Marine Vehicle Engineering

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Naval Architecture

Tahitian Princess in Tórshavn, Faroe Islands, August 2009

Naval architecture, also called **naval engineering**, is an engineering discipline dealing with the design, construction and repair of marine vehicles. Naval architecture involves basic and applied research, design, development, design evaluation and calculations during all stages of the life of a marine vehicle. Preliminary design of the vessel, its detailed design, construction, trials, operation and maintenance, launching and dry-docking are the main activities involved. Ship design calculations are also required for ships being modified (by means of conversion, rebuilding, modernization, or repair). Naval architecture also involves formulation of safety regulations and damage control rules and the approval and certification of ship designs to meet statutory and non-statutory requirements.

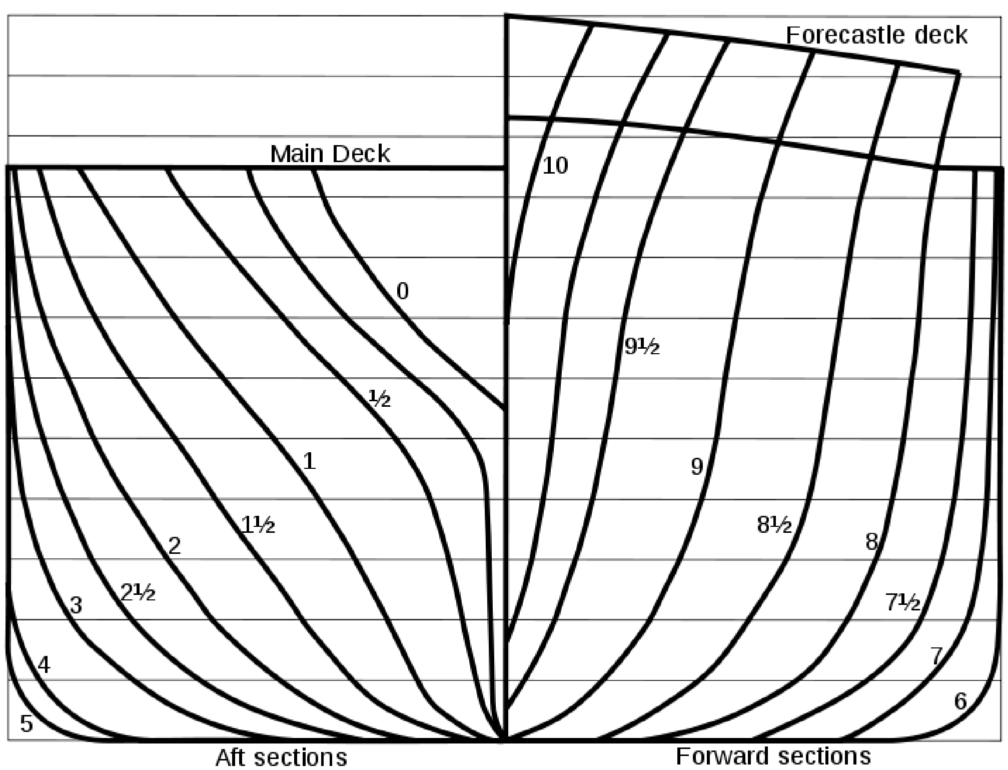
Overview

Due to the complexity associated with operating in a marine environment, naval architecture is a co-operative effort between groups of technically skilled individuals who are specialists in particular fields, often coordinated by a lead naval architect. This inherent complexity also means that the analytical tools available are much less evolved than those for designing aircraft, cars and even spacecraft. This is due primarily to the paucity of data on the environment the marine vehicle is required to work in and the complexity of the interaction of waves and wind on a marine structure.

Elements

The word "vessel" includes every description of watercraft, including non-displacement craft, WIG craft and seaplanes, used or capable of being used as a means of transportation on water. The principal elements of naval architecture are:

Hydrostatics



Body plan of a ship showing the hull form

Concerns the conditions under which the vessel is subjected to while at rest in water and its ability to remain afloat. This involves computing buoyancy, (displacement) and other hydrostatic properties.
Trim - refers to the longitudinal inclination of the vessel.
Stability - Ability of a vessel to restore itself to an upright position after being inclined by wind, sea, or loading conditions.

- **Hydrodynamics**

Concerns the flow of water around the ship's hull, bow, stern and over bodies such as propeller blades or rudder, or through thruster tunnels.
Resistance - resistance towards motion in water primarily caused due to flow of water around the hull. Powering calculation is done based on this.
Propulsion - to move the vessel through water using propellers, thrusters, water jets, sails etc. The energy to drive these is mainly provided by internal combustion engines. Some vessels are electrically powered using nuclear or solar energy.
Ship motions - involves motions of the vessel in seaway and its responses in waves.
Controllability (manoeuvring) - involves controlling and maintaining position and direction of the vessel

Deck of an oil tanker, looking aft.

- **Structures**

Involves selection of material of construction, structural analysis of global and local strength of the vessel, vibration of the structural components and structural responses of the vessel during motions in seaway.

- **Arrangements**

This involves concept design, layout and access, fire protection, allocation of spaces, ergonomics and capacity.

- **Construction**

Construction depends on the material used. When steel or aluminium is used this involves welding of the plates and profiles after rolling, marking, cutting and bending as per the structural design drawings or models, followed by erection and launching. Other joining techniques are used for other materials like fibre reinforced plastic and glass-reinforced plastic.

The craft of naval architecture

The air craft carrier USS Kitty Hawk (CV 63) at Naval Station Pearl Harbor.

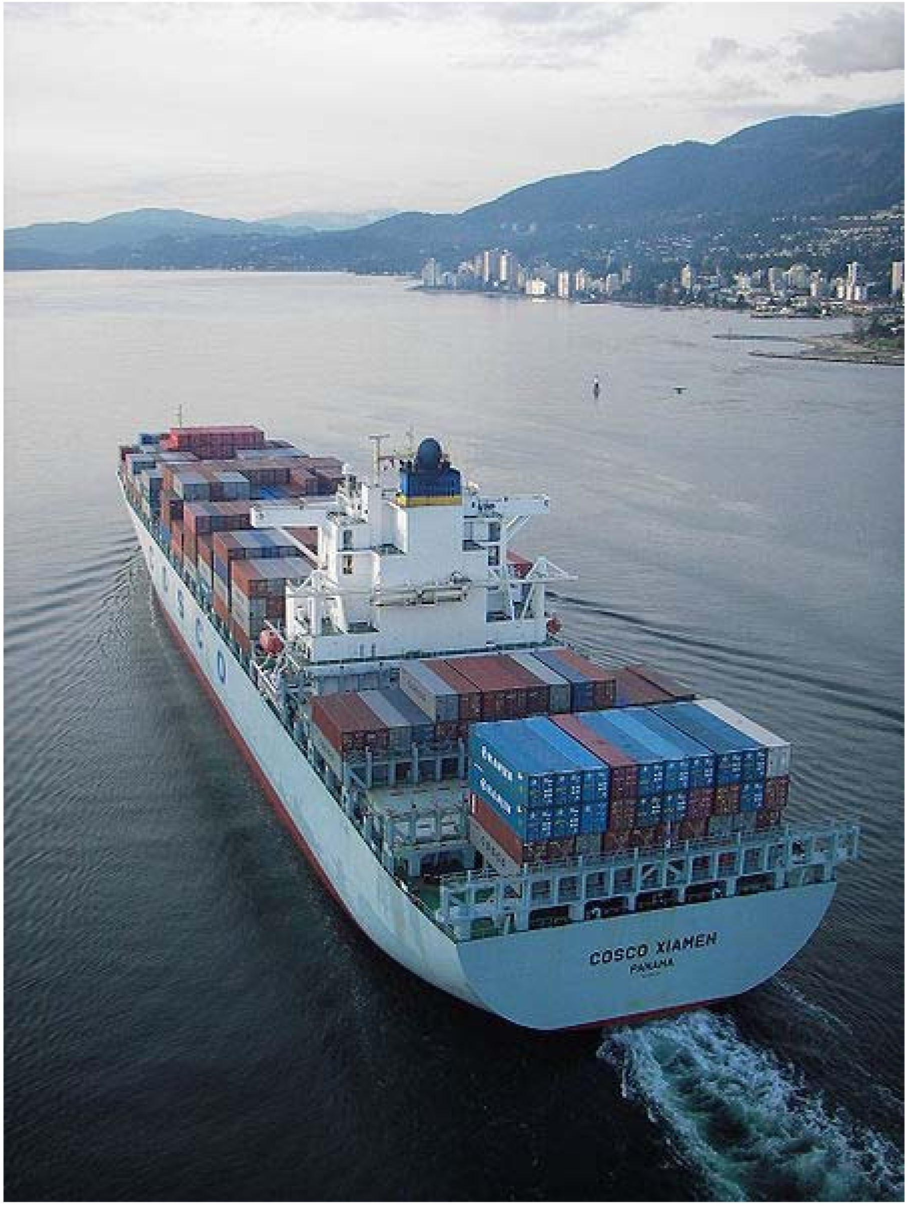
Traditionally, naval architecture has been more craft than science. The suitability of a vessel's shape was judged by looking at a half-model of a vessel or a prototype. Ungainly shapes or abrupt transitions were frowned on as being flawed. This included, rigging, deck arrangements, and even fixtures. Subjective descriptors such as ungainly, full, and fine were used as a substitute for the more precise terms used today. A vessel was, and still is described as having a ‘fair’ shape. The term ‘fair’ is meant to denote not only a smooth transition from fore to aft but also a shape that was ‘right.’ Determining what is ‘right’ in a particular situation in the absence of definitive supporting analysis encompasses the art of naval architecture to this day.

The science of naval architecture

Modern low-cost digital computers and dedicated software, combined with extensive research to correlate full-scale, towing tank and computational data, have enabled naval architects to more accurately predict the performance of a marine vehicle. These tools are used for static stability (intact and damaged), dynamic stability, resistance, powering, hull development, structural analysis, green water modelling, and slamming analysis. Data is regularly shared in international conferences sponsored by RINA, Society of Naval Architects and Marine Engineers (SNAME) and others. Computational Fluid Dynamics is being applied to predict the response of a floating body in a random sea.

The Naval Architect

A naval architect is an engineer who is responsible for the design, construction, and/or repair of ships, boats, other marine vessels, and offshore structures, both commercial and military, including:



Containership Cosco Xiamen exiting Burrard Inlet (Vancouver's harbour)

- Merchant ships - oil tankers, gas tankers, cargo ships, bulk carriers, container ships
- Passenger/vehicle ferries, cruise ships
- Warships - frigates, destroyers, aircraft carriers, amphibious ships
- Submarines and underwater vehicles
- Icebreakers
- Offshore drilling platforms, semi-submersibles
- High speed craft - hovercraft, multi-hull ships, hydrofoil craft
- Workboats - barges, fishing boats, anchor handling tug supply vessels, platform supply vessels, tug boats, pilot vessels, rescue craft
- Yachts, power boats, and other recreational watercraft

Some of these vessels are amongst the largest such as supertanker and most complex such as Aircraft carriers and highly valued movable structures produced by mankind. They are the most efficient method of transporting the world's raw materials and products known to man. Modern engineering on this scale is essentially a team activity conducted by specialists in their respective fields and disciplines. Naval architects integrate these activities. This demanding leadership role requires managerial qualities and the ability to bring together the often-conflicting demands of the various design constraints to produce a product which is fit for the purpose.

In addition to this leadership role, a naval architect also has a specialist function in ensuring that a safe, economic, and seaworthy design is produced. To undertake all these tasks, a naval architect must have an understanding of many branches of engineering and must be in the forefront of high technology areas. He or she must be able to effectively utilize the services provided by scientists, lawyers, accountants, and business people of many kinds.

Naval architects typically work for shipyards, ship owners, design firms and consultancies, equipment manufacturers, Classification societies, regulatory bodies (Admiralty law), navies, and governments.

