. The primary reason that steam conditions have been the center of controversy is that any change in steam conditions usually carried with it many other machinery design changes and the problems attendant with design.

One thing is quite apparent from the recurring battles; steam conditions could not go up until metallurgical progress permitted. In many cases the new problems associated with new steam conditions were really generated by some other accompanying design improvement not directly connected with the change in steam conditions. Each change in steam conditions has been accompanied by a period of machinery problems, design changes, charges and counter charges.

Such was the atmosphere as a tremendous controversy shook the marine engineers of the Navy in 1938 and finally involved Secretary of the Navy Edison. This controversy exemplifies the excitement of one of these battles, which split the professional Navy into two camps.

This was probably one of the reasons for the reorganization of the Bureau of Engineering and the Bureau of Construction and Repair into the Bureau of Ships.

The nature of this problems in illustrated by the following excerpts from the New York Times of November 4, 1938:

SHAKE-UP IN NAVY HITS SHARP CRITICS OF NEW WARSHIPS STEAM PLANT CHIEF ISSUE

"One officer in the Navy Departments' Board of Inspection and Survey, which is charged, among other duties, with inspection of new ships, has been transferred and the president of the Board, Rear Admiral H. L. Brinser, has requested transfer, it was learned today.

The transfer made and the one requested followed criticisms by these officers of many of the Navy's newest ships and the overriding of their recommendations for improvements. The Board is understood to have reported numerous and often serious defects in many of the new men-of-war." . . . . .

"Some of the criticism of the board of inspection and survey had recently been leveled against engineering plants built to use high-pressure steam, heated to a considerable degree of superheat. Some of the new destroyers are actually equipped with engineering plants of this type.

Objection to Steam Pressure

But when it was learned in the Department that not only the four new battleships, for which bids were opened yesterday, but also the *Washington* and *North Carolina*, battleships already building, were to be equipped with the high-pressure installation, objection was voiced by officers who felt that high-pressure steam for marine use was still perhaps experimental and unproved."

. . . .

"Those advocates of high-pressure, high-temperature steam installations, which in some of the new ships are designed to operate at 600 or more pounds pressure and from 650 to 850 degrees of superheat, contend that those new destroyers which have been equipped with such machinery have a far greater efficiency and a far longer cruising radius than ships not so equipped.

"While this is generally admitted and the speeds and fuel efficiency of some of these new destroyers are highly praised, many officers feel that metallurgical progress has not kept pace with the advance in steam engineering and that it is doubtful whether the equipment of the new ships will "stand up" under the high temperatures over a period of time. For this reason their reliability is questioned.

"Mr. Edison pointed out that the new high-pressure, high-temperature steam installations were relatively only "higher" than those formerly in use in the Navy, and that they did not yet by any means approximate pressures and temperatures used in shore installations, or in some marine installations abroad."

. . . . . .

"If the new ships prove over a period of years that they can "take it" and if the complexity of operation is simplified and accessibility of machinery is improved, steps toward which are now being taken, then many of the caustic criticisms now being made will be ended."

Fortunately, the progressives in the Navy, led by Secretary Edison, were the winners in this controversy and the basic tenets of 600 psi 850°F steam of the modern World War II Navy machinery plants were developed after much "blood, sweat and tears."

This decision along with many supporting decisions was basic to the excellent performance of our Naval ships in World War II. Most of the world now agrees that steam conditions for marine power plants of any appreciable size should be at least 600 psi 850°F.

1938 THROUGH WORLD WAR II

In the years that followed, the building was accelerated, and with this acceleration came the improvement in naval propulsion plants.

By 1939 the United States was drawing close to Great Britain, and ahead of all the other naval powers in important ship tonnage, with 15 capital ships, 5 aircraft carriers, 34 cruisers, 221 destroyers and 89 submarines for a total of 364 ships and 1,380,000 tons. In addition, 88 combatant ships were under construction. (From Report of Secretary of the Navy 1939) Building continued at an accelerated pace into and through the years of World War II and it would serve no purpose to tabulate the extent of this shipbuilding program.

As we have come to expect, the machinery improvements during the pre-war and war years, 1938 to 1945, were generally in the nature of refinements rather than in new developments.

In 1938 a single uptake two furnace boiler was used in the *Gleaves* class destroyers to reduce space. This general boiler design, Figure 12, was called the "M" type and was used in most of the combatant vessels of World War II with steam conditions of 600 psi 850°F. It provided a good degree of steam temperature control. A modified "A" or Guest drum-type boiler with a radiant convection type separately fired superheater saw only limited service during the War because it did not easily adapt to rapid load changes and steaming at low rates characteristic of naval operations.

The World War II destroyer escorts used a single furnace boiler with steam conditions of 450 psi 750°F, Figure 13. It was called the "D" type, because of the shape of its generating elements and is the forerunner of post-war boiler designs.

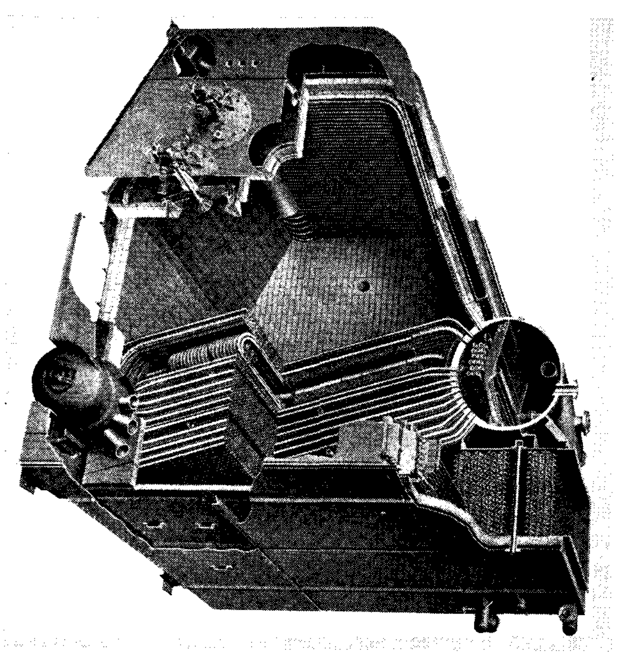


Figure 13. Combustion Engineering Single Furance Destroyer Escort "D" Type Boiler.

One method of improving efficiency at the partial power operating conditions required by the Navy was the use of cruising turbines. On the original DD 364 and DD 381 classes of destroyers (See machinery Figure 14) the cruising turbines were always in gear on all ships in which cruising units were installed. The cruising turbines exhausted into the high pressure turbine during cruising speed, and to the low pressure turbine inlet at high powers, when cooling steam was fed to the cruising turbine. Arrangements were also made for obtaining extraction steam for feedwater heating from either the cruising turbine exhaust or any one of several stages of the high pressure turbine. Separate hand control valves were used so that the appropriate stage could be selected to match pressure required for feed heating. On later ships the cruising turbine cooling steam was discharged to the low pressure turbine exhaust. This was the cause of severe overheating and turbine failures at high powers due to insufficient vacuum to induce flow through the cruising turbine. This was later corrected by increasing the pipe size of cruising turbine exhaust and supplying a metered amount of cooling steam through an orifice from the high pressure turbine first stage. The cruising turbine was fitted on many World War II ships with low percentages of cruising power to improve endurance, but their complexity of operation and lesser reliability dictated their omission from some of the ships built during the latter part of the War. At least two designs provided for induction of excess auxiliary turbine exhaust into appropriate lower pressure stages of the main turbine.

For combatant ships of 25,000 SHP/shaft and above a two casing cross compound design with a double-flow low pressure turbine was used in World War II. See Figure 15. Somes [7] indicated that this design retained the advantages of compactness and high efficiency by providing increased last-stage annulus area without reduction in speed, which greatly affects weight and space.

The low pressure turbine exhausted directly to the main condenser at a vacuum of about 27.5 in. Hg. Scoop injection of cooling water to the main condenser was provided at speeds above about 10 knots. A main circulating water pump was fitted which operated only at low speeds ahead and for astern operation.

With the increase to 600 psi steam the problems associated with accelerated oxygen pitting in economizers and other boiler parts led to the introduction of the closed contact or deaerating feed heater, an adaptation from land plant practice, which became

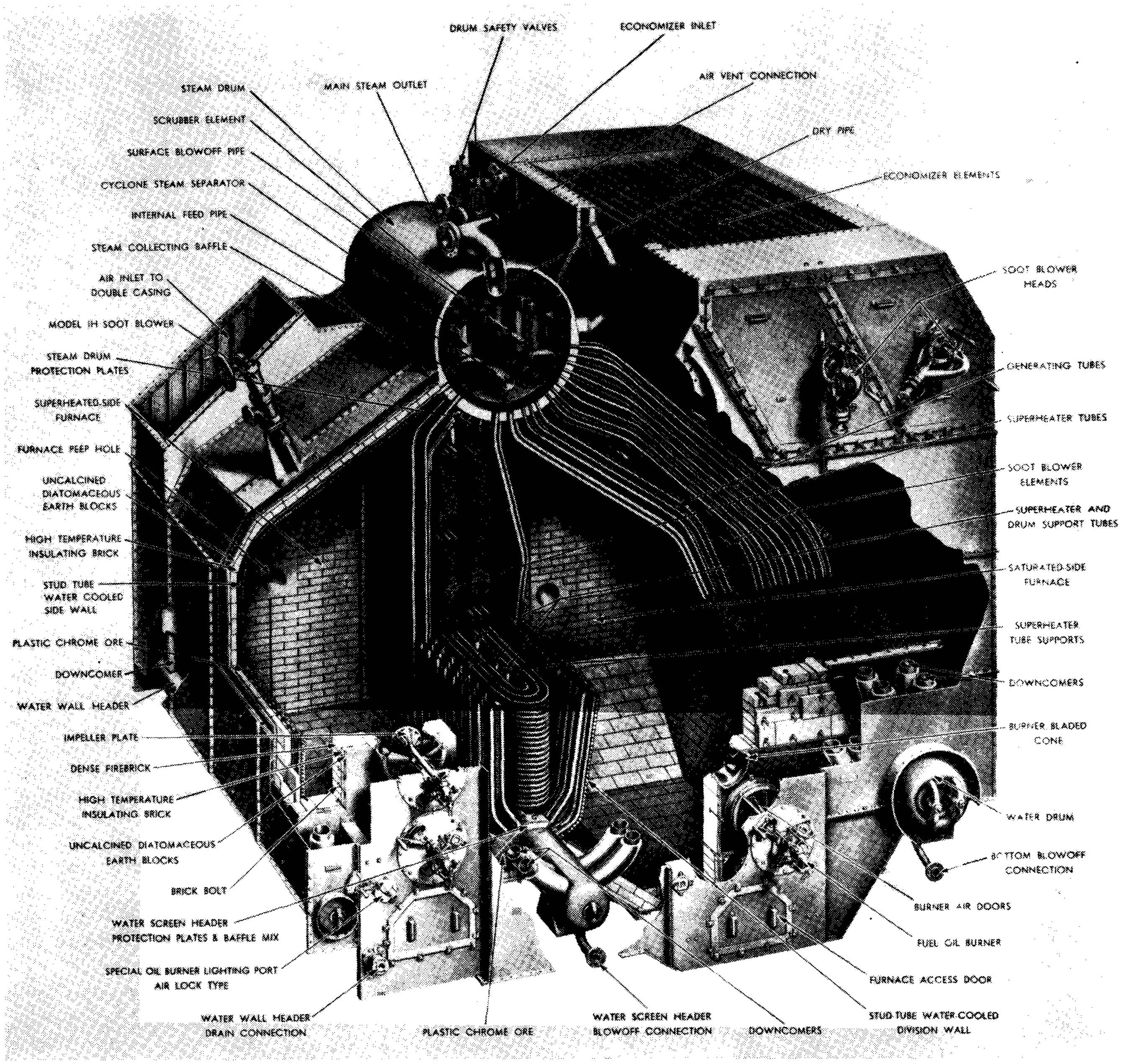


Figure 12. Babcock and Wilcox "M" Type Single-Uptake Controlled Superheat Marine Boiler "M" Type.