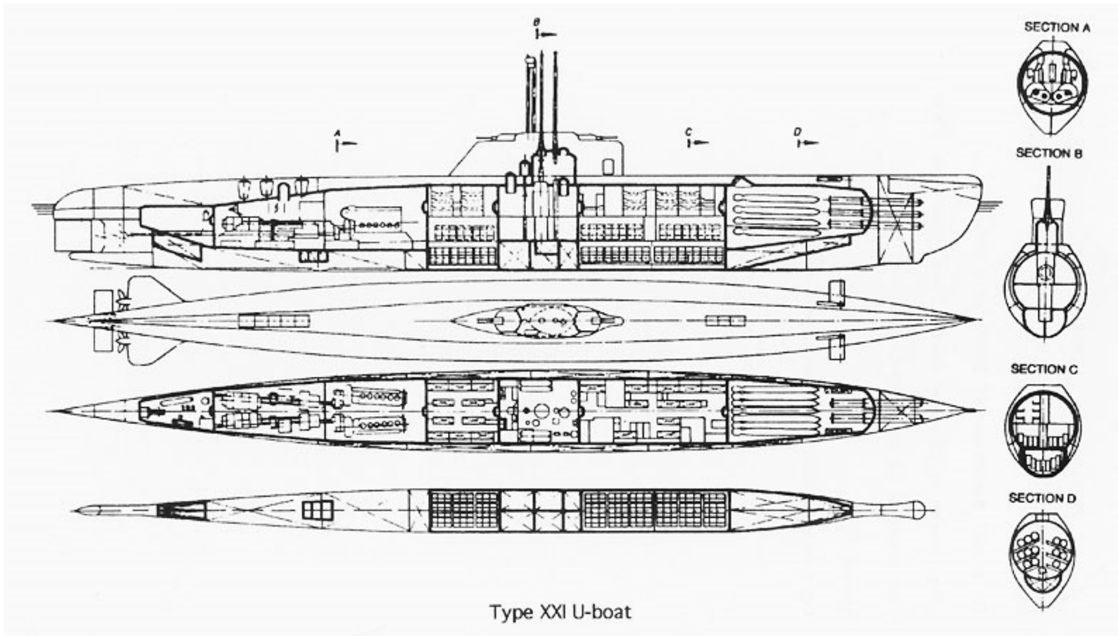
Chapter 2

Submarine Hull

U-995, Type VIIC/41 U-Boat of WWII, showing the typical combination of ship-like non-watertight outer hull with bulky strong hull below

The term **light hull** (**casing** in British usage) is used to describe the outer hull of a submarine, which houses the pressure hull, providing hydrodynamically efficient shape, but not holding pressure difference. The term **pressure hull** is used to describe the inner hull of a submarine, which holds the difference between outside and inside pressure.

Submarine hull



Type XXI U-Boat, late WWII, with pressure hull almost fully enclosed inside the light hull

Modern submarines are usually cigar-shaped. This design, already visible on very early submarines is called a "teardrop hull", and was patterned after the bodies of whales. It significantly reduces the hydrodynamic drag on the sub when submerged, but decreases the sea-keeping capabilities and increases the drag while surfaced.

History

Since the limitations of the propulsion systems of early military submarines forced them to operate most their time on the surface, their hull designs were a compromise. Because of the slow submerged speeds of those subs, usually well below 10 knots (19 km/h), the increased drag for underwater travel was considered acceptable. Only late in World War II, when technology enhancements allowed faster and longer submerged operations and increased surveillance by enemy aircraft forced submarines to stay most of their times below the surface, did hull designs become teardrop shaped again, to reduce drag and noise. On modern military submarines the outer hull is covered with a thick layer of special sound-absorbing rubber, or anechoic plating, to make the submarine more difficult to detect by SONAR.

Types

All small modern submarines and submersibles, as well as the oldest ones, have a single hull. However, for large submarines, the approaches have separated. All Soviet heavy submarines are built with a double hull structure, but American submarines usually are single-hulled. They still have light hull sections in bow and stern, which house main ballast tanks and provide hydrodynamically optimized shape, but the main, usually cylindrical, hull section has only a single plating layer.

Light hull

The double hull of a submarine is different from a ship's double hull. The external hull, which actually forms the shape of submarine, is called the outer hull, casing or light hull. This term is especially appropriate for Russian submarine construction, where the light hull is usually made of steel that is only 2 to 4 millimeters thick, as it has the same pressure on both sides. The light hull can be used to mount equipment, which if attached directly to the pressure hull could cause unnecessary stress. The double hull approach also saves space inside the pressure hull, as the ring stiffeners and longitudinals can be located between the hulls. These measures help minimise the size of the pressure hull, which is much heavier than the light hull. Also, in case the submarine is damaged, the light hull takes some of the damage and does not compromise the boat's integrity, as long as the pressure hull is intact.

Pressure hull

Inside the outer hull there is a strong hull, or pressure hull, which actually withstands the outside pressure and has normal atmospheric pressure inside. The pressure hull is generally constructed of thick high-strength steel with a complex structure and high strength reserve, and is separated with watertight bulkheads into several compartments. The pressure and light hulls aren't separated, and form a three-dimensional structure with increased strength. The interhull space is used for some of the equipment which doesn't require constant pressure to operate. The list significantly differs between submarines, and generally includes different water/air tanks. In case of a single-hull submarine, the light hull and the pressure hull are the same except for the bow and stern.

The task of building a pressure hull is very difficult. No matter how large the submarine is, its hull must be constructed with very high precision. Inevitable minor deviations are resisted by the stiffener rings, but even a one inch (25 mm) deviation from roundness results in over 30 percent decrease of hydrostatic load. The total pressure force of several million tons must be distributed evenly over the hull and be oriented longitudinally, as no material could resist such force by bending. A submarine hull has to use expensive transversal construction, with the stiffeners rings located more frequently than the longitudinals. All hull parts must be welded without defects, and all joints are checked several times with different methods. This contributes to very high cost of modern submarines (for instance, a *Virginia*-class attack submarine costs 2.6 billion dollars, over $200,000 per ton of displacement).

Dive depth

The dive depth cannot be increased easily. Simply making the hull thicker increases the weight and requires reduction of the weight of onboard equipment, ultimately resulting in a bathyscaphe. This is affordable for civilian research submersibles, but not military submarines, so their dive depth was always bound by current technology.

The World War One submarines had their hulls built of carbon steel, and could not submerge below 100 meters. During World War Two, high-strength alloyed steel was introduced, allowing for depths up to 200 meters. High-strength alloyed steel is still the main material for submarines today, with 250-350 meters depth limit, which cannot be exceeded on a military submarine without sacrificing other characteristics. To exceed that limit, a few submarines were built with titanium hulls. Titanium is stronger and lighter than steel, and is non-magnetic. Titanium submarines were especially favored by the Soviets, as they had developed specialized high-strength alloys, built an industry for producing titanium with affordable costs, and have several types of titanium submarines. Titanium alloys allow a major increase in depth, but other systems need to be redesigned as well, so test depth was limited to 1000 meters for the Soviet submarine *Komsomolets*, the deepest-diving military submarine. An Alfa-class submarine may have successfully operated at 1300 meters, though continuous operation at such depths would be an excessive stress for many submarine systems. Despite its benefits, high costs of titanium construction led to abandonment of titanium submarines idea as the Cold War ended.

Other types

There are examples of more than two hulls inside a submarine. The light hull of Typhoon-class submarines houses two main pressure hulls, a smaller third pressure hull constituting most of the sail, two other for torpedoes and steering gear, and between the main hulls 20 MIRV SLBMs along with ballast tanks and some other systems. The Royal Netherlands Navy *Dolfijn*- and *Potvis*-class submarines housed three main pressure hulls.

Chapter 3

Shipbuilding

An expedition's shipwrights building a brigantine, 1541.

Shipbuilding is the construction of ships. It normally takes place in a specialized facility known as a shipyard. **Shipbuilders**, also called **shipwrights**, follow a specialized occupation that traces its roots to before recorded history.

Shipbuilding and ship repairs, both commercial and military, are referred to as the "naval engineer". The construction of boats is a similar activity called boat building.

The dismantling of ships is called ship breaking.

History

Prehistory

Archaeological evidence indicates that humans arrived on New Guinea at least 60,000 years ago, probably by sea from Southeast Asia during an ice age period when the sea was lower and distances between islands shorter. The ancestors of Australian Aborigines and New Guineans went across the Lombok Strait to Sahul by boat over 50,000 years ago.

4th millennium BC

Evidence from Ancient Egypt shows that the early Egyptians knew how to assemble planks of wood into a ship hull as early as 3000 BC. The Archaeological Institute of America reports that some of the oldest ships yet unearthed are known as the Abydos boats. These are a group of 14 discovered ships in Abydos that were constructed of wooden planks which were "sewn" together. Discovered by Egyptologist David O'Connor of New York University, woven straps were found to have been used to lash the planks together, and reeds or grass stuffed between the planks helped to seal the seams. Because the ships are all buried together and near a mortuary belonging to Pharaoh Khasekhemwy, originally they were all thought to have belonged to him, but one of the 14 ships dates to 3000 BC, and the associated pottery jars buried with the vessels also suggest earlier dating. The ship dating to 3000 BC was 75 feet long and is now thought to perhaps have belonged to an earlier pharaoh. According to professor O'Connor, the 5,000-year-old ship may have even belonged to Pharaoh Aha.

3rd millennium BC

Early Egyptians also knew how to assemble planks of wood with treenails to fasten them together, using pitch for caulking the seams. The "Khufu ship", a 43.6-meter vessel sealed into a pit in the Giza pyramid complex at the foot of the Great Pyramid of Giza in the Fourth Dynasty around 2500 BC, is a full-size surviving example which may have fulfilled the symbolic function of a solar barque. Early Egyptians also knew how to fasten the planks of this ship together with mortise and tenon joints.

The oldest known tidal dock in the world was built around 2500 BC during the Harappan civilisation at Lothal near the present day Mangrol harbour on the Gujarat coast in India. Other ports were probably at Balakot and Dwarka. However, it is probable that many small-scale ports, and not massive ports, were used for the Harappan maritime trade. Ships from the harbour at these ancient port cities established trade with Mesopotamia. Shipbuilding and boatmaking may have been prosperous industries in ancient India. Native labourers may have manufactured the flotilla of boats used by Alexander the Great to navigate across the Hydaspes and even the Indus, under Nearchos. The Indians also exported teak for shipbuilding to ancient Persia. Other references to Indian timber used for shipbuilding is noted in the works of Ibn Jubayr.

2nd millennium BC

The ships of Ancient Egypt's Eighteenth Dynasty were typically about 25 meters (80 ft) in length, and had a single mast, sometimes consisting of two poles lashed together at the top making an "A" shape. They mounted a single square sail on a yard, with an additional spar along the bottom of the sail. These ships could also be oar propelled.

The ships of Phoenicia seems to have been of a similar design. The Greeks and probably others introduced the use of multiple banks of oars for additional speed, and the ships were of a light construction for speed and so they could be carried ashore.

1st millennium BC

The naval history of China stems back to the Spring and Autumn Period (722 BC–481 BC) of the ancient Chinese Zhou Dynasty. The Chinese built large rectangular barges known as "castle ships", which were essentially floating fortresses complete with multiple decks with guarded ramparts.

Early 1st millennium AD

The ancient Chinese also built ramming vessels as in the Greco-Roman tradition of the trireme, although oar-steered ships in China lost favor very early on since it was in the 1st century China that the stern-mounted rudder was first developed. This was dually met with the introduction of the Han Dynasty junk ship design in the same century.

Medieval Europe, Sung China, Abbasid Caliphate, Pacific Islanders

Viking longships developed from an alternate tradition of clinker-built hulls fastened with leather thongs. Sometime around the 12th century, northern European ships began to be built with a straight sternpost, enabling the mounting of a rudder, which was much more durable than a steering oar held over the side. Development in the Middle Ages favored "round ships", with a broad beam and heavily curved at both ends. Another important ship type was the galley which was constructed with both sails and oars.

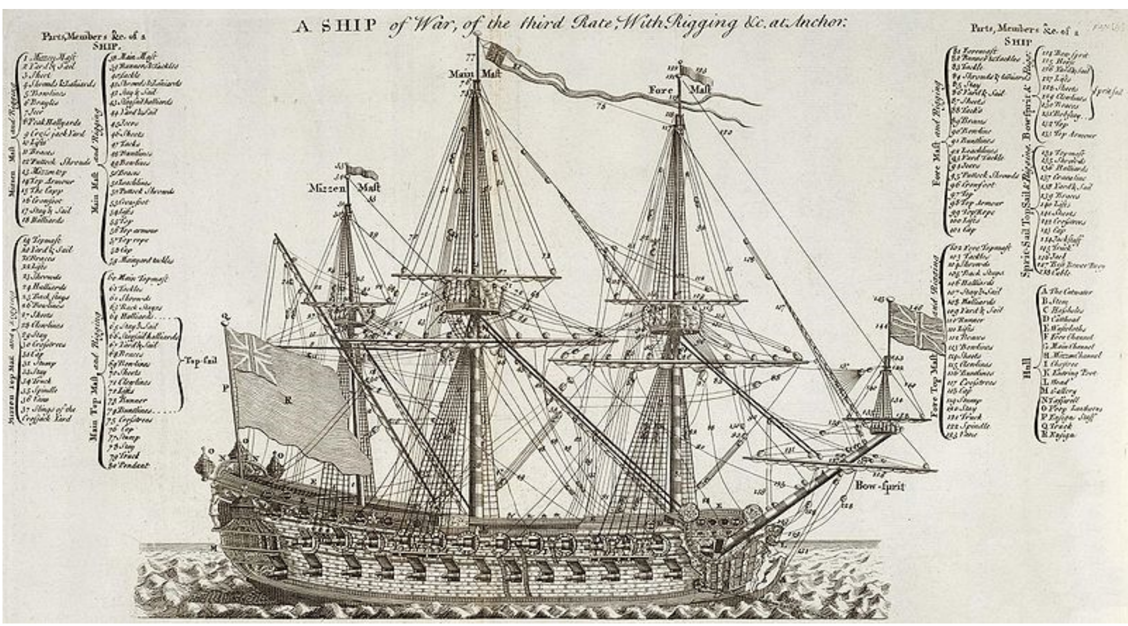
An insight into ship building in the North Sea/Baltic areas of the early medieval period was found at Sutton Hoo, England, where a ship was buried with a chieftain. It was nearly 90 feet long and, at its wides, 14 feet wide. Upward from the keel, the hull was made by overlapping nine planks on either side with rivets fastening the oaken planks together.In its days on the whale-road it could hold upwards of thirty men.

The first extant treatise on shipbuilding was written ca. 1436 by Michael of Rhodes, a man who began his career as an oarsman on a Venetian galley in 1401 and worked his way up into officer positions. He wrote and illustrated a book that contains a treatise on ship building, a treatise on mathematics, much material on astrology, and other materials. His treatise on shipbuilding treats three kinds of galleys and two kinds of round ships.

Outside Medieval Europe, great advances were being made in shipbuilding. The shipbuilding industry in Imperial China reached its height during the Sung Dynasty, Yuan Dynasty, and early Ming Dynasty, building commercial vessels that by the end of this period were to reach a size and sophistication far exceeding that of contemporary Europe. The mainstay of China's merchant and naval fleets was the junk, which had existed for centuries, but it was at this time that the large ships based on this design were built. During the Sung period (960–1279 AD), the establishment of China's first official standing navy in 1132 AD and the enormous increase in maritime trade abroad (from Heian Japan to Fatimid Egypt) allowed the shipbuilding industry in provinces like Fujian to thrive as never before. The largest seaports in the world were in China and included Guangzhou, Quanzhou, and Xiamen.

In the Islamic world, shipbuilding thrived at Basra and Alexandria, the dhow, felucca, baghlah and the sambuk, became symbols of successful maritime trade around the Indian Ocean; from the ports of East Africa to Southeast Asia and the ports of Sindh and Hind (India) during the Abbasid period.

At this time islands spread over vast distances across the Pacific Ocean were being colonised by the Melenesians ans Polynesians, who built giant canoes and progressed to great catamarans.



18th century perspective: 148 ship parts, 18 labeled hull sections (from Cyclopaedia, Volume 2, 1728).

Early Modern

With the development of the carrack, the west moved into a new era of building the first regular ocean going vessels. These were of unprecedented size, complexity and cost. Shipyards became large industrial complexes and the ships built were financed by consortia of investors.

These considerations led to the documentation of design and construction practices in what had previously been a secretive trade run by master shipwrights, and ultimately led to the field of naval architecture, where professional designers and draughtsmen played an increasingly important role, although this is often overlooked. Even so, construction techniques changed only very gradually. The ships of the Napoleonic Wars were superior to those of the Spanish Armada of two centuries earlier but were still built more or less to the same basic plan.

Nevertheless, there were many subtle changes in ship design and construction in this period. Ships incorporated new design features. One example was tumblehome, a narrowing of the hull as it rises further from the waterline. Another example, is that fundamental to the strength of any boat or ship is the type and composition of the fastenings used to secure the timbers. Often these remained hidden beneath paints, protective coatings or sheathing. In the early modern period, in some circumstances, iron gave way to copper and later to hardened copper for use in fastenings below the waterline. This was in response to the advent of copper sheathing as a deterrent to shipworm and to fouling with weed and barnacles.

Industrial Revolution

Other than its widespread use in fastenings, Iron was gradually adopted in ship construction, initially in discrete areas in a wooden hull needing greater strength, (e.g. as deck knees, hanging knees, knee riders and the like). Then, in the form of plates rivetted together and made watertight, it was used to form the hull itself. Initially copying wooden construction traditions with a frame over which the hull was fastened, Isambard Kingdom Brunel's *Great Britain* of 1843 was the first radical new design, being built entirely of wrought iron. Despite her success, and the great savings in cost and space provided by the iron hull, compared to a copper sheathed counterpart, there remained problems with fouling due to the adherence of weeds and barnacles. As a result composite construction remained the dominant approach where fast ships were required, with wooden timbers laid over an iron frame (the *Cutty Sark* is a famous example). Later *Great Britain's* iron hull was sheathed in wood to enable it to carry a copper-based sheathing. Brunel's *Great Eastern* represented the next great development in shipbuilding. Built in association with John Scott Russell, it used longitudinal stringers for strength, inner and outer hulls, and bulkheads to form multiple watertight compartments. Steel also supplanted wrought iron when it became readily available in the latter half of the 19th century, providing great savings when compared with iron in cost and weight. Wood continued to be favored for the decks, and is still the rule as deckcovering for modern cruise ships. Scotts Shipbuilding & Engineering Co. Ltd, Greenock, Scotland is a superb example of a shipbuilding firm that lasted nearly 300 years.

Modern worldwide shipbuilding industry

MS Oasis of the Seas, the world's second-largest passenger ship, was built by STX Europe in Turku, Finland. STX Europe is a subsidiary of South Korean shipbuilder STX Offshore & Shipbuilding.

A TI class supertanker built by Daewoo Shipbuilding & Marine Engineering in Okpo, South Korea.

In the 20th century, shipbuilding (which encompasses the shipyards, the marine equipment manufacturers, and many related service and knowledge providers) grew as an important and strategic industry in a number of countries around the world. This importance stems from:

- The large number of skilled workers required directly by the shipyard, along with supporting industries such as steel mills and engine manufacturers; and
- A nation's need to manufacture and repair its own navy and vessels that support its primary industries

Historically, the industry has suffered from the absence of global rules and a tendency towards (state-supported) over-investment due to the fact that shipyards offer a wide range of technologies, employ a significant number of workers, and generate foreign currency income (as the shipbuilding market is both global and dollar-based).

Shipbuilding is therefore an attractive industry for developing nations. Japan used shipbuilding in the 1950s and 1960s to rebuild its industrial structure; South Korea started to make shipbuilding a strategic industry in the 1970s, and China is now in the process of repeating these models with large state-supported investments in this industry.

As a result, the world shipbuilding market suffers from over-capacities, depressed prices (although the industry experienced a price increase in the period 2003–2005 due to strong demand for new ships which was in excess of actual cost increases), low profit margins, trade distortions and widespread subsidisation. All efforts to address the problems in the OECD have so far failed, with the 1994 international shipbuilding agreement never entering into force and the 2003–2005 round of negotiations being paused in September 2005 after no agreement was possible.

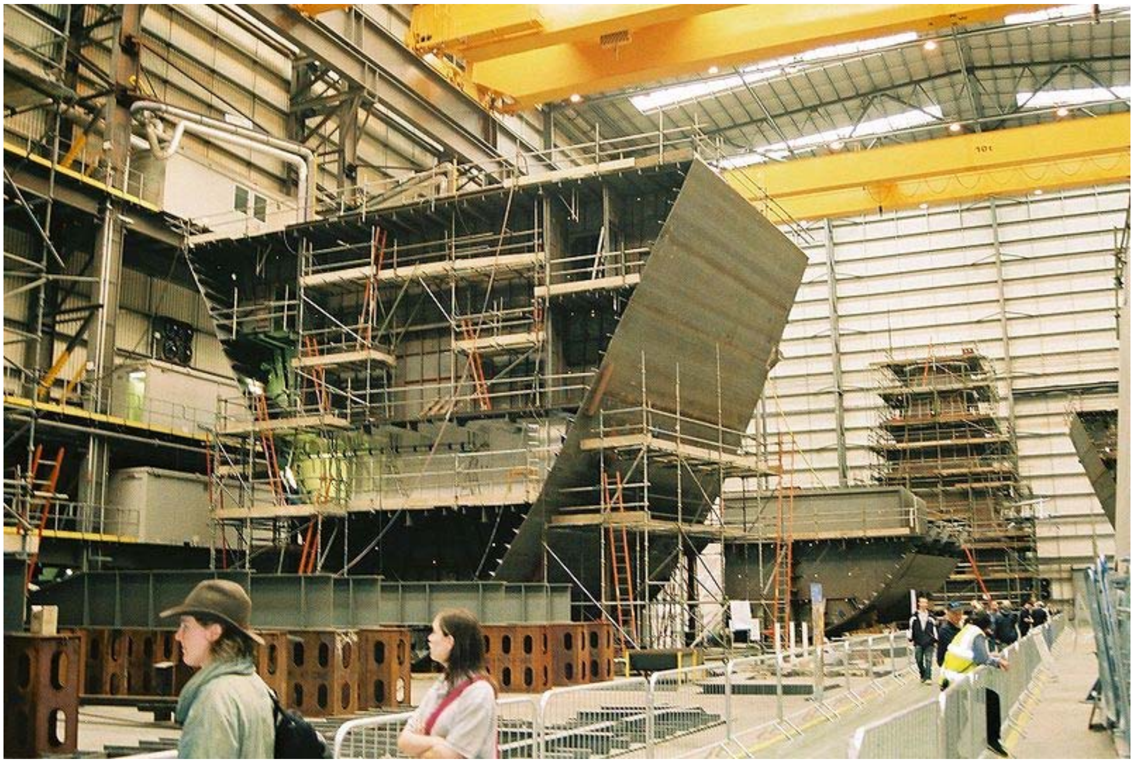
Where state subsidies have been removed and domestic industrial policies do not provide support, in high-cost nations shipbuilding has usually gone into steady, if not rapid, decline. The British shipbuilding industry is one of many examples of this. From a position in the early 1970s where British yards could still build the largest types of sophisticated merchant ships, British shipbuilders today have been reduced to a handful specialising in defence contracts and repair work. In the U.S.A., the Jones Act (which places restrictions on the ships that can be used for moving domestic cargoes) has meant that merchant shipbuilding has continued, but such protection has failed to penalise shipbuilding inefficiencies. The consequence of this is contract prices that are far higher than those of any other nation building oceangoing ships.

World shipbuilding industry in the 21st century

China is the largest shipbuilder in the world in terms of compensated gross tons of ships as of 2010, at a total of 15.9 million tons, followed by South Korea with 11.77 million compensated gross tons. In terms of monetary value of the ships, South Korea is still the largest shipbuilder in the world as of 2010, followed by China, at a total value of $30.61 billion.

Japan lost its leading position in the industry to South Korea in 2004, and its market share has since fallen sharply. The entire European market share has fallen to only a tenth of South Korea's, and the outputs of the United States and the rest of the world have become negligible.

Modern shipbuilding manufacturing techniques



Construction of prefabricated module blocks of HMS *Dauntless* at BAE's Portsmouth Shipyard.

Modern shipbuilding makes considerable use of prefabricated sections. Entire multi-deck segments of the hull or superstructure will be built elsewhere in the yard, transported to the building dock or slipway, then lifted into place. This is known as "block construction". The most modern shipyards pre-install equipment, pipes, electrical cables, and any other components within the blocks, to minimize the effort needed to assemble or install components deep within the hull once it is welded together. This was first introduced by Alstom Chantiers de l'Atlantique when they built the largest Ocean Liner in the world Cunard's RMS Queen Mary 2.