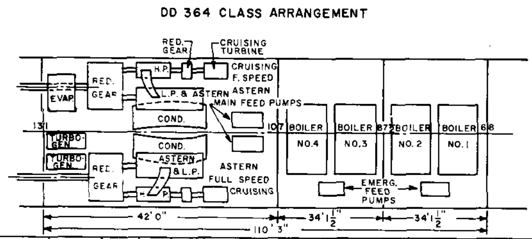
standard on all combatant and some auxiliary ship designs.

Steam jet air ejectors were used for air removal from the main and auxiliary condensers because of their simplicity and reliability. Multiple effect distilling plants were developed, which utilized the exhaust steam from the power plant auxiliaries.

One ship design, the DD 692 class destroyer, required the addition of 14 ft. of length to the later ships of the class due in part to unrealistic assumptions on operation of the machinery plant. The design endurance was based on a cross-connected plant *peace time* operation with only one of its four boilers and associated auxiliaries supplying all the steam at the cruise condition. Actual operation during the war was split plant operation with at least two boilers on the line at all times. This variation between design and actual conditions was so significant that additional fuel was added to bring the ship to its specified endurance. This added 14 ft. was also reflected in an improved speed length ratio.

Among the larger combatant type ships the steam plant cycle had been leveled off at 600 psi 850°F with a closed feed system and usually one stage of feed heating in a triple-purpose combined deaerating feed heater and surge tank.

Typical classs were the *North Carolina* and *Iowa* class battleships with a total of 212,000 SHP, the *Essex* class carriers with 150,000 SHP, the *Cleveland* class cruisers with 150,000 SHP, the DD 445 class



MAIN ENGINES	MAIN RED. GEARS	PROPELLER RPM	SPEED KNOTS	AUX. GENS	EMERG. GENS.	MAIN BOILERS	MAIN FEED PUMPS	AUX. FEED PUMPS	EMERG FEED PUMPS	EVAPORATORS	LENGTH B.P. DISPLACEMENT	
2-TURBINE 50,000 SHP	DOUBLE RED.	400	36.5	2-175 KVA 2-25 KW [illegible] KW	1 KW	4-400 LBS.	2-600 G.P.M.		2-280 G.P.M.	2-10,000 G. 24 HRS.		

Figure 14. DD 364 Class Arrangement.

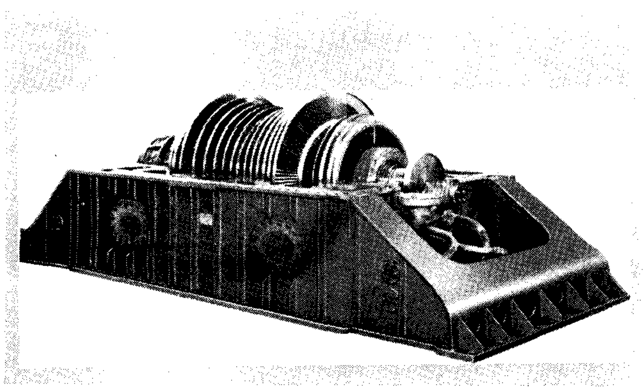


Figure 15. DD 692 Class Double Flow General Electric Low Pressure Turbine.

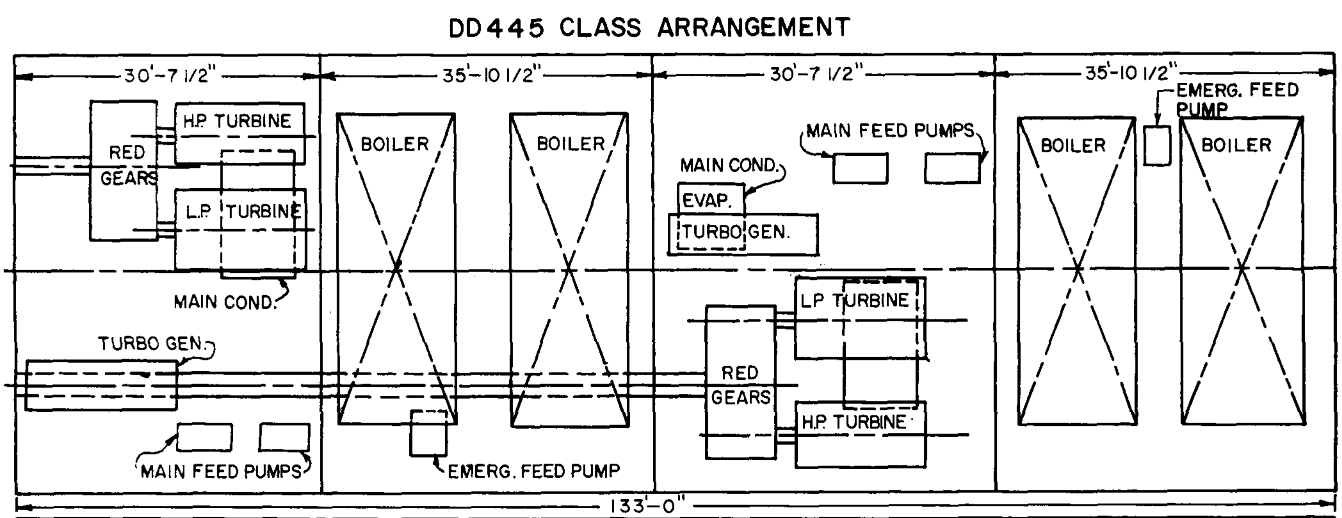
destroyers and the DD 692 class destroyers with *60,000 SHP*. A typical destroyer machinery arrangement, for DD 445 class is shown in Figure 16.

Electric load increased during the World War II period due to increased fire control and electric auxiliary requirements. The introduction of sonar and radar also were influencing factors during the latter part of the War. Electric generators were turbine driven, exhausting to their own condensers. Most auxiliaries such as pumps and blowers were driven by small stage, non condensing turbines and their exhaust steam was used for a single stage of feed heating in the deaerating feed tank. The smaller horsepower auxiliaries were usually split with the operator having a choice of either a motor or turbine driven pump, so that the plant could be properly balanced thermodynamically.

A typical fuel rate was .60 lbs. per SHP-hr at full power for an overall plant efficiency of 23 percent. By the time World War II had ended, the machinery designs had well proven their long endurance and reliability as compared to ships of foreign powers. One of the lessons of the war however, was that complex refinements to gain a small per cent of efficiency did not pay off. Operators were given many machinery operational choices. With the two furnace express type boiler, the operator could choose to lower the design steam temperature, probably expecting to have less maintenance problems. But lower steam temperatures brought other problems including moisture erosion in turbines. Turbine bleed and induction and cruising turbines all involved manipulation by the ship's force, and often were not used when most required. The choice between motor driven and steam driven auxiliaries often was dictated by considerations other than good power plant economy.

DIESEL ENGINES

The diesel engine was quickly utilized in all submarines for operation on the surface, but many more types of craft, amphibious, mine craft, and others came into being that were more suited to, and were therefore fitted with, diesel engines.



MAIN ENGINES	MAIN RED. GEARS	PROPELLER R.P.M.	SPEED KNOTS	AUX. GENS.	EMERG. GENS.	MAIN BOILERS	MAIN FEED PUMPS	AUX. FEED PUMPS	EMERG. FEED PUMPS	EVAPORATORS	LENGTH BP. DISPLACEMENT	
2— 30,000 H.P. TOTAL 60,000 HP	2— DOUBLE RED.	390	35	2— 200 K.W. TURBO	1-100 KW DIESEL ENG. UPPER DK	4	4-425 G.P.M.	2-875 G.P.M.	2-120 G.P.M.	360 GAL. HR.		

Figure 16. DD 445 Class Machinery Arrangement.

Since diesel developments have been adequately covered in a recent 1963 Journal Article "The Submarine Propulsion Plant" [8] no mention will be made of detailed engine characteristics. The diesel engine came into its own as a main propulsion plant for surface ships during World War II. It was used extensively in the destroyer escort designs both in geared and electric drive. Other applications of diesels included minesweepers, patrol craft, tug boats and some auxiliary types. By the end of World War II the total amount of diesel power installed exceeded that of the steam plant. A diesel engine was installed on almost every ship either as a main propulsion unit or as an emergency generator.

In the period from 1900 to 1945 the steam plant became of age in naval machinery, and the diesel plant assumed a very strong role as the power plant for submarines and naval auxiliaries and smaller combatant craft. The advancements in steam plant design in the latter part of the period were more in the nature of refinements involving better use of materials and more application of theory than radical changes in concept. Figure 17 shows the band of improvement in full power efficiency of the overall steam power plant including all auxiliary loads vs. time.

If only the main propulsion plant with its associated auxiliaries were to be considered as is usually the case with land plants the efficiency curve would be appreciably higher. Efficiency is defined as BTU heat input of fuel divided by propulsion SHP output of ship.

Figure 18 shows the reduction in plant heat rate of naval machinery vs. time, with some of the significant events affecting the trend of the curve.

Figure 19 shows the types and power range of naval power plants in use at the end of World War II in the U.S. Navy.

These and many other factors were considered in the design of post World War II naval machinery. Many new types of power plants have also become available since World War II. These latest developments in naval machinery design as well as the most promising types of machinery for the future will be discussed in the final paper of this series.

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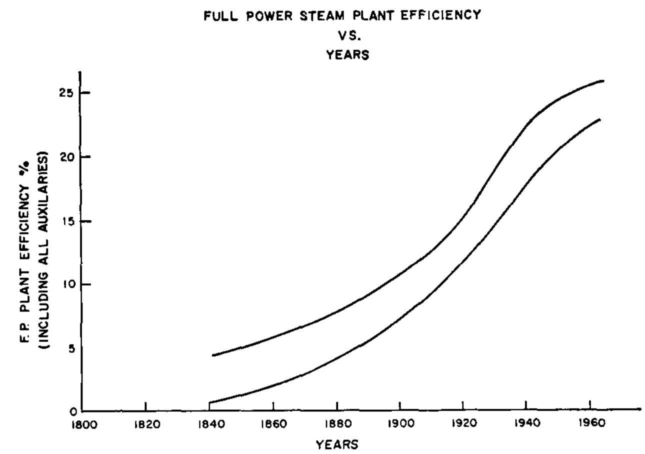


Figure 17. Full Power Plant Efficiency vs Time.

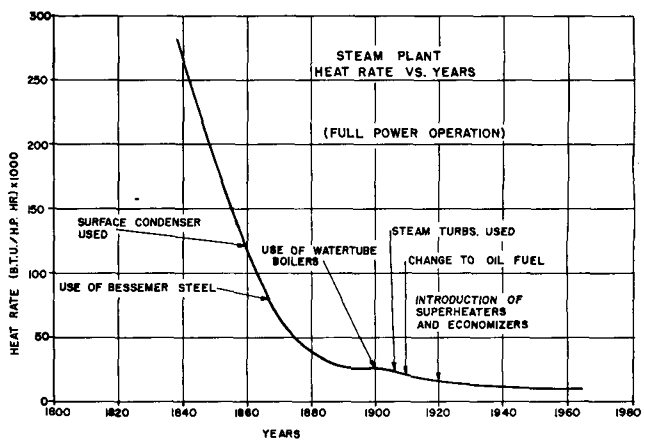


Figure 18. Plant Heat Rate vs Time.

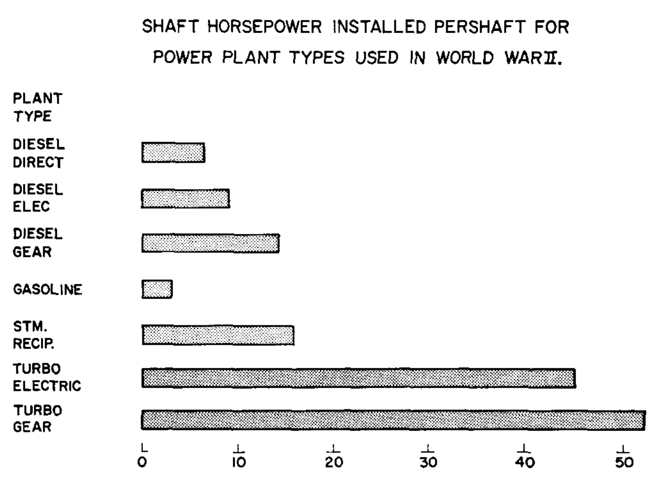


Figure 19. Shaft Horsepower Installed Per Shaft For Power Plant Types Used in World War II.

G. M. BOATWRIGHT, M. WELLING and M. R. HAUSCHILDT

NAVAL PROPULSION MACHINERY POST WORLD WAR II

THE AUTHORS

Editor's Note: The biographies of the authors may be found on page 687 of the October 1963 issue of the NAVAL ENGINEERS JOURNAL.

EXPERIMENTAL DESIGN

THE FIRST FORWARD step after the wartime freezing of machinery design was the destroyer USS *Timmerman,* in 1945. The purpose of its machinery design was to make the maximum possible investigation of the state of the art; to determine how far the designer could go in improving a geared steam turbine plant from the standpoint of weight, space, efficiency and operating techniques. Reduction of long standing design margins and in factors of safety were some of the approaches used. Guarantees were required only as to workmanship and materials; no guarantees were required as to performance. Innovations included a 2000 psi-1050°F steam plant on one of the two shafts, with forced circulation boilers. Compact "D" type single furnace natural circulation boilers at 875 psi-1050°F were provided for the other shaft. Gears were highly loaded with tooth line contact K factors as high as 400. Welded pipe joints for main steam piping was another innovation.

FIRST MODERN FRIGATE

Although *Timmerman* never became fully operational, the knowledge gained from much of its design development was invaluable and was carried over into the design of the destroyer leaders, later renamed frigates. These ship designs exemplified by the USS *Mitscher* and the USS *Wilkinson* were initiated in 1947. They were fitted with the first of the modern 1200 psi-950°F combatant steam plants. Specific machinery weight was down to 30 lbs per SHP, and there was a significant improvement in ship's speed, endurance, and weapons load over the DD-692 class. These ships were also the first of the fleet to make considerable use of electric power for propulsion system pumps. Reduction gear K factors were as high as 350; nearly twice that of the DD-692 class. Boilers, finally installed in these ships were compact "D" type natural circulation types and were provided with forced draft blowers capable of developing a static head of 95 inches of water. Main condensers were almost half the size of those on World War II ships, the designers taking

60 YEARS OF DESTROYER CHARACTERISTICS

Table 1

CLASS	YR. AUTH.	NO. IN CLASS	DIMENSIONS LOA	B	D	DISPLACEMENT STD.	FULL	RATED SPEED	COMPL. OFF-EM	MACHINERY BOILERS-SHP-SCREWS-ELEC PWR	ARMAMENT
DD 1 *Bainbridge*	'98	16	250	23	$6\frac{1}{2}$	420	592	28	3-72	4B-8000-2-5KW(D-C)	2-12 PDRS; 5-6 PDRS; 2-18"T.T.
DD 17 *Smith*	'06	26	294	26	$8\frac{1}{2}$	700	902	28	4-82	4B-12000-2-10KW(DC)	5-3"/50; 3-18" LONG T.T.
DD 43 *Cassin*	'11	14	305	$30\frac{1}{2}$	$9\frac{1}{2}$	1020	1139	29	6-89	4B-16000-2-50KW(DC)	4-4"/50; 4 TWIN 18" T.T.
DD 57 *Tucker*	'13	18	315	30	$9\frac{1}{2}$	1090	1205	29	6-89	4B-16500-2-50KW(DC)	4-4"/50; 4 TWIN 21" T.T.
DD 75 *Wickes*	'16	273	314	31	13	1100	1600	35	8-124	4B-27000-2-50KW(DC)	4-4"/50; 2-1 PDR. A.A.: 4-21" TRIP T.T.
DD 348 *Farragut*	'19	48	341	34	17	1365	2255	36	11-171	4B-42,800-2-354KW(AC)	5-5"/38; 2-21" QUAD T.T.
DD 356 *Porter*	'33	13	381	37	18	1850	2840	35	15-225	4B-50,000-2-400KW(AC)	8-5"/38; 2-21" QUAD T.T.
DD 409 *Sims*	'34	112	348	36	17	1570	2465	38	16-235	4B-50,000-2-400KW(AC)	4-5"/38; 2- TWIN 40MM; 2-21" QUAD T.T.
DD 445 *Fletcher*	'40	197	376	40	18	2050	2940	35	20-309	4B-60,000-2-500KW(AC)	5-5"/38; 5-TWIN 40MM; 2-21" QUAD T.T.
DD 692 *Sumner*	'42	70	376	41	$18\frac{1}{2}$	2200	3320		20-325	4B-60,000-2-800KW(AC)	6-5"/38; 2-TWIN, 2-QUAD 40MM; 2-21" QUIN T.T.
DD 710 *Gearing*	'42	105	391	41	$18\frac{1}{2}$	2425	3540		20-325	4B-60,000-2-800KW(AC)	6-5"/38; 2-TWIN, 2-QUAD 40MM; 2-21" QUIN T.T.
DL 1 *Norfolk*	'48	1	540	54	26	5600	7300		42-504	4B-80,000-2-3000KW(AC)	8-3"/70; 4-MK108 INCHRS; 4-MK31 INCHRS; 3-MK24 FIXED T.T.
DL 2 *Mitscher*	'48	4	493	50	21	3500	4770		29-374	4B-80,000-2-2000KW(AC)	2-5"/54; 4-3"/70; 2MK108 INCHRS; 4MK31 INCHRS; 4-MK24 FIXED T.T.
DD 931 *Sherman*	'51	18	418	45	19	2800	3960		22-315	4B-70,000-2-2000KW(AC)	3-5"/54; 4-3"/50; 2 MK 11 PRG; 4MK25 T.T.; 2MK32 T.T.
DLG 6 *Farragut*	'56	10	513	52	25	4150	5709		28-359	4B-85,000-2-3000KW(AC)	1-DUAL ARM TERRIER; 1-5"/54; 4-3"/70; ASROC 2MK32 T.T.
DDG 2 *Adams*	'57	23	432	47	$21\frac{1}{2}$	3190	4500		24-330	4B-70,000-2-2000KW(AC)	1-TARTAR LNCHR; 2-5"/54; ASROC; 2MK32 T.T.
DLG 16 *Leahy*	'58	9	533	$53\frac{1}{2}$	25	4650	7000		31-360	4B-85,000-2-4000KW(AC)	2-TERRIER LNCHRS; 4-3"/50; ASROC; 2MK32 TRIP T.T.
DLGN 25 Bainbridge	'59	1	564	57	27	7100	8783		34-463	60,000-2-12,500KW(AC)	2-TERRIER LNCHRS; 4-3"/50; ASROC; 2MK32 TRIP T.T.
DLG 26 *Belknap*	'61	9	547	55	28	5340	7930		31-387	4B-85,000-2-6000KW(AC)	1-TERRIER/ASROC LNCHR; 1-5"/54; 2-3"/50; DASH; 2-MK 25T.T.; 2-MK32 TRIP T.T.
DES *Evarts* (GMT)	'41	99	289	35	11	1140	1430	21	15-183	DIESEL 6000-2-600KW(AC)	3-3"/50, 1 QUAD 40MM
DE 51 *Buckley* (TE)	'42	460	306	37	13	1400	1740	21	15-201	DIESEL 6000/12000-2-600KW (AC)	3-3"/50,3 TWIN 40MM
DE 1006 *Dealey*	'51	13	315	37	12	1340	1950		11-159	2B-20,000-1-600KW(AC)	4-3"/50; DC TRACK; 6MK6 DC PROJ; 1MK108 LNCHR; 2MK32 T.T.
DE 1033 *Jones*	'56	4	310	37	12	1370	1750		15-160	DIESEL 9200-1-600KW(AC)	2-3"/50; 2MK10 PROJ; 2MK32 T.T.
DE 1037 *Bronstein*	'60	2	$371\frac{1}{2}$	$40\frac{1}{2}$	$23\frac{1}{2}$	1890	2650		16-180	2B-20,000-1-2000KW(AC)	3-3"/50; ASROC; 2MK32 T.T.; DASH
DE 1041	'61	6	$414\frac{1}{2}$	44	24	2624	3400		16-231	2B-35,000-1-2500KW(AC)	2-5"/38; ASROC; DASH; 2MK25 T.T.; 2MK32 T.T.
AGDE 1/DEG1	61/62	4	$414\frac{1}{2}$	44	24	2643	3426		17-231	2B-35,000-1-2500KW(AC)	1-5"/38; 1 TARTAR LNCHR; ASROC; DASH, 2MK25, MK32 T.T.

advantage of *Timmerman* studies that showed it undesirable to carry a condenser sufficiently large to give high vacuum at full power. The smaller condenser still permitted high vacuum at the cruising speed and the condenser weight saving far outweighed the slight increase in cruising radius fuel. A single stage of feed heating was provided by a combined deserating feed heater (DFT) and storage tank in a closed feed system. The DFT and its feed and feed booster pumps were located in the fireroom, under the eye of the boiler operators. Thermal efficiency of the plant was about 25 per cent.

The *Dealey* class of single screw destroyer escorts was inaugurated in 1951. These carried the major improvements of the *Mitscher* machinery, but the steam conditions were reduced to 600 psi-850°F because the lower SHP would not give sufficient gain in efficiency and in weight saving at higher steam conditons.

DESTROYER CLASSES

The *Forrest Sherman* class, begun in 1952, was the machinery prototype for a long line of twin screw destroyers and guided missile destroyers. Steam conditions were again 1200 psi-950°F. There was some retrenchment as a result of operating experience with the *Mitscher* class, but, in general, much of the post war improvements were retained.

LATER STEAM PLANTS

The *Saratoga* class of supercarriers and the *Koontz* class of guided missile frigates in 1955, as well as later frigate classes, also were designed with the same basic type of 1200 psi-950°F steam plant.

SUMMARY OF POST WAR MACHINERY DESIGN

The ten-year period following the end of World War II might be considered as the post war development phase for the advanced steam plants that have just been highlighted. The resultant improvements through 1954 relative to World War II included reduction in propulsion plant weights of 19 per cent, reduction in overall engineering plant weights of 10 per cent, and improvement of cruising economy of 14 per cent. These combined gains resulted in a total weight of engineering plant plus fuel reduction of 22 per cent [2]. Table I from [1] summarizes most of the principal dimensions and characteristics of destroyer types from 1898 through 1962.

REVIEW OF DESIGN CRITERIA

With the advent of modern weapons systems, requiring large electric plants and many other components that required space, weight and much skilled manpower, the U. S. Navy again undertook a review of machinery plant design philosophy. Design criteria were expanded from the original concept of least total weight of machinery plus endurance fuel, consistent with maximum reliability—many other factors were considered. Combined plants using lightweight gas turbines for boost power were given serious consideration. Overall cost over the life of the ship, complexity, and ease of automation were some of the many factors considered.

FUTURE NAVAL POWER PLANTS

Predicting the long term trend of future naval power plants for surface ships using petroleum type fuel, is far more difficult than to review the history of the past. Existing types of plants plus those under development, and proposed for development or research offer many possibilities. For this section the prediction will be limited to ten years. This is believed to permit consideration of only those basic types of prime movers that have already been developed. These prime movers are readily recognized as steam turbines, gas turbines, diesels, gasoline engines, steam reciprocating engines and mechanical or thermal combinations thereof.

Figure 1 indicates the types and maximum sizes of Naval Power plants that have been installed or contracted for in recent years. Those studied including several noticably missing from the figure, such as COSAG and COGAS, indicate the interest in examining the possibilities of utilizing combined type power plants in future ships. Numerous papers and articles discussing possible combined plants have also been published, [3] and [4] are recent and typical and contain references to others. The biggest contender to the steam turbine for large blocks of power appears to be the gas turbine alone or in combination. The following section outlines some of its history and possibilities of its future.