Ship design work, also called naval architecture, may be conducted using a ship model basin. Modern ships, since roughly 1940, have been produced almost exclusively of welded steel. Early welded steel ships used steels with inadequate fracture toughness, which resulted in some ships suffering catastrophic brittle fracture structural cracks. Since roughly 1950, specialized steels such as ABS Steels with good properties for ship construction have been used. Although it is commonly accepted that modern steel has eliminated brittle fracture in ships, some controversy still exists. Brittle fracture of modern vessels continues to occur from time to time as the use of grade A and grade B steel of unknown toughness or fracture appearance transition temperature (FATT) in way of ships' side shells can be less than adequate for all ambient conditions.

Ship repair industry

All ships need maintenance and repairs. A part of these jobs must be carried out under the supervision of the Classification Society. A lot of maintenance it is carried out while at sea or in port by ship's staff. However a large number of repair and maintenance works can only be carried out while the ship is out of commercial operation, in a Shiprepair Yard. Prior to undergoing repairs, tankers must dock at a Deballasting Station for if necessary completing the tank cleaning operations and pumping ashore its slops (dirty cleaning water and hydrocarbon residues) ashore.

Chapter 4

Drydock

U.S. Navy submarine USS *Greeneville* in dry dock following collision with the Ehime Maru.

A **drydock** (also commonly **dry dock**) is a narrow basin or vessel that can be flooded to allow a load to be floated in, then drained to allow that load to come to rest on a dry platform. Drydocks are used for the construction, maintenance, and repair of ships, boats, and other watercraft.

History

Greco-Roman world

According to the ancient Greek author Athenaeus of Naucratis (V 204c-d), the drydock was invented in Ptolemaic Egypt, some time after the death of Ptolemy IV Philopator (reigned 221-204 BC):

But after that (the reign of Ptolemy IV Philopator) a Phoenician devised a new method of launching it (a ship), having dug a trench under it, equal to the ship itself in length, which he dug close to the harbour. And in the trench he built props of solid stone five cubits deep, and across them he laid beams crosswise, running the whole width of the trench, at four cubits' distance from one another; and then making a channel from the sea he filled all the space which he had excavated with water, out of which he easily brought the ship by the aid of whatever men happened to be at hand; then closing the entrance which had been originally made, he drained the water off again by means of engines (organois); and when this had been done the vessel rested securely on the before-mentioned cross-beams.

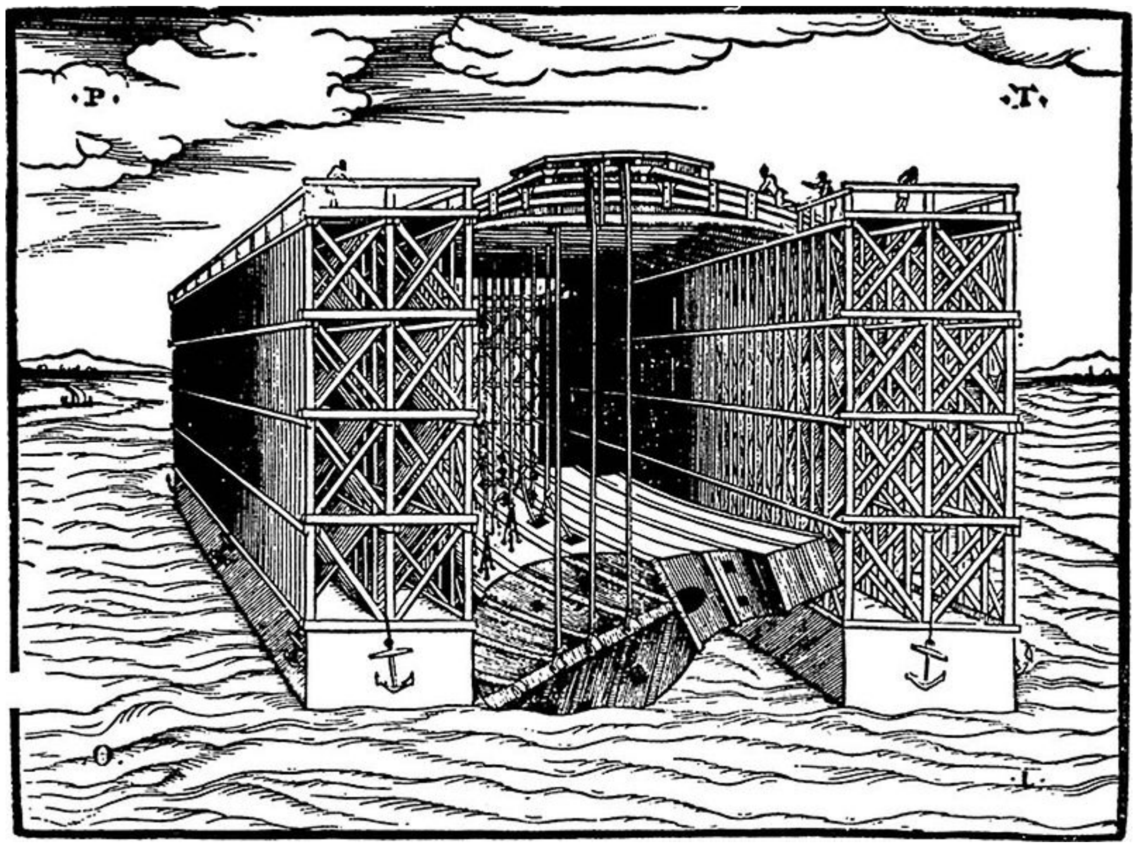
Since Athenaeus recorded the event 400 years later (around 200 AD), there is sufficient reason to believe that drydocks had been known throughout classical antiquity. The Roman shipyard at Narni, Italy, which is still studied may have served as a dry dock.

China

Drydocks appeared in China by 1070 A.D. In 1088, Song Dynasty scientist and statesman Shen Kuo (1031–1095) wrote in his *Dream Pool Essays*:

At the beginning of the dynasty (c. +965) the two Che provinces (now Chekiang and southern Chiangsu) presented (to the throne) two dragon ships each more than 200 ft. in length. The upper works included several decks with palatial cabins and saloons, containing thrones and couches all ready for imperial tours of inspection. After many years, their hulls decayed and needed repairs, but the work was impossible as long as they were afloat. So in the Hsi-Ning reign period (+1068 to +1077) a palace official Huang Huai-Hsin suggested a plan. A large basin was excavated at the north end of the Chin-ming Lake capable of containing the dragon ships, and in it heavy crosswise beams were laid down upon a foundation of pillars. Then (a breach was made) so that the basin quickly filled with water, after which the ships were towed in above the beams. The (breach now being closed) the water was pumped out by wheels so that the ships rested quite in the air. When the repairs were complete, the water was let in again, so that the ships were afloat once more (and could leave the dock). Finally the beams and pillars were taken away, and the whole basin covered over with a great roof so as to form a hangar in which the ships could be protected from the elements and avoid the damage caused by undue exposure. (Wade-Giles spelling.)

Renaissance Europe



Floating Dock. Woodcut from Venice (1560).

The first European and oldest surviving drydock was commissioned by Henry VII of England at HMNB Portsmouth in 1495. This drydock currently holds the world's oldest commissioned warship, HMS Victory.

Possibly the earliest description of a floating dock comes from a small Italian book printed in Venice in 1560, called *Descrittione dell'artifitiosa machina*. In the booklet, an unknown author asks for the privilege of using a new method for the salvaging of a grounded ship and then proceeds to describe and illustrate his approach. The included woodcut shows a ship flanked by two large floating trestles, forming a roof above the vessel. The ship is pulled in an upright position by a number of ropes attached to the superstructure.

Modern times

The Alfredo da Silva Dry Dock, of the Lisnave Dockyards in Almada, Portugal, was the largest in the world until 2000, when it was closed after the moving of Lisnave operations to Setúbal.

Currently, Harland and Wolff Heavy Industries in Belfast, Northern Ireland, is the largest in the world. The massive cranes are named after the Biblical figures Samson and Goliath. Goliath stands 96m tall, while Samson is taller at 106m.

Northrop Grumman Newport News Shipbuilding's Dry Dock 12 is the largest drydock in the USA. The Saint-Nazaire's Chantiers de l'Atlantique owns one of the biggest in the world: 1,200 by 60 metres (3,900 × 200 ft). The largest graving dock of the Mediterranean as of 2009 is at the Hellenic Shipyards S.A. (HSY S.A., Athens, Greece). The by far largest roofed dry dock is at the German Meyer Werft Shipyard in Papenburg, Germany, it is 504m long, 125m wide and stands 75m tall.

Types

The brig *Stockholm* in one of the historical drydocks on the island Beckholmen in central Stockholm.

Graving

The classic form of drydock, properly known as graving dock, is a narrow basin, usually made of earthen berms and concrete, closed by gates or by a caisson, into which a vessel may be floated and the water pumped out, leaving the vessel supported on blocks. The keel blocks as well as the bilge block are placed on the floor of the dock in accordance with the "docking plan" of the ship. More routine use of drydocks is for the cleaning (removal of barnacles and rust) and re-painting of ship's hulls.

Some fine-tuning of the ship's position can be done by divers while there is still some water left to manoeuvre it about. It is extremely important that supporting blocks conform to the structural members so that the ship is not damaged when its weight is supported by the blocks. Some anti-submarine warfare warships have protruding sonar domes, requiring that the hull of the ship be supported several metres from the bottom of the drydock.

Once the remainder of the water is pumped out, the ship can be freely inspected or serviced. When work on the ship is finished, water is allowed to re-enter the dry dock and the ship is carefully refloated.

Modern graving docks are box-shaped, to accommodate the newer, boxier ship designs, whereas old drydocks are often shaped like the ships that are planned to be docked there. This shaping was advantageous because such a dock was easier to build, it was easier to side-support the ships, and less water had to be pumped away.

U.S. Navy ballistic missile submarine USS *Michigan* inside a flooded drydock.

Drydocks used for building Navy vessels may occasionally be built with a roof. This is done to prevent spy satellites from taking pictures of the drydock and any ships or submarines that may be in it. During World War II, fortified drydocks were used by the Germans to protect their submarines from Allied air raids; however, their effectiveness in that role diminished towards the end of the war as bombs became available that could penetrate them. Today, covered drydocks are usually used only when servicing or repairing a fleet ballistic missile submarine. Another advantage of covered drydocks is that work can take place independently of the weather; this can save time in bad weather.

Floating

Floating docks, Gdynia, Poland

A floating drydock is a type of pontoon for dry docking ships, possessing floodable buoyancy chambers and a "U" shaped cross-section. The walls are used to give the drydock stability when the floor or deck is below the surface of the water. When valves are opened, the chambers fill with water, causing the drydock to float lower in the water. The deck becomes submerged and this allows a ship to be moved into position inside. When the water is pumped out of the chambers, the drydock rises and the ship is lifted out of the water on the rising deck, allowing work to proceed on the ship's hull.

A typical floating drydock involves multiple rectangular sections. These sections can be combined to handle ships of various lengths, and the sections themselves can come in different dimensions. Each section contains its own equipment for emptying the ballast and to provide the required services, and the addition of a bow section can facilitate the towing of the drydock once assembled. For smaller boats, one-piece floating drydocks can be constructed, potentially coming with their own bow and steering mechanism.

Shipyards operate floating drydocks as one method for hauling or docking vessels. The advantage of floating drydocks is they can be moved to wherever they are needed and can also be sold second-hand. During World War II, the U.S. Navy used such (floating) drydocks extensively to provide maintenance in remote locations. One of these, the 850-foot AFDB-3, an **Advance Base Sectional Dock**, saw action in Guam, was mothballed near Norfolk, Virginia, and was eventually towed to Portland, Maine, to become part of Bath Iron Works' repair facilities.

The "Hughes Mining Barge", or HMB-1, is a covered, floating drydock that is also submersible to support the secret transfer of a mechanical lifting device underneath the *Glomar Explorer* ship, as well as the development of the *Sea Shadow* stealth ship.

The towboat, DOLPHIN I, in a floating drydock on the Mississippi River in Algiers, New Orleans, Louisiana.