GAS TURBINES

In 1940, the Bureau of Ships awarded a contract to Allis Chalmers for a gas turbine which was tested at the U. S. Naval Engineering Experiment Station from 1944 to 1949, yielding a considerable amount of valuable data. A number of other open, semi-closed and closed cycle main propulsion gas turbines contracts were awarded, but none reached the ship installation stage. The first U. S. Navy ship gas turbine installation was a 400 HP Solar T-400 gas turbine driving a 250 KW emergency generator on the USS *Timmerman,* an experimental Destroyer. This gas turbine had its share of difficulties including the accidental ingestion of metal shavings into the compressor, which wrecked the engine. It was replaced by a 500 HP Solar engine, which operated successfully for the life of the ship and con-

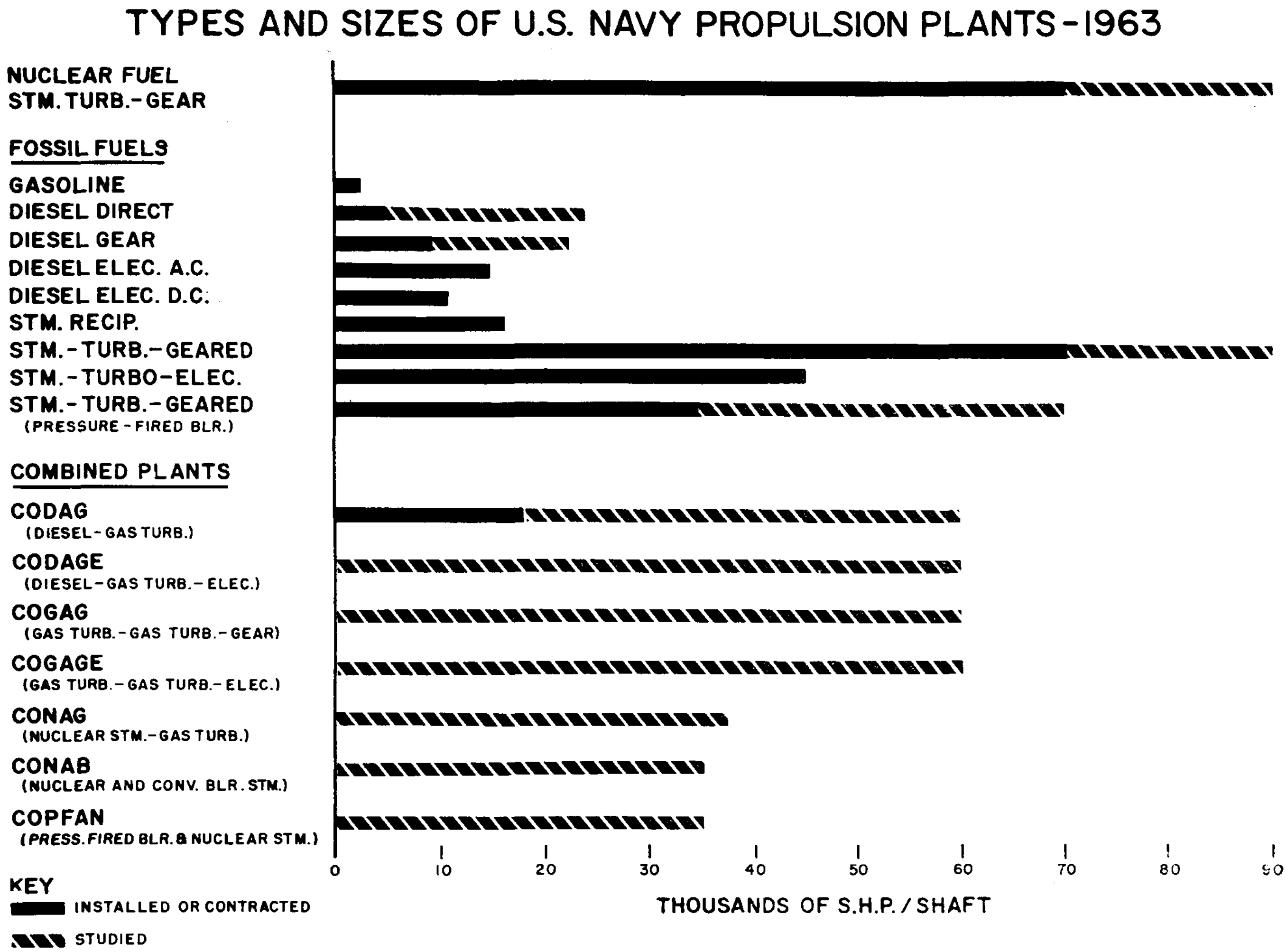
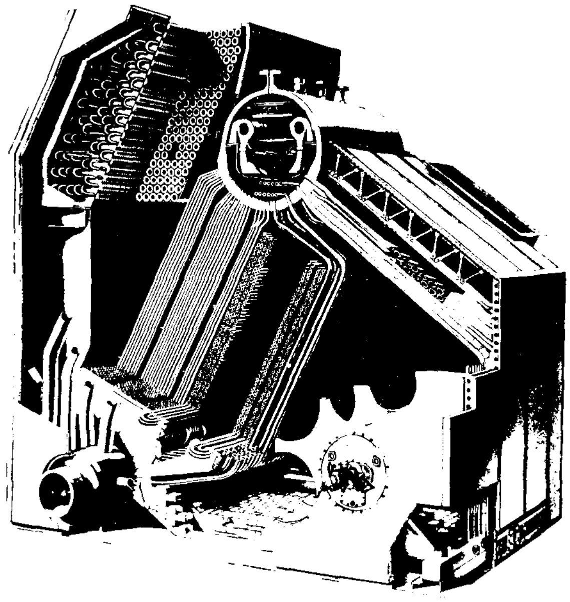
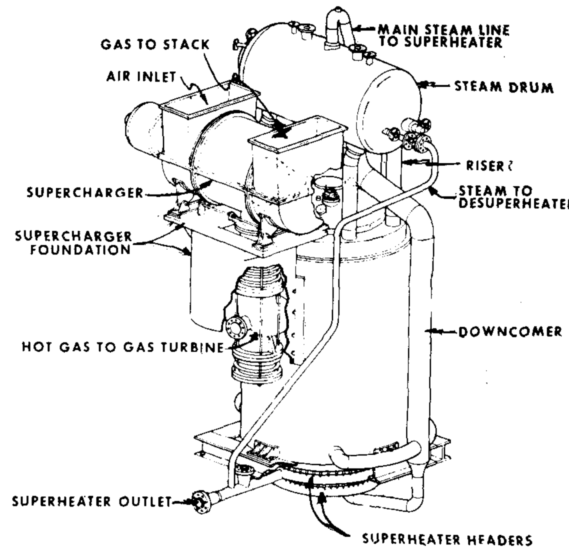


Figure 1. Types and Sizes of USN Propulsion Plants Installed and Studied.

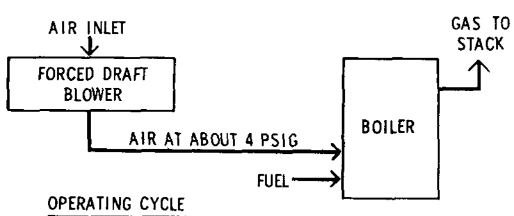
tinued to operate when moved ashore. From this shaky beginning the gas turbine has steadily moved into the Navy prime mover field to challenge both the steam turbine and the diesel engine. The majority of applications to date have been emergency or minesweeper generators and small boat propulsion. The light-weight, non-magnetic properties of gas turbines make them ideal for minesweeper service. Gas turbines were also ideally suited to light weight, low endurance requirements of small boats. The major obstacles to widespread installation of naval gas turbines has been their high fuel consumption compared to diesel and steam, lack of proven reliability in larger sizes, and development time and cost where the ratings required were not available. Many of these obstacles are being overcome. Fuel rates which were about 1 Lb./SHP-Hr. are now below .6 Lb./SHP-Hr. and now a joint armed services competitive development of a 600 HP engine with regenerator, promises a fuel rate of about .45 Lb./SHP-Hr. with a specific weight of 2.5 lbs. per HP. The larger volume of service experience has enabled the gas turbine to demonstrate its inherent good maintenance characteristics. Improved repair and logistics support in the field has also improved the reliability picture.

A greater range of engine ratings is now available particularly in the larger sizes. Tables II and III show the number, rating and installations of gas turbines in the U. S. Navy today. An interesting application of the gas turbine is in the pressure fired boiler design for Navy Destroyers. The gas turbine drives the compressor which pressurizes the combustion air to the boiler. The hot boiler gases generate the required steam and are cooled to below 1000°F before entering the gas turbine blading. The result is a light weight compact boiler and a low temperature long life gas turbine, with excess air requirements even less than that of conventional boilers. The relative weight, space and performance of the pressure fired vs. conventional boiler is illustrated in Figure 2. Figure 3(a) shows an efficient combined gas-steam turbine power plant using





CONVENTIONAL DESTROYER BOILER

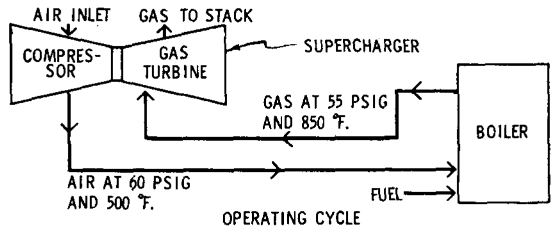


PRINCIPAL BOILER CHARACTERISTICS AT 100% RATING:

OPERATING PRESSURE AT SUPERHEATER OUTLET . . . . 1200 psig
SUPERHEATED STEAM TEMPERATURE . . . . 950°F
TOTAL STEAM GENERATED . . . . *133, 000 lb./hour
BOILER CASING DESIGN PRESSURE . . . . 5.4 psig
FURNACE VOLUME . . . . 420 cu. ft.

*THE STEAMING CAPACITY IS HIGHER THAN FOR THE PRESSURE FIRED BOILER, MUST SUPPLY STEAM FOR THE FORCED DRAFT BLOWERS—NOT REQUIRED WITH THE PRESSURE FIRED BOILER.

PRESSURE FIRED DESTROYER BOILER



PRINCIPAL BOILER CHARACTERISTICS AT 100% RATING:

OPERATING PRESSURE AT SUPERHEATER OUTLET . . . . 1200 psig
SUPERHEATED STEAM TEMPERATURE . . . . 950°F
TOTAL STEAM GENERATED . . . . *121, 000 lb./hour
BOILER CASING DESIGN PRESSURE . . . . 75 psig
FURNACE VOLUME . . . . 126 cu. ft.

PRINCIPAL ADVANTAGES
ABOUT 1/2 THE SIZE AND WEIGHT OF CONVENTION BOILER.
PRACTICALLY NO FURNACE REFRACTORY NEEDED: ADDED SHOCK RESISTANCE AND LOW REFRACTORY MAINTENANCE.

Figure 2. Comparison of Conventional and Pressure Fired (Supercharged) Boiler.

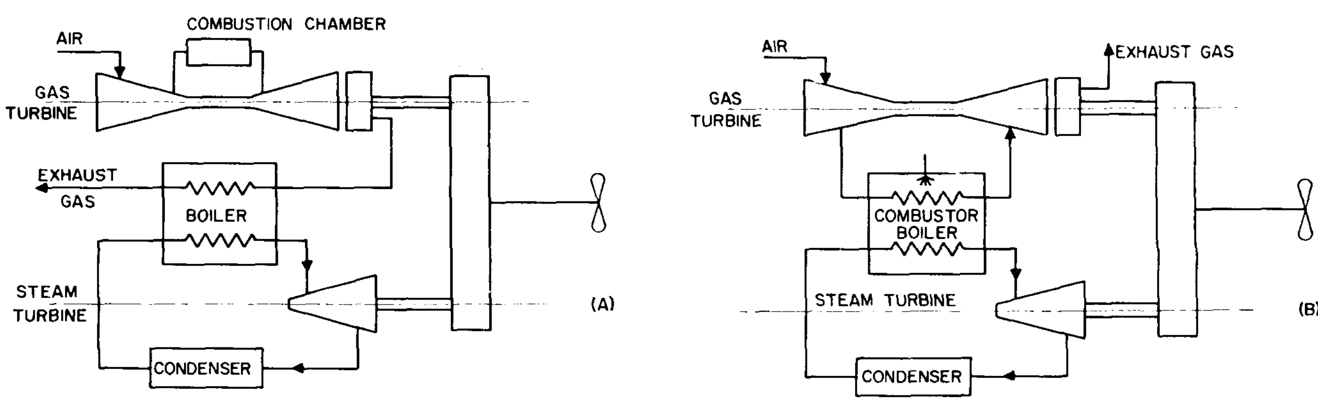


Figure 3. Combined Gas Turbine—Steam Turbine Cycles.