Blohm + Voss Dock 10, at the Port of Hamburg.

Floating drydock located in Sevastopol.

A floating drydock (or boat lift) in a private marina, used to keep small boats out of the water while not in use.

Alternative drydock systems

Apart from graving docks and floating drydocks, ships can also be drydocked and launched by:

- Marine railway — For repair of larger ships up to about 3000 tons ship weight
- Mobile boatlift (also called Travelift, for vessels up to 1000 metric tons
- Shiplift — For repair as well as for newbuilding. From 800 to 25000 ton shipweight
- Slipway, patent slip — For repair of smaller boats and the newbuilding launch of larger vessels

Uses other than for ships

Some drydocks are used during the construction of bridges, dams, and other large objects. For example, the drydock on the artificial island of Neeltje-Jans was used for the construction of the Oosterscheldekering, a large dam in the Netherlands that consists of 65 concrete pillars weighing 18,000 tonnes each. The pillars were constructed in a drydock and towed to their final place on the seabed.

They may also be used for the prefabrication of the elements of an immersed tube tunnel, before they are floated into position.

Chapter 5

Shipyard

Small shipyard in Klaksvík (Faroe Islands), repairing fishing vessels

Fish ladder and shipyard in Grave, Netherlands

Gdynia Shipyard

Kawasaki Shipbuilding Kobe Shipyard & Machinery Works, Kobe, Japan

Zürichsee-Schifffahrtsgesellschaft in Zürich-Wollishofen, Switzerland

Shipyards and **dockyards** are places which repair and build ships. These can be yachts, military vessels, cruise liners or other cargo or passenger ships. Dockyards are sometimes more associated with maintenance and basing activities than shipyards, which are sometimes associated more with initial construction. The terms are routinely used interchangeably, in part because the evolution of dockyards and shipyards has often caused them to change or merge roles.

Countries with large ship building industries include South Korea, Australia, Japan, China, Germany, Turkey, Poland and Croatia. The shipbuilding industry tends to be more fragmented in Europe than in Asia. In European countries there are more smaller companies, compared to the fewer, larger companies in the ship building countries of Asia.

Most ship builders in the United States are privately owned, the largest being Northrop Grumman, a multi-billion dollar defense contractor. The publicly owned shipyards in the US are Naval facilities providing basing, support and repair.

Shipyards are constructed by the sea or by tidal rivers to allow easy access for their ships. In the United Kingdom, for example, shipyards were established on the River Thames (King Henry VIII founded yards at Woolwich and Deptford in 1512 and 1513 respectively), River Mersey, River Tees, River Tyne, River Wear and River Clyde - the latter growing to be the World's pre-eminent shipbuilding centre.

Sir Alfred Yarrow established his yard by the Thames in London's Docklands in the late 19th century before moving it northwards to the banks of the Clyde at Scotstoun (1906–08). Other famous UK shipyards include the Harland and Wolff yard in Belfast, Northern Ireland, where the *Titanic* was built, and the naval dockyard at Chatham, England on the Medway in north Kent.

The site of a large shipyard will contain many specialised cranes, dry docks, slipways, dust-free warehouses, painting facilities and extremely large areas for fabrication of the ships.

After a ship's useful life is over, it makes its final voyage to a shipbreaking yard, often on a beach in South Asia. Historically shipbreaking was carried on in drydock in developed countries, but high wages and environmental regulations have resulted in movement of the industry to developing regions.

History

The world's earliest known dockyards were built in the Harappan port city of Lothal circa 2400 BC in Gujarat, India. Lothal's dockyards connected to an ancient course of the Sabarmati river on the trade route between Harappan cities in Sindh and the peninsula of Saurashtra when the surrounding Kutch desert was a part of the Arabian Sea.

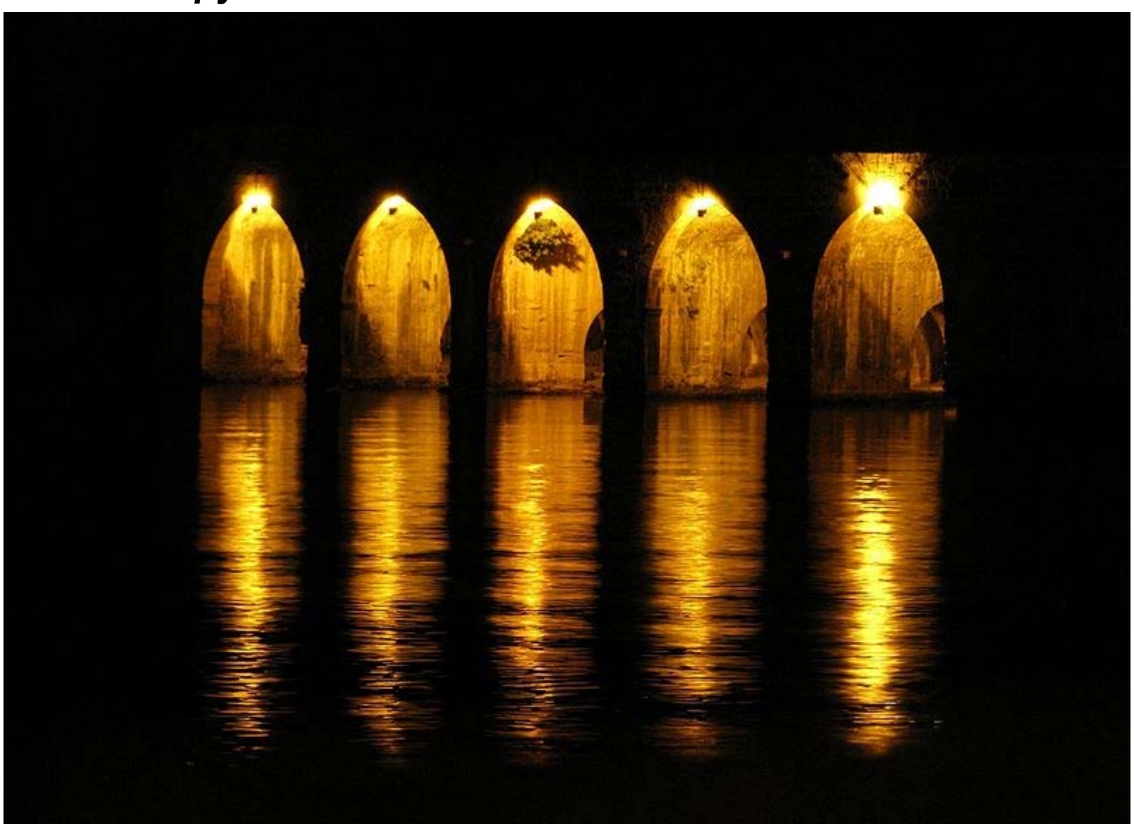
Lothal engineers accorded high priority to the creation of a dockyard and a warehouse to serve the purposes of naval trade. The dock was built on the eastern flank of the town, and is regarded by archaeologists as an engineering feat of the highest order. It was located away from the main current of the river to avoid silting, but provided access to ships in high tide as well.

The name of the ancient Greek city of Naupactus means "shipyeard" (combination of the Greek words ναύς *naus* ship, boat and πήγνυμι *pêgnumi*, *pegnymi* builder, fixer). Naupactus' reputation in this field extends to the time of legend, where it is depicted as the place where the Heraclidae built a fleet to invade the Peloponnesus.

In the Spanish city of Barcelona, the Drassanes shipyards were active from at least the mid-13th century until the 18th century, although it as times served as barracks for troops as well as an arsenal. During its time of operation it was continuously changed, rebuilt and modified, but two original towers and part of the original eight construction naves remain today. It is currently a maritime museum.

Ships were the first items to be manufactured in a factory, several hundred years before the Industrial Revolution, in the Venice Arsenal, Venice, Italy. The Arsenal apparently mass produced nearly one ship every day using pre-manufactured parts, and assembly lines and, at its height, employed 16,000 people.

Historic shipyards



Ancient Shipyard of the Seljuks in Alanya, Turkey. The shipyard, consisting of five docks and constructed in 1226 by the Sultan Alaaddin Keykubat, is 56 metres long and 44 metres deep and is the only remaining shipyard from the Seljuks.

- Lothal in Gujarat, India circa 2400 BC to 1900 BC
- Naupactus
- Roman shipyard of Stifone (Narni)
- Blackwall Yard 1614 to 1987

- Shipyard Kraljevica established on 28 April 1729 and still operating yard
- Scotts Shipbuilding & Engineering Co Ltd, Greenock, Scotland, 1711–1984
- Thames Ironworks and Shipbuilding Co. Ltd 1837 to 1912
- John Brown & Company 1851 to 1972
- Gdańsk Shipyard the birthplace of Solidarity Movement - (still a working yard)
- Swan Hunter - (closed in April 2006 and sold to Bharati Shipyards, India's second largest private sector shipbuilder)
- Harland and Wolff - (still a working yard)
- Cammell Laird - (still a working repair yard)
- Blohm + Voss, where the Bismarck was constructed (still a major yard)
- Royal Naval Dockyards in the UK (including Woolwich, Deptford, Chatham, Portsmouth and Devonport), Gibraltar, Bombay, Bermuda, Hong Kong and elsewhere worldwide
- Bethlehem Steel Corporation had 15 shipyards during World War II
    - Staten Island Shipyard 1895
- Charlestown Navy Yard, later Boston Navy Yard, Boston, Massachusetts 1800 to 1974
- Ulstein Verft, Norway, established in 1917 (still a working yard under the Ulstein Group)
- Navy Island, Ontario, Canada - French in the 18th century, then British 1763 to War of 1812
- Mare Island Naval Shipyard, Mare Island, California, 1854 to 1996
- New York Naval Shipyard (NYNSY), also known as the Brooklyn Navy Yard, the New York Navy Yard, and United States Navy Yard, New York 1801 to 1966
- Philadelphia Naval Shipyard 1799 to 1995, at two locations
- San Francisco Naval Shipyard, later Hunters Point Naval Shipyard, then Treasure Island Naval Station Hunters Point Annex, 1941 to 1994
- Potrero Point, San Francisco, California, 1880s - still a working yard
- Long Beach Naval Shipyard, 1943 to 1997
- Golden Horn Shipyard, (Haliç Tersaneleri), Turkey, established in 1455 - still a working yard
- Portsmouth Naval Shipyard, located on Maine-New Hampshire border; Operational: 1800 to present, making it the oldest continuously-operating shipyard of the US Navy.
- Chantiers de l'Atlantique(Aker Yard France) - established in 1861 (still a working yard)
- 3. Maj - One of the largest shipyard in Mediterranean, established in 1892 in Rijeka (still a working yard)

Prominent dockyards and shipyards

- **North America**
    - Northrop Grumman Newport News, (formerly Newport News Shipbuilding & Drydock Company) is the largest private ship builder in the US and the one best known for its unique capacity to build the *Nimitz*-class aircraft carriers.

        - Ingalls Shipbuilding, part of Northrop Grumman Ship Systems, located in Pascagoula, Mississippi repaired the USS *Cole* and builds offshore drilling rigs, cruise ships and naval vessels.
        - National Steel and Shipbuilding Company (NASSCO) shipyard in San Diego, California, part of General Dynamics; is the primary shipbuilding location on the west coast of the United States.
    - Norfolk Naval Shipyard in Portsmouth, Virginia, is one of the largest shipyards in the world; specializing in repairing, overhauling and modernizing naval ships and submarines. It's the oldest and largest industrial facility that belongs to the United States Navy
    - Electric Boat Division (EBDiv) of General Dynamics in Groton, Connecticut with an accessory facility in Quonset Point, Rhode Island, builder of many Naval submarines over the past 100 years, with some types built only here.
    - Bath Iron Works (BIW), subsidiary of General Dynamics, is a major American shipyard located on the Kennebec River in Bath, Maine.
    - Puget Sound Naval Shipyard in Bremerton, Washington, is also owned by the U.S. Navy. It services ships and submarines from the West Coast.
    - The Portland, Oregon shipyard, operated by Cascade General Ship Repair is the largest such facility on the United States West Coast.
    - The Louisiana Port is along the Mississippi river. It involves the Bollinger company in St. Rose.

Aerial view of Norfolk Naval Shipyard

- **South America**

(Venezuela) in the city of Puerto Cabello it can be found one of the biggest shipyards of Venezuela, where different diversity of ships are constructed. Also, there are services of reparation and maintenance for ships of different flags.

Brasfels Shipyard - Rio de Janeiro

-
    - SCRA (Construction Refurbishment and Armament Service) with two dry docks, ready for naval and general vessel works.
        - Punta de Lobos (Wolves Point) in west Montevideo, established in 1874.
        - Punta Maua (Maua Point) in east Montevideo, established in 1872.
    - Tsakos Industrias Navales S.A.

- **Europe**

Abdela & Mitchell Shipyards, Brimscombe, Gloucestershire, UK: 'Contractors To The Admiralty, War Office, India Office And Allied Governments' 1900-1925. According to research in 2009 the legendary riverboat which starred in the 1951 John Huston movie *The African Queen* was built at the Abdela & Mitchell Brimscombe (Stroud) works around 1912. The yards were owned by Marine architect Isaac J. Abdela. Larger boats built at the Abdela Brimscombe yards were two-deck, galvanised steel, light draught passenger and cargo steamers for South America, including the Islandia of 1903, Humaytha, San Juan and Santa Rosa. The Abdela river-boats were highly-regarded for their elegance and beauty.

Girvan shipyard, Ayrshire, Scotland

-
    - BAE Systems Surface Ships operates three shipbuilding yards in the United Kingdom; Portsmouth, England and Scotstoun and Govan on the River Clyde in Glasgow, Scotland. Major projects include the Type 45 destroyer and the *Queen Elizabeth* class aircraft carriers.
    - BAE Systems Submarine Solutions operates a major shipyard at Barrow-in-Furness in Cumbria, England. It is one of the few yards in the world capable of building nuclear submarines such as the Royal Navy's *Vanguard* class. This division has built surface ships in the past and will manufacture blocks of the *Queen Elizabeth* class.
    - Devonport Dockyard , located in the city of Plymouth, England in the county of Devon is the largest naval base in Western Europe. It has 15 dry docks, four miles (6 km) of waterfront, 25 tidal berths, five basins and covers 650 acres (2.6 km²). It is the main refitting base for Royal Navy nuclear submarines and also handles work on frigates. It is the base for seven of the Trafalgar class nuclear powered hunter-killer submarines and many frigates, exploiting its convenient access to the Atlantic Ocean. It supports the Vanguard class Trident missile nuclear ballistic missile submarines in a custom-built refitting dock. It houses the

HMS *Courageous*, a nuclear powered submarine used in the Falklands War and open to the general public . Facilities in the local area also include a major naval training establishment and a base for the Royal Marines.
    - SOBRENA located in the city of Brest, FRANCE, on the western entrance to the English Channel operates 3 drydocks (up to 420 x 80 m)

- **East Asia**
    - Hyundai Heavy Industries Ulsan Shipyard, in South Korea, is currently the largest in the world and has the capability to build a variety of vessels including Commercial Cargo, Offshore and Naval vessels.
    - Yantai Raffles Shipyard is the largest offshore builder in China located in Yantai. Its predominant feature is the 20,000 ton crane Taisun, holder of the Heavy Lift World Record. Yantai Raffles' portfolio includes offshore platforms, pipe lay and other specialized vessels.

- **South Asia**
    - Northstar Shipyard is one of the leading shipyard in India for small & Mid size ships, barges, oil tankers, tugs, etc.
    - [**Sulkha Shipyard**, is 500 year Old Ship builder who are specialized in build cargo vessels, Pleasure Yachts, Supply boats, Tugs, Patrol boats and Fishing trawlers, ferry boats, *in steel, Fiberglass and Wood*]

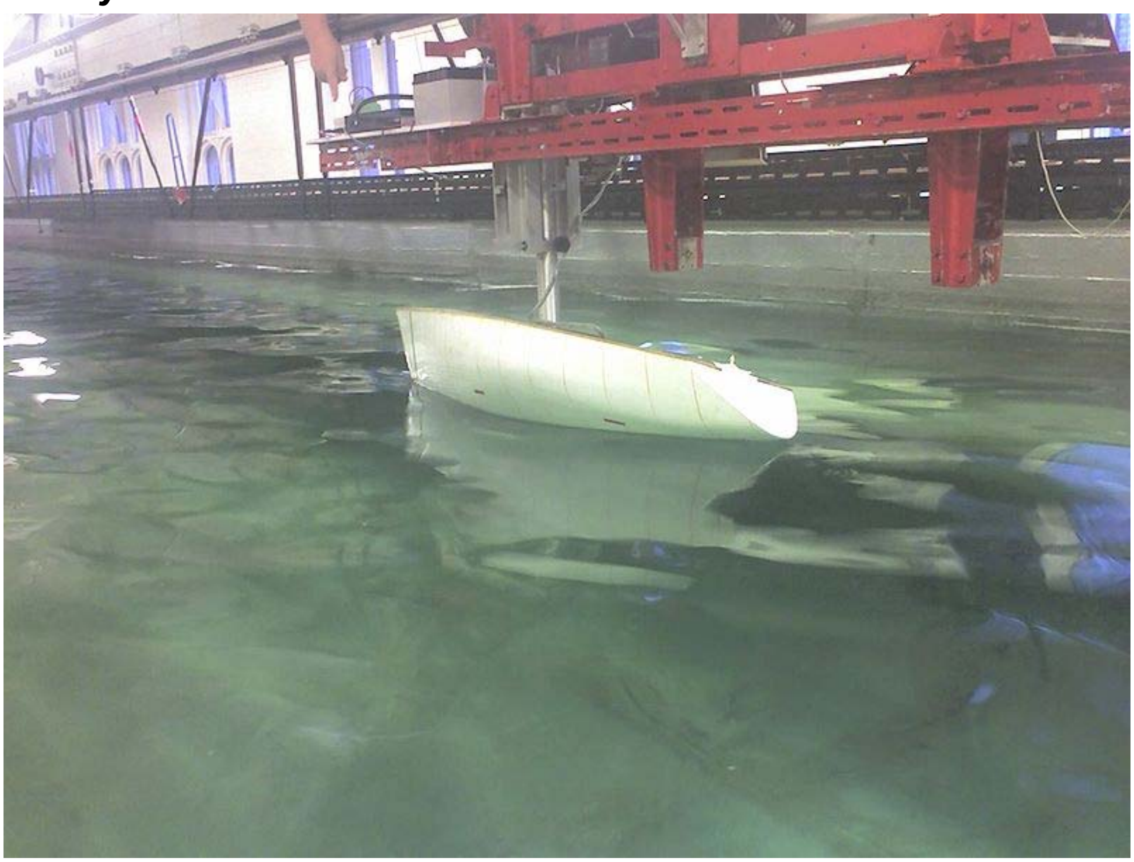
    - Cochin Shipyard is the largest shipyard in India. Currently an aircraft carrier, the Indigenous aircraft carrier (IAC) is under construction at Cochin shipyard.
    - Garden Reach Shipbuilders and Engineers is located in India. It is owned by the Government of India and is constructing the Shardul class Large landing ship tank for the Indian Navy.
    - Karachi Shipyard is the only shipbuilding company in Pakistan located in Karachi. It has built numerous cargo ships, tugboats and support vessels, Naval vessels, submarines and Frigates.
    - Mazagaon Dockyard, operated by state-owned Mazagaon Dock Limited, is one of India's largest shipyards. It constructs a variety of ships both for the defence and civilian sector. The dockyard is known for constructing Britain's HMS *Trincomalee*. Currently the shipyard is building three Shivalik class frigates and three Kolkata class destroyers for the Indian Navy.
    - The beach at Alang in the Indian state of Gujarat is the site of a large complex of shipbreaking yards which processes 50% of the ships that are salvaged.

Chapter 6

Ship Stability

Ship stability is an area of Naval Architecture and ship design that deals with how a ship behaves at sea, both in still water and in waves. Considerations are made as to the center of gravity and center of buoyancy of vessels and how they interact.

History



A model yacht being tested in the towing tank of Newcastle University

Ship stability is a complicated aspect of naval architecture which has existed in some form or another for hundreds of years. Historically, ship stability calculations for ships relied on rule-of-thumb calculations, often tied to a specific system of measurement. Some of these very old equations continue to be used in naval architecture books today, however the advent of the ship model basin allows much more complex analysis.

Master shipbuilders of the past used a system of adaptive and variant design. Ships were often copied from one generation to the next with only minor changes being made, and by doing this, serious problems were not often encountered. Ships today still use the process of adaptation and variation that has been used for hundreds of years, however computational fluid dynamics, ship model testing and a better overall understanding of fluid and ship motions has allowed much more in-depth analysis.

Transverse and longitudinal waterproof bulkheads were introduced in ironclad designs between 1860 and the 1880s, anti-collision bulkheads having been made compulsory in British steam merchant ships prior to 1860. Prior to this, a hull breach in any part of a vessel could flood the entire length of the ship. Transverse bulkheads, while expensive, increase the likelihood of ship survival in the event of damage to the hull, by limiting flooding to breached compartments separated by bulkheads from undamaged ones. Longitudinal bulkheads have a similar purpose, but damaged stability effects must be taken into account to eliminate excessive heeling. Today, most ships have means to equalize the water in sections port and starboard (cross flooding), which helps to limit the stresses experienced by the structure, and also alter the heel and/or trim of the ship.

Add-on stability systems

These systems are designed to reduce the effects of waves or wind gusts. They do not increase the stability of the vessel in a calm sea. The IMO International Convention on Load Lines does not mention active stability systems as a method of ensuring stability. The hull must be stable without active systems.

Passive systems

Bilge keel

A bilge keel

A bilge keel is a long fin of metal, often in a "V" shape, welded along the length of the ship at the turn of the bilge. Bilge keels are employed in pairs (one for each side of the ship). A ship may have more than one bilge keel per side, but this is rare. Bilge keels increase the hydrodynamic resistance when a vessel rolls, thus limiting the amount of roll a vessel has to endure.

Outriggers

Outriggers may be employed on certain vessels to reduce rolling. Rolling is reduced either by the force required to submerge buoyant floats or by hydrodynamic foils. In some cases these outriggers may be of sufficient size to classify the vessel as a trimaran, however on other vessels they may simply be referred to as stabilizers.

Antiroll tanks

Antiroll tanks are tanks within the vessel fitted with baffles intended to slow the rate of water transfer from the port side of the tank to the starboard side. The tank is designed such that a larger amount of water is trapped on the higher side of the vessel. This is intended to have an effect completely opposite to that of the free surface effect.

Paravanes

Paravanes may be employed by slow moving vessels (such as fishing vessels) to increase stability.

Active stability systems

Many vessels are fitted with active stability systems. Active stability systems are defined by the need to input energy to the system in the form of a pump, hydraulic piston, or electric actuator. These systems include stabilizer fins attached to the side of the vessel, or tanks in which fluid is pumped around to counteract the motion of the vessel.

Stabilizer fins

Active fin stabilizers are normally used to reduce the roll that a vessel experiences while under way. The fins extend beyond the hull of the vessel below the waterline, and alter their angle of attack depending upon heel angle of the vessel. They operate in a very similar way to airplane wings. Cruise ships frequently use this type of stabilizer system because the high cost of incorporating it into the vessel can be justified. Pleasure yachts down to 15M LOA will increasingly choose active fin stabilization as the cost/benefit ratios are perceived to improve. This system may have any of the following disadvantages:

- Because the fins may be retractable, they may take up valuable space in the engine compartment.
- When fins are not retractable, they constitute fixed appendages to the hull, possibly extending the beam or draft envelope; at a minimum, requiring attention for additional hull clearances.

- Altering the angle of attack requires the vessel to use fuel in supplying the power required to do so. However the power expended for fin motion may be offset by power recovered through more stable tracking on course. Power saved by following a more accurate course may be difficult to quantify.
- The fin and actuator mechanism is expensive to manufacture and fit into the vessel, especially when compared to a bilge keel.

While the typical "active fin" stabilizer will effectively counteract roll for ships under way, some active fin systems have been shown capable of reducing roll motion when vessels are not under way. Referred to as Stabilization while not under way or Stabilization at Rest, these systems work by moving fins of special design, with the requisite acceleration and impulse timing to create effective roll cancellation energy.