TABLE II
Navy Gas Turbine Applications
PROPULSION

Turbine	Power (hp)	—Vessel— Type	Number	Number of Turbines	Total Power (hp)
Solar T-522	500	LCPL	4	4	2000
Boeing 502-10C	220	Mine	26	26	5720
GE T-58	750	LVTP-10	1	1	750
GE T-58	800	LVTP	1	1	800
O'bd. Marine OMTR-1	125	Pers. Boat	1	2	250
Bristol Proteus	3800	PCH-1	1	2	7600
Solar 10-MV	1140	LCA	1	2	2280
Solar 10-MV	1000	LCSR	14	28	28,000
Solar 10-MV	1000	LVH	1	1	1000
Solar 10-MV	1000	LVHX2	1	2	2000
Lycoming T-55	1500	LVW	2	2	3000
Lycoming T-53	1000	LVHX1	2	2	2000
Solar 10-MV	1000	SKM	1	2[2]	2000
P & W JT-3D	20,000	HYD[3]	1	1[3]	20,000
GE LM 1500	12,750	AGEH	1	2	25,000[1]
P & W FT-12	3000	LCM	1	1	3000
Lycoming T-55	1500	EXP	1	1	1500[1]
Solar 10-MV	1000	LCPL	1	1	1000
G. E. LM 1500	14,000	PGM	2	2	28,000[1]
		Totals	63	83	135,900

[1] To be installed.
[2] One lift, one propulsion.
[3] Test vehicle for foils.

TABLE III
Navy Gas Turbine Applications
ELECTRICAL AND AUXILIARY POWER

Turbine	Power (hp)	—Vessel— Type	Number	Number of Turbines	Total Power (hp)
Solar T-520	500(G)	Destroyer	1	1	500
Solar 10-MC	1130(G)	Cruiser	1	1	1130
Solar 10-MC	1130(G)	CLG	5	5	5650[1]
Solar 10-MC	1130(G)	DE	10	10	11,300[1]
Solar 10-MC	1130(G)	AGS	1	1	1130[1]
Solar T-520	500(G)	DLG	15	15	7500[1]
Solar T-520	500(G)	AGOR	5	5	2500[1]
R.H. T.E.	430(G)	AGOR	2	2	860[1]
Solar T-62	65(G)	PCH 1	1	1	65[1]
Solar T-520	500(M)	Mine	2	4	2000
Boeing 502-6	160(M)	Mine	46	184	29,440
Boeing 502-10C	220(M)	Mine	26	26	5720
Solar T-45	45(A)	Mine	64	91	1170
Solar T-522	500(M)	Mine	6	12	6000
Solar 10MV	1000(M)	Mine	12	12	12,000[1]
Solar T-45	45(F)	LCU	15	15	675
Solar T-45	45(P)	Various	—	62	2790
Solar T-62	65(H)	PCH 1	1	1	65
Boeing 502-10C	220(M)	Mine	1	1	220[1]
AiResearch CC100-1	500(A)	CVA	1	8	4000[1]
Clark Bros. 22LC	2200(M)	Mine	8	8	17,600[1]
Elliott E1-6	3000(B)	DE	9	18	54,000[1]
I.R. Awd G.E.	3000(B)	DE	5	10	30,000[1]
		Totals	237	493	196,315

[1] To be installed.
(A) Air supply; (P) Fire Pump; (G) Auxiliary generator; (F) Pump and fog; (H) Hydraulic; (B) Boiler supercharger; (M) Minesweep Generators.

gas turbine exhaust to generate main propulsion steam. Figure 3(b) shows an alternate approach with the combustion taking place in the boiler.

Previous gas turbine installations have been specifically designed for marine use. Recently, the extreme light weight power plant requirements for hydrofoil and hydroskimmer craft have focused attention on aircraft type gas turbines as marine prime mover gas generators. This has required the development of a split wheel gas turbine and redesign of various internals to withstand the salt atmosphere and more demanding life requirements of a marine installation. A combined diesel and gas turbine plant is characteristic of these installations.

The use of combined power plants opens up a wide range of arrangements of machinery, some of which are sketched in Figures 4-7. Some of these combinations consist of the combining with gearing of a base load and boost type of gas turbine. The base load gas turbine should provide a lower fuel

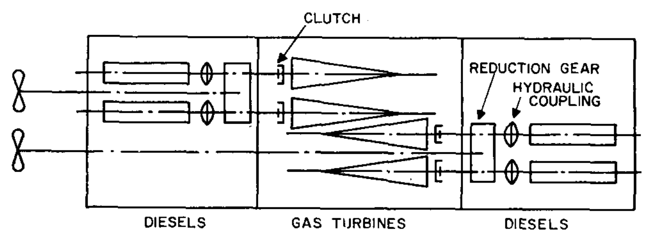


Figure 4. Proposed CODAG Machinery Plant Arrangement.

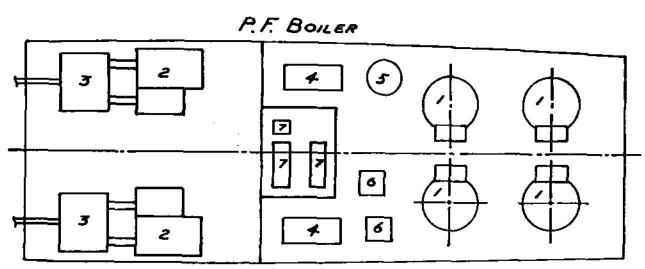


Figure 5. Proposed Pressure Fired Boiler Machinery Arrangement. Legend: 1. P. F. Boiler; 2. Prop. Turbines; 3. Red. Gear; 4. Diesel Gen., 1000 KW; 5. D.F.T.; 6. Distiller; 7. SWBD.

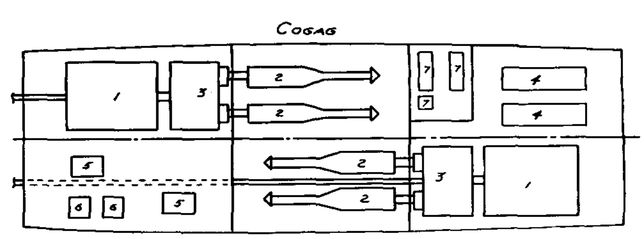


Figure 6. Proposed COGAG—Gear Plant Arrangement. Legend: 1. Base Plant G.T.; 2. Gas Turbine; 3. Red. Gear; 4. Diesel Gen. 1000 KW; 5. Aux. Boiler; 6. Distiller; 7. SWBD.

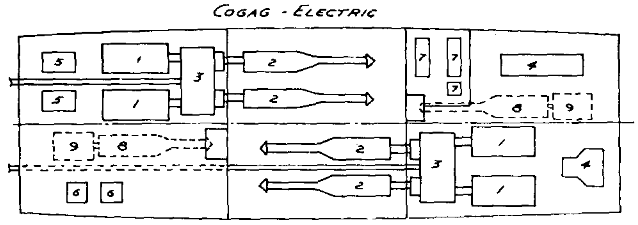


Figure 7. Proposed COGAG—Electric Plant Arrangement. Legend: 1. Main Prop. Motor; 2. Gas Turbine; 3. Red. Gear; 4. Diesel Gen. 1000 KW; 5. Aux. Boiler; 6. Distiller; 7. SWBD; 8. Gen. Gas Turbine; 9. Prop. Gen.

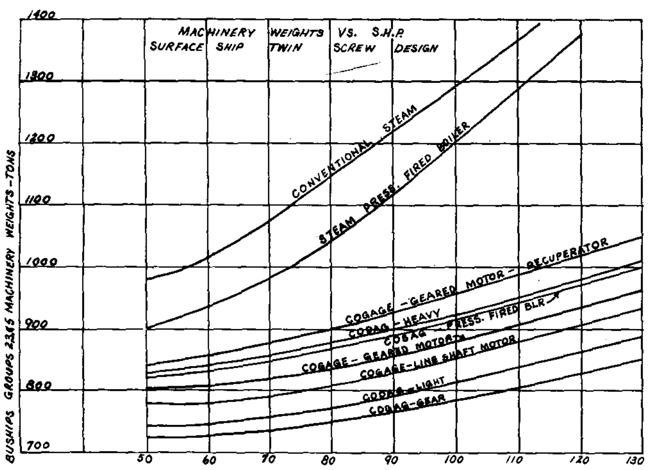


Figure 8. Machinery Weight Vs Shaft Horsepower Surface Ships—Twin Screw Designs.

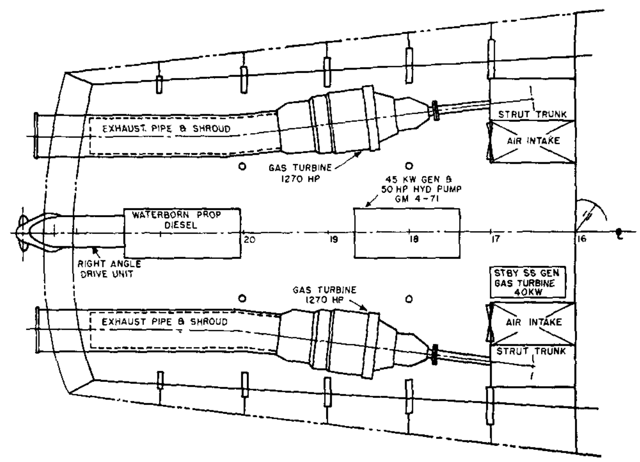


Figure 9. Hydro Foil Patrol Craft PC-H Machinery Arrangement.

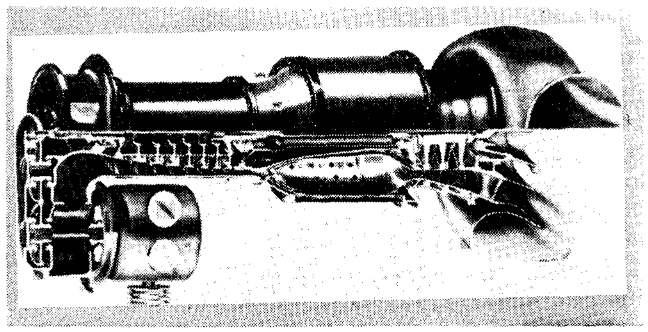


Figure 10. Solar-Saturn 10 MC Engine.

consumption at cruising loads, while the light weight aircraft gas turbines provide short life boost power at high speeds. Figure 8 shows the relative weights of a series of conventional and combined power plants designed for a given ship size and endurance vs. shaft horsepower. It is obvious that the gas turbine has decided weight advantages when used as a boost power plant. Some recent gas turbine applications are described below:

Eighteen Solar 7-520 powered 300 KW emergency generator sets are being installed in Guided Missile Destroyers. The first units have already been installed. The engine is a 500 HP single shaft engine and is fitted with a combustion starter to achieve full generator output within 10 seconds from a cold stand still condition.

The USS *High Point* (PC(H)-1), Figure 9, built by Boeing Company utilizes two model 1273 Marine Proteus engines built by Bristol-Siddeley. Rating is 3800 HP take-off and 3100 HP cruise under standard Navy conditions. These engines have had considerable background of marine service in British "*Brave*" Class boats. The ship operated successfully on trials in 1963.