Gyroscopic Internal Stabilizers

The first use of gyro's to control a ship roll was in the late 1920s and early 1930s for warships and then passenger liners. The most ambitious use of large gyros to control a ship's roll was the Italian passenger liner, the SS Conte di Savoia, in which three large gyros constructed by Sperry Gyroscope Company, were mounted in the forward part of the ship. While it proved successful in drastically reducing roll in the west bound trips, they system had to be disconnected on the east bound leg for safety reasons.

Gyro stabilizers consist of a spinning flywheel and gyroscopic precession that outputs boat-righting torque on the hull structure.

The Angular momentum of the gyro’s flywheel is a measure of the extent to which the flywheel will continue to rotate about its axis unless acted upon by an external torque. The higher the angular momentum the more the ability of the flywheel to react to external torques (in this case more ability to cancel boat roll).

A gyroscope has three axes: a spin axis, an input axis, and an output axis. The spin axis is the axis about which the flywheel is spinning and is vertical for a boat gyro. The input axis is the axis about which input torques are applied. For a boat, the principal input axis is the longitudinal axis of the boat since that is the axis around which the boat rolls. The principal output axis is the transverse (athwartship) axis about which the gyro rotates or precesses in reaction to an input.

When the boat rolls, the rotation acts as an input to the gyro, causing the gyro to generate rotation around its output axis such that the spin axis rotates to align itself with the input axis. This output rotation is called precession and, in the boat case, the gyro will rotate fore and aft about the output or gimbal axis.

Angular Momentum is the measure of effectiveness for a gyro stabilizer, analogous to horsepower (HP) ratings on a diesel engine or kilowatts (kW) on a generator. In specifications for gyro stabilizers, the total Angular Momentum (moment of inertia multiplied by spin speed) is the key quantity. In modern designs, the output axis torque can be used to control the angle of the stabilizer fins to counteract the roll of the boat so that only a small gyroscope is needed. The idea for gyro controlling a ships fin stabilizers was first purposed in 1932 by a scientist, Dr Alexanderson, who worked for General Electric. In his design a gyro would control the current to the electric motors on the stabilizer fins by actuating instructions from thyratron vacuum tubes.

Calculated stability conditions

When a hull is designed, stability calculations are performed for the intact and damaged states of the vessel. Ships are usually designed to slightly exceed the stability requirements (below), as they are usually tested for this by a classification society.

Intact stability

Intact stability calculations are relatively straightforward and involve taking all the centers of mass of objects on the vessel and the center of buoyancy of the hull. Cargo arrangements and loadings, crane operations, and the design sea states are usually taken into account.

Damaged Stability

Damaged stability calculations are much more complicated than intact stability. Finite element analysis is often employed because the areas and volumes can quickly become tedious and long to compute using other methods.

The loss of stability from flooding may be due in part to the free surface effect. Water accumulating in the hull usually drains to the bilges, lowering the centre of gravity and actually increasing the metacentric height (GMt). This assumes the ship remains completely stationary and upright. However, once the ship is inclined to any degree (a wave strikes it for example), the fluid in the bilge moves to the low side. This results in a list.

Stability is also lost due to flooding when, for example, an empty tank is holed and filled with seawater. The lost buoyancy of the tank results in that section of the ship lowers into the water slightly. This creates a list unless the tank is on the centerline of the vessel.

In stability calculations, when a tank is holed, its contents are assumed to be lost and replaced by seawater. If these contents are lighter than seawater, (light oil for example) then buoyancy is lost and the section lowers slightly in the water accordingly.

For merchant vessels, and increasingly for passenger vessels, the damage stability calculations are of a probabilistic nature. This is a concept in which the chance that a compartment is damaged is combined with the consequences for the ship, resulting in a damage stability index number that has to comply with certain regulations.

Required stability

In order to be acceptable to classification societies such as the Bureau Veritas, American Bureau of Shipping, Lloyd's Register of Ships and Det Norske Veritas, the blueprints of the ship must be provided for independent review by the classification society.

Calculations must also be provided which follow a structure outlined in the regulations for the country in which the ship intends to be flagged.

For U.S. flagged vessels, blueprints and stability calculations are checked against the U.S. Code of Federal Regulations (CFR) and SOLAS conventions. Ships are required to be stable in the conditions to which they are designed for, in both undamaged and damaged states. The extent of damage required to design for is included in the regulations. The assumed hole is calculated as fractions of the length and breadth of the vessel, and is to be placed in the area of the ship where it would cause the most damage to vessel stability.

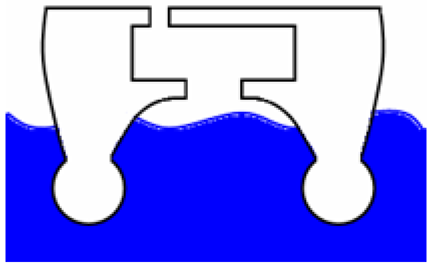
In addition, U.S. Coast Guard rules apply to vessels operating in U.S. ports and in U.S. waters. Generally these Coast Guard rules concern a minimum metacentric height or a minimum righting moment. Because different countries may have different requirements for the minimum metacentric height, most ships are now fitted with stability computers that calculate this distance on the fly based on the cargo or crew loading. CargoMax or MACS3 are popular computer programs used for this task.

Chapter 7

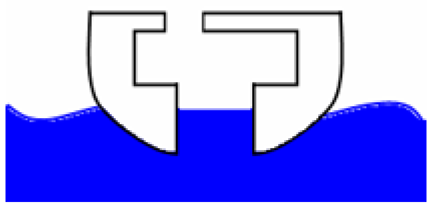
Moon Pool

Underside of the Research Vessel Western Flyer, showing its moon pool between the two hulls.

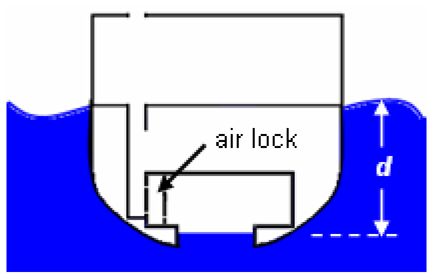
Moon pools in four different situations, shown in cross-section



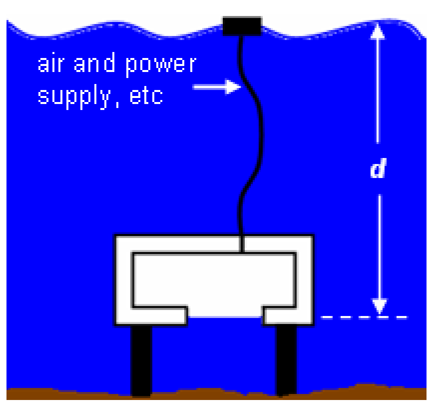
A) An open moon pool above the waterline, in a catamaran or a semi-submersible platform



B) An open moon pool at the waterline, in a ship or floating structure



C) A moon pool below the waterline in an airtight chamber, in a ship or floating structure



D) A moon pool below the waterline in an airtight submerged chamber

A **moon pool** is a feature of marine drilling platforms and drillships, some marine research and underwater exploration or research vessels, and underwater habitats, in which it is also known as a **wet porch**. It is an opening in the floor or base of the hull, platform, or chamber giving access to the water below, allowing technicians or researchers to lower tools and instruments into the sea. It provides shelter and protection so that even if the ship is in high seas or surrounded by ice, researchers have the opportunity to work in shirt-sleeved comfort compared to being on a deck exposed to the elements. A moon pool also allows divers or small submersible craft to enter or leave the water easily in a more protected environment.

Moon pools can be used in chambers below sea level, especially for the use of scuba divers, and their design requires more complex consideration of air and water pressure acting on the moon pool surface.

First use in oil drilling at sea

Moon pools originated in the oil drilling industry, which uses them in drilling at sea or in lakes, to pass drilling equipment into the water from a platform or drillship. Drill pipes need to run vertically through the structure or hull and the moon pool provides the means to do this.

Types of moon pools and associated structures

Above the waterline

In a drilling platform, the moon pool is usually above sea level, and is open to the air above and below. The research vessel *Western Flyer* (pictured) also has a moon pool above the waterline, which its SWATH (twin-hull) design allows. See part A of the diagram. The chamber above the moon pool is also connected to the open air via stair wells and passages.

At the waterline

In a monohull ship the bottom of the hull is below sea level and the water rises inside the opening of the moon pool, so that from inside the hull, the moon pool looks like a swimming pool in the floor. Water will not enter the hull and sink the ship provided the sides of the moon pool extend up inside the hull well above the waterline, as shown in part B of the diagram. This kind of moon pool is also open to the air above the ship. Doors would be used to close the bottom of the moon pool when the ship is moving, or in rough weather. The sides of the moon pool are quite deep as they need to be greater than the draft of the ship by a margin of safety.

Below the waterline

It is possible to have a moon pool below the waterline and to keep water out of the chamber above it, if the chamber is airtight rather than open to the atmosphere above in any way. This arrangement is shown in part C of the diagram. Air pressure inside the chamber prevents water rising in the moon pool up to sea level. To keep the chamber airtight, access from the chamber to the rest of the ship is via an airlock with airtight doors. The design of the ship and its safety systems need to take into account the possibility of an air leak or catastrophic failure of the airlock.

In this arrangement the sides of the moon pool can be fairly shallow, and it can be used in a deep-draft ship without wasting space.

In underwater habitats

Very deep moon pools are used in underwater habitats—submerged chambers used by divers engaged in underwater research, exploration, marine salvage, and recreation. In this case, shown in part D of the diagram, there is no dry access between the chamber and the sea surface, and the moon pool is the only entry or exit to the chamber. Submerged chambers provide dry areas for work and rest without the need to ascend to the surface. This kind of submerged chamber uses the same principles as the diving bell, except they are fixed to the seafloor, and may be called a **wet porch**, **wet room**, or **wet bell**. Sometimes the term moon pool is used to mean the complete chamber, not just the opening in the bottom and the air–water interface.

The alternative to a moon pool in an underwater habitat is the lock-out chamber, which is essentially like a fixed submarine, maintaining internal air pressures lower than ambient sea pressure down to 1 atmosphere, with an airlock to enable entry and exit underwater. Underwater habitats may have connected chambers with moon pools and lock-out chambers.

Examples of underwater habitats with moon pools

- SEALAB II (US Navy)
- Aquarius (laboratory), Florida has a moon pool in one of its three chambers, called the wet porch.
- Jules' Undersea Lodge, Key Largo, Florida. Page includes photo of moon pool.

Pressure considerations in below-waterline moon pools

Airtight chambers with below-waterline moon pools contain air that is pressurised by the weight of the sea above it, which tries to force water up into the chamber through the moon pool. The air is compressed by the water until its pressure equals that of the water at the surface of the pool, and a state of hydrostatic equilibrium is reached. Air pressure in the chamber can be calculated from the depth d of the moon pool surface below the waterline using formulas for hydrostatic pressure. Note that it is not necessary to pressurise the air in the chamber with a compressor or to keep it pressurised unless there is a leak, or a need to replenish air breathed.

Divers use a 'rule of thumb' that every 10 m depth of water adds about 1 atmosphere of pressure (14.7 PSI or about 1 kilogram-force per square centimetre, in practical but non-SI units: a physicist would use pascals). Using this rule, if the depth d in diagram part C is 6 m (about 20 feet), the pressure in the chamber is *atmospheric pressure* + 0.6 atmospheres = 1.6 atmospheres.

If the depth *d* in part D is 50 m (about 160 feet), the pressure is 6 atmospheres.

These principles are the same as those used in diving and diving bells for working out the pressure of the air inhaled by the diver. The same medical and safety principles with regard to air supply, oxygen and carbon dioxide content of the air, nitrogen narcosis, and the bends applies to airtight chambers with below-waterline moon pools. If the moon pool is more than 30 m below the waterline, the possibility of nitrogen narcosis becomes a factor, and methods of decompression may need to be used in exiting through the airlock from the chamber into any other part of the ship or structure which are at normal atmospheric pressure, as well as in ascending to the surface via the water.

Note that submarines and small submersible craft generally use normal atmospheric pressure and the hulls have to be made immensely strong to resist being crushed by water pressure at depth. The huge difference in pressure presents problems for divers entering and exiting from such vessels.

Submerged chambers with moon pools do not have to be constructed to prevent crushing, since they do in fact contain air at a higher pressure than the water over their surface except for the bottom, where it is equal. Containing air at the same pressure as the surrounding water is also an advantage to divers who can enter a deep chamber from the water without undergoing decompression.