A Solar 10MC gas turbine powered 750 KW generator set, Figure 10, completed a 1000 hour test and was installed onboard the USS *Oklahoma City* (CLG 5) in September 1960. Initial problems involved with the installation have been resolved and three additional units have been delivered for other CLG's.

The development program of the 1000 HP Solar 10MV gas turbine engine is completed. Testing of this propulsion engine, complete with a reverse and vee-drive gear has been completed in a 40 foot LCP(L). Two engines have been installed in the prototype of the LCA amphibian. Four of these engines are being installed in the 20 ton Hydroskimmer, see Figure 11, and twenty-eight in 14 LCSR's. The SKMR-1 has just completed a successful set of trials exceeding the design speed of 70 knots.

The Bureau of Ships is now procuring and installing gas turbine driven minesweeping generator sets of 1480 KW and 1750 KW capacity aboard MSC type minesweepers. Solar has delivered nine 1480 KW sets using two model T-522 engines, mounted above the generator, driving through a combination reduction gear and a flywheel. Clark Brothers will supply four 1480 KW sets using a model 22LC engine without a flywheel and four 1750 KW sets also using a model 22LC engine without a flywheel. The first Clark Brothers 1480 KW sets were delivered in 1963. Solar is supplying nine Solar model T 1000s engines to drive 1750 KW sets. These sets will uti-

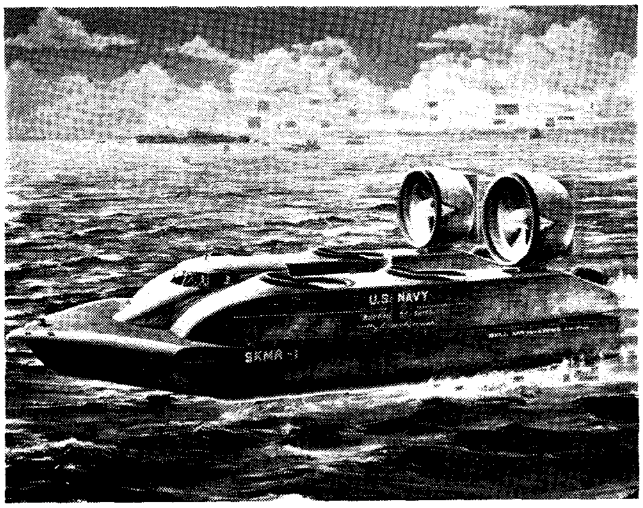


Figure 11. Hydro Skimmer SKMR-1.

lize one T 1000s engine driving through a flywheel.

The AGEH, 300 ton, 200 foot hydrofoil is now under contract, to Puget Sound Bridge and Drydock Company (see Figure 12). The engines to be used for foilborne propulsion are General Electric Company Model LM1500. Two engines will be used when testing subcavitating foils and four engines will be used when testing supercavitating foils. The LM1500 is a J79 jet engine fitted with a power turbine and modified, for marine use. The engines will be rated at 17,000 HP for takeoff conditions and at a conservative 12,750 HP for cruising conditions.

A contract has also been awarded to Pratt and Whitney to develop a marine gas turbine by adapting their existing J75 jet engine to a power turbine. The engine is being considered for hydrofoil and for combined diesel and gas turbine plants (CODAG) or combined gas turbine plants (COGAG) for various types of surface ships. The engine has completed a number of tests successfully at the Naval Boiler and Turbine Laboratory. See Figure 13.

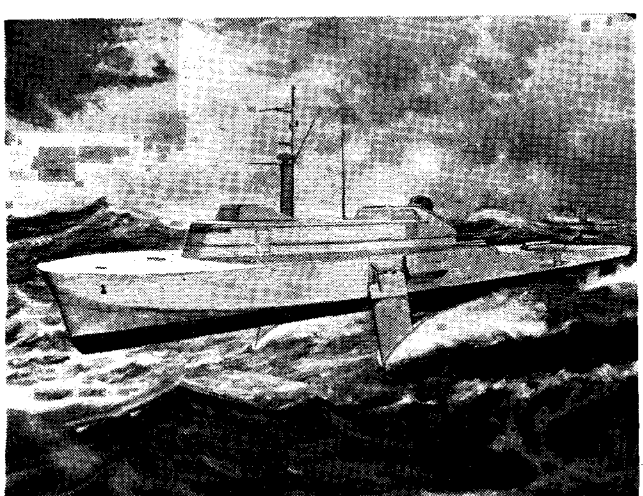


Figure 12. Artists Conception of AGEH.

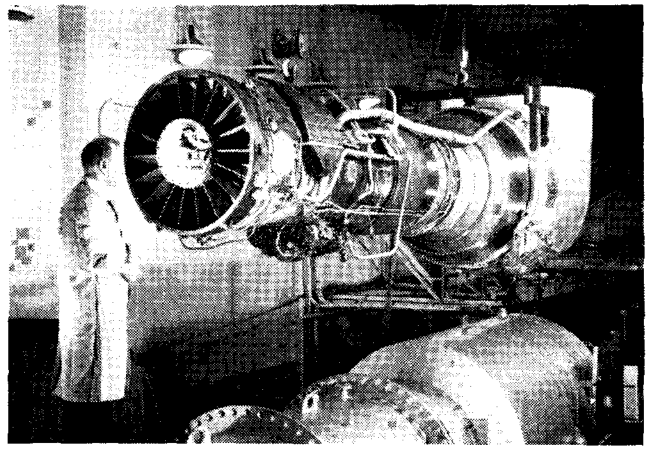


Figure 13. Pratt & Whitney FT4A-2 Marine Gas Turbine.

Graves and Sawyer [5] give a summary of the state of the gas turbine art in the Navy as of 1963. Figures 14 and 15 presented in [5] show the progress made in gas turbine developments since 1955.

It is estimated that total installed Navy gas turbine SHP will reach 1,000,000 by 1970.

It is clear from recent developments that the gas turbine is well on its way to becoming a major prime mover of the U. S. Navy. It is expected that it will eventually rank with steam and diesel power in total shaft horsepower installed. Most of the increase in gas turbine installed power will come at the expense of steam plants, but it also is replacing the diesel in short range light weight applications.

Some of the uses of gas turbines alone and in combination have been discussed. In the following, the effect of achieving lighter machinery weight and better efficiency on the size and cost of a high speed destroyer type ship will be illustrated.

For displacement type surface ships the propulsion power required varies approximately as the speed cubed. Thus if the cruising speed equals 70 per cent or less of the maximum speed the cruising power required is about one-third or less of the total installed. This condition exists for nearly all naval combatant ships of the destroyer escort type or larger. The quantity of fuel provided to meet the endurance requirement is normally based on a specified cruising speed. In actual operation naval ships operate at many different speeds but well over 80 per cent of the total operating time is at speeds requiring less than one-third of the installed power. This relationship accounts for the use of cruising turbines on many naval ships. It also plays a large part in the existing relatively light weight (lbs. per SHP) of naval plants as compared to merchant ships which operate a far greater portion of their time at or near full power.

The above conditions frequently referred to as the "Speed vs Time Profile" or "Power vs Time

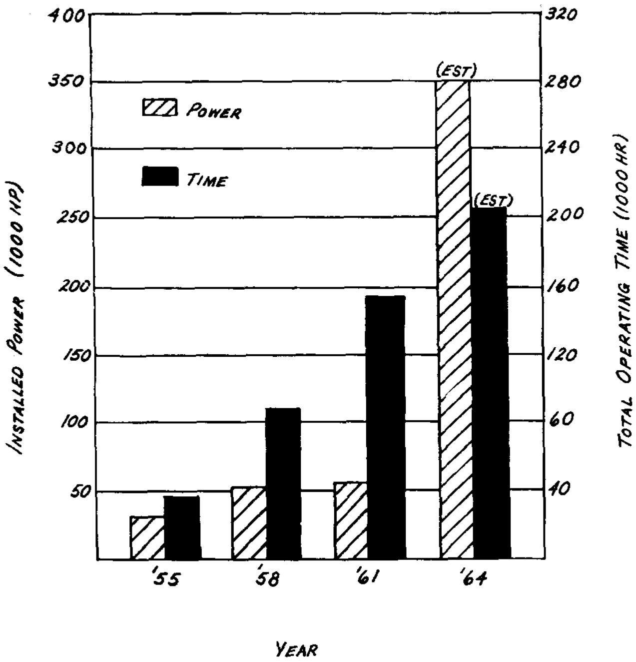


Figure 14. Navy Gas Turbine Power-Operating Time.

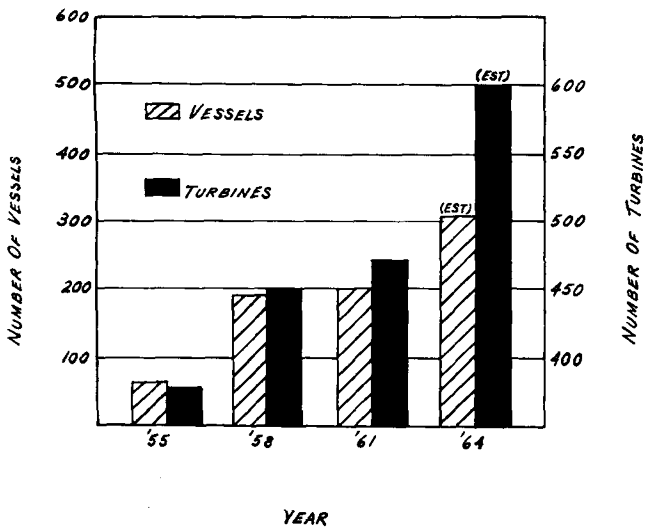


Figure 15. Navy Gas Turbine Installation.

Profile" has led to many suggestions for combined type power plants. In such a plant the base load portion would utilize a relatively high efficiency prime mover of adequate power to meet the cruising requirements for many hours between overhauls. To attain higher speeds a less efficient prime mover with less hours between overhauls would be quite acceptable as a means of substantially augmenting the base load if an overall low specific weight of machinery would be achieved. The improvement in specific weight must not sacrifice reliability or other factors.

To fully assess the benefits and possibilities of light-weight and/or efficient power plants the overall ship with its payload must be considered. Mandel [6], in reporting work done at the request of the Navy by the National Academy of Science, includes among others the following conclusions of particular significance with respect to propulsion plants:

"(a) The modest increases in speed of water-borne vehicles that have taken place during the past several decades, stem from increased power concentration (horsepower per ton of vehicle displacement) and not from improvements in lift/drag ratio." (Where lift corresponds to displacement and drag to vehicle resistance.)

"(b) The existing destroyer types of ship has advantages over any of the proposed new ship types* in terms of it's ability to carry a larger payload weight at a specified speed and endurance in moderate weather. Moreover, because of it's ability to transport and employ at sea a variety of types of payloads, the destroyer type is, in general, better suited to multi-mission applications than any of the proposed new types."

"(c) Application of the new technology in the field of power plants, that is being utilized in the field of current hydro-foil programs, to the design of surface ship types would also permit significant advances in their performance. For example, the maximum speed of a destroyer type could be increased from 35 knots to 50 knots or more with no sacrifice in payload or in endurance at cruising speed if the specific weight of it's power plant could be reduced by a factor of three."

The above paper and conclusions emphasize the possibilities of attaining materially higher speeds by the installation of nearly three times the power with about the same total machinery weight as current ships. However, the need or cost-effectiveness of ships with a 50 knot maximum speed may be questionable. Therefore, the influence of both power plant weight and cruising fuel rate have been examined for an assumed destroyer type ship with less maximum speed and an assumed fixed payload.

The basic method utilized for comparing ships with varying power plants is essentially that used by Mandel [6], except that payload is held constant. The pertinent portions of the method have been extracted and are included here with other assumptions for ready reference.

(a) Destroyer experience indicates that the per cent of total displacement devoted to hull structure averages about 30 per cent; to steering gear, anchors and handling, and other systems necessary for ship operation six per cent; and margin six per cent resulting in a total of 42 per cent. The remaining 58 per cent is available for machinery, fuel and payload.

(b) Payload is assumed to include armament (BuShips weight group 700) electronics (group

*These are the catamaran, lengthened slender destroyer, low freeboard ship, escort research ship, "shark form," semi-submarine, ground effect machines and hydro-foils.

400), ventilation, air conditioning, electric plant (group 300) and all consumables exclusive of fuel and machinery liquids. Thus contrary to many ship studies, complement, stores and effects are assumed to be part of the payload. For the purpose of this hypothetical ship the payload has been assumed at 1000 tons. This is greater than that of the DD 692 World War II type, but considering the tremendous increase in sensors and the supporting auxiliary equipment [7] it is believed typical of some future destroyer type within the spectrum of DE, DDG, DLG.

(c) The propulsive coefficients (including appendage drag) used in computing SHP was 0.55 at 25, 35 and 40 knots.

(d) In computing endurance a service factor of 1.25 over clean bottom power requirements was assumed.

(e) The endurance speed has been arbitrarily chosen as 25 knots on the assumption that the higher speeds of nuclear submarines as compared to those using diesel-battery in World War II will require higher average operating speeds of the surface ship.

(f) The smooth water drag characteristics are shown in Figure (16) for a 2000 ton DD with large Sonar Bulb. With the exception of the bulb, the volumetric coefficient* is 2.0×10^{-3} and corresponds fairly closely to the World War II DD 692 class destroyer and the recent DE 1040 class. This value is intermediate between that of the DD 945 and DLG 16 classes.

(g) The L/D ratios of Figure 16 are used to estimate roughly the powering requirements of a

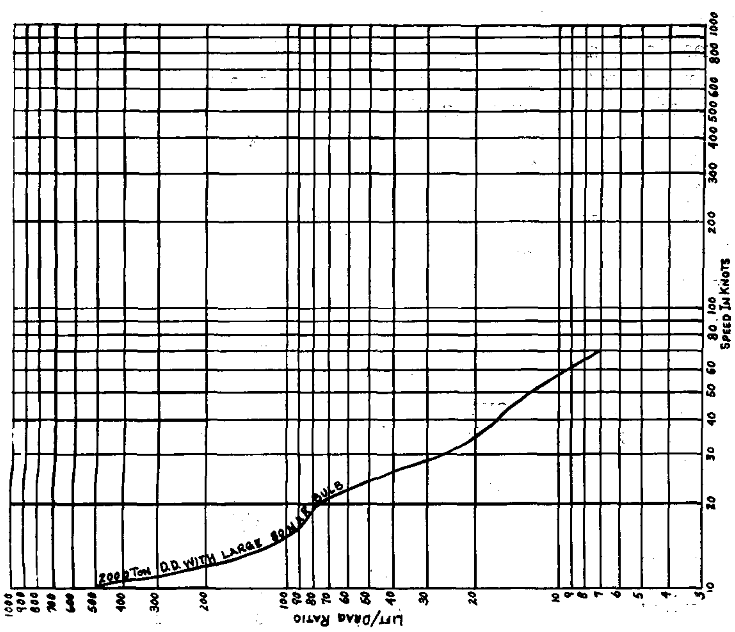


Figure 16. ***Lift* Drag ratio versus calm weather speed (from [6]).**

*Ratio of underwater volume to the cube of maximum underwater ship length.

series of geometrically similar destroyers by assuming that the L/D of the 2000 ton ship at any speed, V_{2000}, is the same as the L/D of an N-ton ship at a speed,

$$V_N = V_{2000}\left(\frac{N}{2000}\right)^{1/6}$$

To avoid an error that would be introduced by assuming a 7000 ton ship's sonar bulb geometrically similar to a 2000 ton ship was also a consideration in selecting 25 knots as a cruising speed. At about this speed and above Mandel has indicated L/D are the same with or without bulbs.

(h) The relationship between L/D and SHP is:

$$SHP = \frac{6.87 \times V x \Delta}{\eta \times L/D}$$

where

V = Speed in knots
Δ = Full load displacement, tons
L = Lift or displacement in lbs.
D = Drag or resistance in lbs.
η = Propulsive coefficient

Table four illustrates the use of the above assumptions in development of the data used to plot Figure 17. Figure 18 was derived similarly.

To utilize the resultant curves of these Figures, some appreciation of the parameters is necessary. The parameters of specific weight of machinery and specific fuel rate at cruising cover the spread from the minimum to the maximum that it is considered reasonable to expect for high rating naval power plants within the next ten years. The combination of 30 lb./SHP and 0.7 lbs./SHP-hr. might be considered as typical of conventional World War II type of steam plants [6]. The combination of 10 lb./SHP and 0.4 lb./SHP-hr. is believed to approximate what may be possible within ten years with a COGAG type plant. Such a plant would likely use light weight long life base load gas turbines, with temperatures higher than currently acceptable, and added complexity over the simple cycle including substantial regeneration to achieve all purpose fuel rates approaching that possible with a heavier weight diesel. Such a base load gas turbine will require a considerable portion of the ten year period and sizeable development costs to achieve as an operational unit.

Intermediate values of the weight and fuel rate are considered practical with current technology and type of existing hardware using various types of combined plants or improved steam plants. Where the specific fuel rate approaches or equals 0.4 lb./SHP a CODAG plant using a diesel or equally efficient base load prime mover is generally implied. Where it approaches, equals or slightly exceeds 0.7 lb./SHP a non-regenerative COGAG, COSAG or steam plant is implied depending on the specific weight. The specific fuel rate is all purpose and not just the propulsion plant prime-mover. Linear interpolation at any given displacement for either intermediate values of specific weight or fuel

TABLE IV

35 Knot Ship—1000 Ton Payload

Full load displacement, Δ		2000			4000			5000			6000			7000	
$V\Delta$ Max knots		35			35			35			35			35	
$\Delta/2000$		1			2			2.5			3			3.5	
$(\Delta/2000)^{1/6}$		1			1.1224			1.165			1.201			1.232	
Max $V_{2000}=V_{35}/(\Delta/2000)^{1/6}$ knots		35			31.1			30			29.1			28.4	
L/D @ V_{2000} from Fig. 16		19.5			24			26			27			28.5	
$SHP_{35}=\frac{6.87\times 35\times\Delta}{.55\times L/D}$		44,800			72,900			84,000			97,000			107,000	
Cruise $V_{2000}=V_{25}/(\Delta/2000)^{1/6}$ knots		25			22.25			21.45			20.8			20.25	
L/D @ V_{2000} from Fig. 16		45			60			70			75			79	
$SHP_{25}=\frac{6.87\times 25\times\Delta\times 1.25}{.55\times L/D}$		17,400			26,000			28,000			31,000			34,600	
Weights															
LB/SHP Installed, Assumed		10	20	30	10	20	30	10	20	30	10	20	30	10	20	30
MACH Weight	Tons	200	400	600	325	650	975	375	750	1125	433	866	1300	478	956	1433
Hull, Misc. & Margin—42%×Δ	Tons		840			1680			2100			2520			2940	
Payload Assumed	Tons		1000			1000			1000			1000			1000	
Remainder, Fuel	Tons	—40	—240	—440	995	670	345	1525	1150	775	2047	1614	1181	2582	2103	1625
ENDURANCE @ $25K=\frac{Tons\times 2240\times 25}{SHP\times SfC}$																
Assume SfC=.7 lb./SHP-hr.	Miles	—184	—1100	—2020	3060	2060	1060	4350	3280	2210	5270	4160	3050	5980	4850	3750
.6	Miles				3580	2410	1240	5080	3830	2580	6150	4860	3560	6950	5670	4375
.5	Miles				4300	2885	1488	6100	4600	3100	7400	5830	4270	8350	6800	5250
.4	Miles	—322	—1930	—3540	5350	3600	1858	7620	5750	3870	9250	7300	5340	10,450	8500	6560

rate may be made. Intermediate values were omitted for clarity.

Knowing the approximate possibilities of achieving certain specific weights and specific fuel rates, Figures 17 and 18, or similar curves developed for different payloads and speeds, can be utilized to predict the possibilities of achieving a desired endurance within any limiting full load displacement.

For example, it is assumed that a 40 knot ship with a 5000 mile endurance at 25 knots is desired. The following possibilities are indicated:

A light weight type of plant, without stress on fuel rate improvement, as might be represented by the parameters of 10 lb./SHP and 0.7 lb./SHP-hr. is considered possible in the near future. Because of the fuel rate influence, a ship of 6,250 tons full load displacement would be required.

With greater stress on fuel rate, which may require added weight to achieve, a plant type represented by parameters of 15 lb./SHP and 0.45 lb./SHP-hr. is also considered realistic within a short period. In this case by interpolation the full load displacement would be 5000 tons.

Using a developmental type of power plant not yet available with a machinery weight of 10 lb./SHP and a fuel rate of 0.4 lb./SHP-hr. the full load displacement would be 4150 tons.

As an indication of the initial and operating fuel cost savings that might arise from the use or development of lighter weight and/or more efficient machinery, Figures 17 and 18 also include estimated ship total first costs and, by using an auxiliary curve, the sum of the first cost plus the present worth of twenty years of fuel.

These costs have been approximated in the following manner:

The average total cost of all Naval ships over the five-year period 1957 to 1961 as indicated in the graph of [7] was about $10,000 per ton. It is recognized that this includes a wide variety of ships from the smallest to the largest; however, it is considered acceptable for use as a base from which variations in cost due to speed and endurance requirements may be shown.

For a base ship it is assumed that a 40 knot 5000 ton ship with 122,000 SHP costs $10,000 per ton or $50,000,000 total. To approximate, plus or minus variations of about 40 per cent in displacement and maximum power, cost changes of $850 per ton of full load displacement and $50 per installed SHP have been found to approximate total cost changes determined by more rigorous estimating methods where the type of payload and its weight is maintained constant.

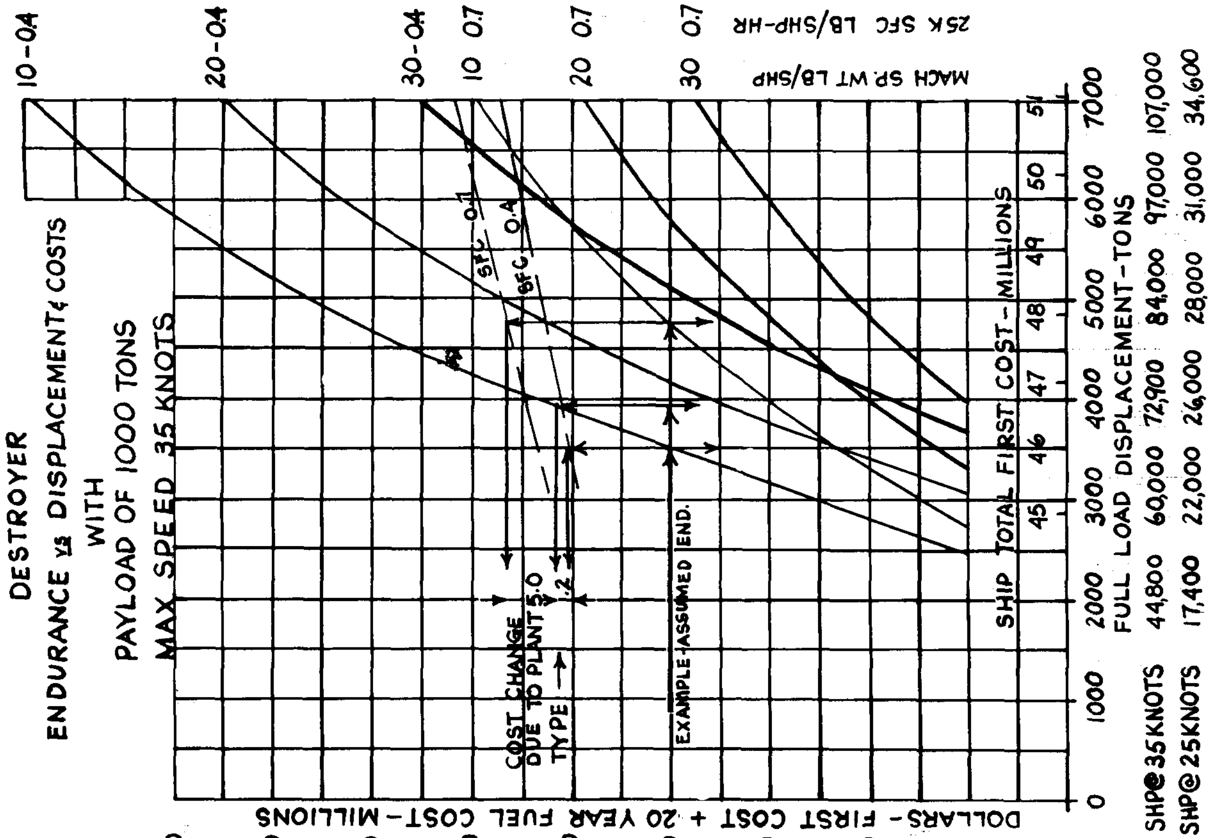


Figure 17. Destroyer Endurance Vs Displacement and Costs 35K—1000 Ton Payload.

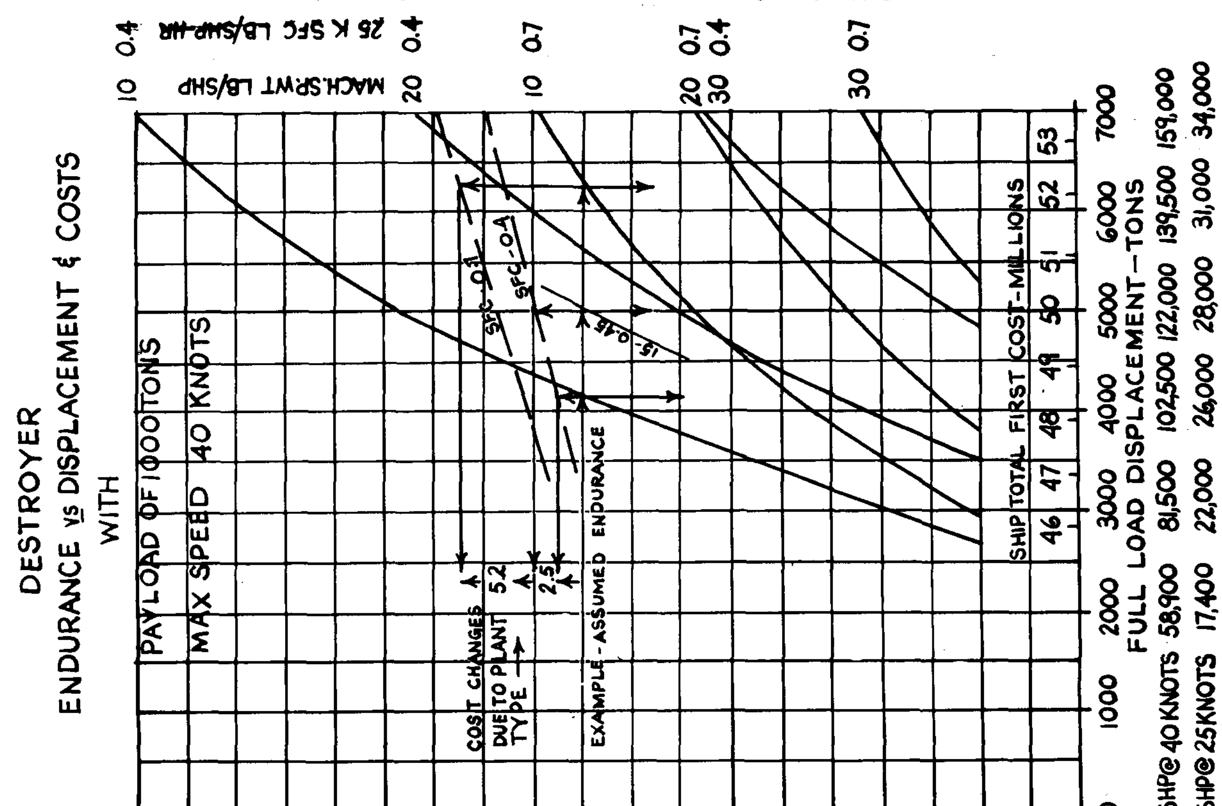


Figure 18. Destroyer Endurance Vs Displacement and Costs 40K—1000 Ton Payload.

The approximate cost of Navy Special fuel burned per year is estimated for peace time usage to average about $250,000 for destroyer types in service. This cost does not include any charges for delivery from Navy fuel depots to ships at sea. The types of plants represented by most of the parameters used in Figures 17 and 18 will probably require a distillate type fuel. If such fuel were used in current destroyer types and in addition some realistic charge for delivery at sea were made the gross cost for current destroyer types would be of the order of $600,000 per year. For use in the foregoing figures it is assumed that this value is most nearly approached by the 4000 ton ship with a 25 knot fuel rate of 0.7 lb./SHP-hr. All other values of fuel cost per year are estimated on the assumption that they vary directly at both 25 knots SHP and 25 knot fuel rate. The 20 year present worth (PW) of fuel assumes a 4 per cent compound interest rate in determining the present value of 20 equal annual costs for fuel. The PW is thus 13.59 times the estimated annual cost.

The foregoing curves of costs, even though of a very approximate nature, indicate the gains to be made in both initial overall ship costs and fuel costs over the ship's life by reductions in specific weight and specific fuel rate. Such analysis, certainly in more refined detail for a given application, can and should be utilized in determining the acceptable development costs in achieving these gains for any specific ship building program. The cost differences due to changes in the maximum speed and endurance requirements must be weighed against the changes in military effectiveness and would be out of place here except to indicate the magnitude.

Continuing with the examples previously used, in both text and in the figures, Table V compares the resultant ship size, variations in first cost, PW of fuel cost for 20 years, and the sum of the two for 35 and 40 knot ships with an assumed endurance requirement of 4000 and 5000 miles at 25 knots using three different types of power plants.

Several conclusions can be drawn from Figures 17 and 18 and Table V.

(a) An increase in speed for destroyer type ships from 35 to 40 knots will increase the cost from 1.5 to five million dollars depending principally on the type of plant represented by the parameters of specific weight and specific fuel rate. The smaller cost is associated with light weight high performance plants not yet developed and the higher cost with plant types similar to those of World War II steam ships.

(b) An increase of 1000 miles in 25 knot endurance will increase the cost from $0.4 million to $2.5 million. Again the variations are dependent on specific weight and specific fuel rate with maximum speed also influencing the variation.

(c) Substantial reduction in both fuel rates and machinery weights, associated with World War II steam plant levels, must be achieved if reasonable 25 knot endurances are to be achieved without skyrocketing costs.

(d) The particular speed and endurance requirements, the development time and costs and the number of ships over which the developments may be amortized may dictate whether weight or fuel rate improvements should receive the greater emphasis. The total fuel costs over the life of the ship should be included in the determination of emphasis.

FUTURE POWER PLANTS

The following are predicted for longer term developments perhaps ten to twenty years hence.

Thermoelectric Generators

The overall efficiency of thermoelectric generators must be considerably improved before they become feasible for ship propulsion on any large power generation system. Overall thermal efficiencies of about 10 per cent have been obtained.

The main advantage is quiet operation, however, the auxiliaries required for cooling will generate noise.

Major problem is the discovery of thermoelectric materials with improved performance characteristics.

Thermoelectric refrigeration devices have been developed which are competitive with other types of refrigeration devices but cost is much higher.

Thermoelectrics may eventually develop as a topping device and waste heat source from conventional plants such as gas turbines, steam plants, or nuclear power plants.

Fuel Cells

Fuel cells have also had considerable development in recent years. While practical in small horsepowers, with excellent efficiencies, they have been quite expensive and heavy. Their application in naval propulsion plants must await future developments particularly with regard to weight reduction and increased power outputs. The quietness of operation and excellent efficiency are two important characteristics to consider for future applications. Recent developments indicate efficiencies of 62 per cent at a weight of 50 lbs./shaft horsepower. A new unit has just been developed which weighs about 7 lbs./k.w. The byproduct of the fuel cell reaction, pure clean water, is also of particular interest to the Navy. Maximum kw rating to date is 15.

They undoubtedly will be found useful for auxiliary power sources, especially where weight is not important.

Magnetohydrodynamics (MHD)

Magnetohydrodynamics is a new type of power converter for the generation of electricity without

TABLE V

Example of Cost Variations with Maximum Speed, 25K Endurance and Plant Types

Maximum Speed, Knots	40						35					
Endurance @ 25K, Miles	5000			4000			5000			4000		
Plant, lb./SHP	10	15	10	10	15	10	10	15	10	10	15	10
Plant, lb./SHP-hr.	0.7	0.45	0.4	0.7	0.45	0.4	0.7	0.45	0.4	0.7	0.45	0.4
FL Δ, Tons	6250	5000	4150	5200	4600	3800	5700	4400	3900	4800	3950	3500
Change 1st Cost, $[1]	2.2	Base	—1.6	0.3	—0.8	—2.2	—0.7	—2.6	—3.5	—2.1	—3.3	—4.0
PW—20 yr. Fuel Cost, $	10.2	5.3	4.3	8.7	4.9	4.1	9.7	4.9	4.2	8.6	4.8	4.1
PW Total Cost Change, $[2]	12.4	5.3	2.7	9.0	4.1	1.9	9.0	2.3	0.7	6.5	1.5	0.1

[1] All costs are in millions—Base cost $50 Million.
[2] Amount over base cost of $50 Million needed to cover 1st cost +PW of 20 yr. of fuel.

any moving parts. It also offers possible weight reduction in machinery plants. It also offers higher efficiencies in the future.

At present MHD generators are usually devices in which the working fluid is a hot ionized gas.

The physical principle underlying MHD is Faraday's Law, namely, that a potential difference is established in a conductor which cuts magnetic lines of force.

The simplest form of MHD is shown in Figure 19.

From the standpoint of the heat engine cycle, the MHD generator is a gas turbine. The moving gas carries electrons to do work in the magnetic field. Through interaction between the electrons and atoms and positive ions in the gas, the energy required to do this work is removed, which causes a cooling of the gas.

Preheated air and fuel are introduced into the combustion chamber. To enhance ionization, a sodium or potassium compound with low dissociation temperature is simultaneously introduced. The fuel burns, heating the air to a high temperature and causing appreciable ionization. The hot air expands through the duct at high velocity. A magnetic field is maintained in the duct. Since the gas is a conductor cutting lines of force in the magnetic field, a potential difference is established. Electrodes placed in the side of the duct permit current to be passed through an external load.

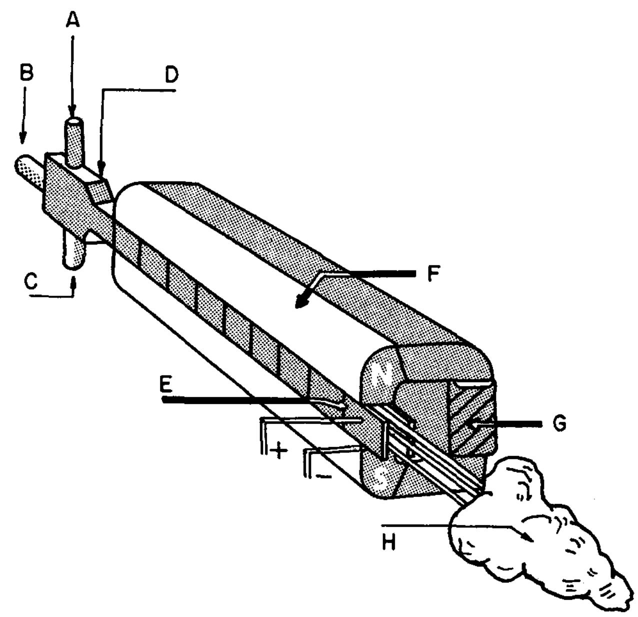


Figure 19. Magnetohydrodynamics Diagram. Direct-Current Generator. With a Conductive Gas. A—Fuel; B—Seed; C—Air; D—Combustion Chamber; E—Collection Plate; F—Magnet Iron; G—Electro Magnet oil; H—Flow of Gas.

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