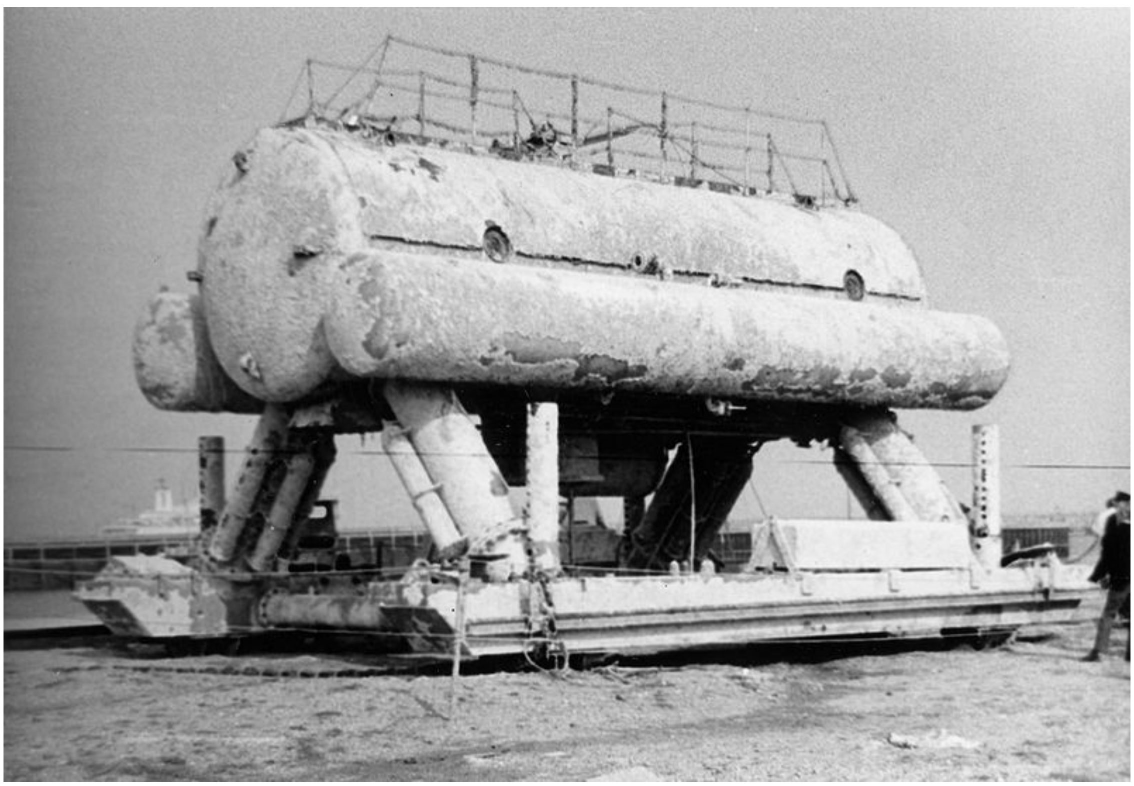
Leaks in submerged moon-pool chambers

If a submerged chamber with a moon pool is holed in the floor, there is no trade to the moon pool water level or the air pressure inside the chamber—it has no effect. If such a chamber is holed in its side or roof, many might predict that water would squirt or gush in through the hole and flood the chamber, as it would in a submarine. In fact this scenario is completely incorrect: instead air will leak out of the hole into the water and prevent water coming in, even if the hole is very large, and the surface level of the moon pool will rise up into the chamber until it reaches the top of the hole, at which point it will stop rising, air will stop escaping, and an air space will be left above the hole.

This is because the air in the chamber has a pressure higher than the water on the outside of the hole. The air pressure in the chamber equals the water pressure at the surface of the moon pool; the water pressure at the hole is less than this by an amount determined by the height difference between hole and moon pool surface. If the hole is 2.4 m higher than the moon pool surface, using the divers' rule of thumb, the air pressure will be 0.24 atm (about 3.5 PSI) higher than the water on the outside of the hole. This figure does not vary with the depth of the chamber below sea level. Compare the situation with a submarine having an internal air pressure of 1 atm. At a hole in its hull 20 m below sea level, the seawater will have a pressure 2 atm (30 PSI) higher than the air and will come through the hole as a jet.

Chapter 8

Underwater Habitat



German underwater laboratory, "Helgoland", ca. 1969

Underwater habitats are underwater structures in which people can live for extended periods and carry out most of the basic human functions of a 24-hour day, such as working, resting, eating, attending to personal hygiene, and sleeping. In this context 'habitat' is generally used in a narrow sense to mean the interior and immediate exterior of the structure and its fixtures, but not its surrounding marine environment. Most early underwater habitats lacked regenerative systems for air, water, food, electricity, and other resources. However, recently some new underwater habitats allow for these resources to be delivered using pipes, or generated within the habitat, rather than manually delivered.

An underwater habitat has to meet the needs of human physiology and provide suitable environmental conditions, and the one which is most critical is breathing air of suitable quality. Others concern the physical environment (pressure, temperature, light, humidity), the chemical environment (drinking water, food, waste products, toxins) and the biological environment (hazardous sea creatures, microorganisms, fungi). Much of the science covering underwater habitats and their technology designed to meet human requirements is shared with diving, diving bells, submersible vehicles and submarines, and spacecraft.

There have been numerous underwater habitats designed, built and used around the world since the early 1960s, either by private individuals or by government agencies. In that time they have been used almost exclusively for research and exploration, but in recent years at least one underwater habitat has been provided for recreation and tourism. Research has been devoted particularly to the physiological processes and limits of breathing gases under pressure, for aquanaut and astronaut training, as well as for research on marine ecosystems.

Basic types of habitats

Underwater habitats are designed to operate in two fundamental modes.

1. Open to ambient pressure via a moon pool, meaning the air pressure inside the habitat equals underwater pressure at the same level, such as SEALAB, and which makes entry and exit easy as there is no physical barrier other than the moon pool water surface
2. Closed to the sea by hatches, with internal air pressure less than ambient pressure and at or closer to atmospheric pressure; entry or exit to the sea requires passing through hatches and an airlock

A third or composite type has compartments of both types within the same habitat structure and connected via airlocks, such as Aquarius (laboratory).

Conshelf I, II and III

Conshelf, short for Continental Shelf Station, was a series of undersea living and research stations undertaken by Jacques Cousteau's team in the 1960s. The original design was for five of these stations to be submerged to a maximum depth of 300m over the decade; in reality only three were completed with a maximum depth of 100m. Much of the work was funded in part by the French Petrochemical industry, who, along with Cousteau, hoped that such manned colonies could serve as base stations for the future exploitation of the sea. Such colonies did not find a productive future, however, as Cousteau later repudiated his support for such exploitation of the sea and put his efforts toward conservation. It was also found in later years that industrial tasks underwater could be more efficiently performed by undersea robot devices and men operating from the surface or from smaller lowered structures, made possible by a more advanced understanding of diving physiology. Still, these three undersea living experiments did much to advance man's knowledge of undersea technology and physiology, and were valuable as "proof of concept" constructs. They also did much to publicize oceanographic research and, ironically, usher in an age of ocean conservation through building public awareness.

Along with Sealab and others, it spawned a generation of smaller, less ambitious yet longer-term undersea habitats primarily for marine research purposes. (See below)

Conshelf I (Continental Shelf Station), constructed in 1962 was the first inhabited underwater habitat. Developed by Jacques-Yves Cousteau to record basic observations of life underwater, Conshelf I was submerged in 10 metres of water near Marseilles, and the first experiment involved a team of two spending seven days in the habitat. The two oceanauts, Albert Falco and Claude Wesly, were expected to spend at least five hours a day outside of the station, and were subject to daily medical exams. They were among the first to breath a mixture of helium and oxygen, avoiding the normal nitrogen/oxygen mixture which when breathed under pressure can cause temporary mental instability. This was also an early effort in saturation diving, in which the oceanauts' body tissues were allowed to become totally saturated by the helium in the breathing mixture, a result of breathing the gases under pressure. Normally, this would prove fatal when the team returned to the surface, at which time reduced pressure would cause the helium to bubble out into the divers joints and tissues, afflicting them with the bends. The conventional solution would have been to subject the divers to lengthy and complex decompression; however, in this case the divers' instead breathed an oxygen-rich mixture of gases for a few hours before returning to the surface in order to purge the excess helium from their tissues. They suffered no apparent ill effects.

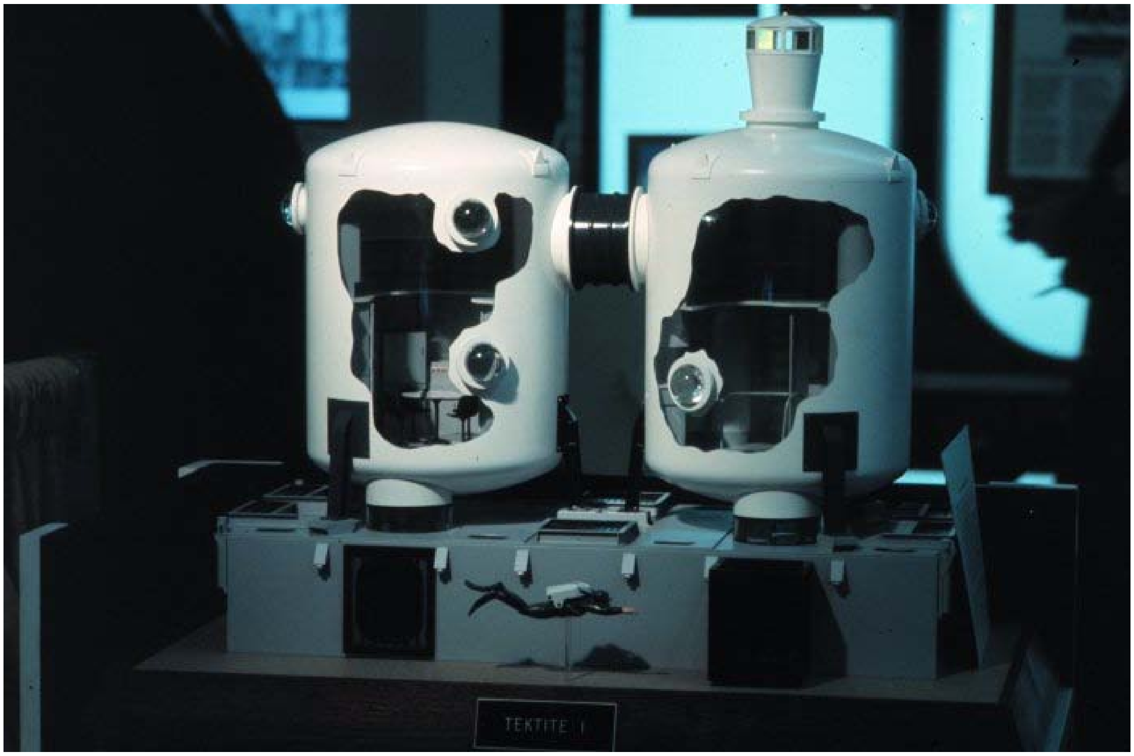
Conshelf Two, the first ambitious attempt for men to live and work on the sea floor, was launched in 1963. In it, a half-dozen oceanauts lived 10 meters down in the Red Sea off Sudan in a starfish-shaped house for 30 days. The undersea living experiment also had two other structures, one a submarine hangar that housed a small, two man submarine referred to as the "diving saucer" for its resemblance to a science fiction flying saucer, and a smaller "deep cabin" where two oceanauts lived at a depth of 30 meters for a week. The undersea colony was supported with air, water, food, power, all essentials of life, from a large support team above. Men on the bottom performed a number of experiments intended to determine the practicality of working on the sea floor and were subjected to continual medical examinations. Conshelf II was a defining effort in the study of diving physiology and technology, and captured wide public appeal due to its dramatic "Jules Verne" look and feel. A Cousteau-produced feature film about the effort was awarded an Academy Award for Best Documentary the following year.

Conshelf III was tested in 1965, six divers lived in the habitat at 102.4 metres (336 feet) in the Mediterranean near the Cap Ferrat lighthouse, between Nice and Monaco, for three weeks. In this effort, Cousteau was determined to make the station more self-sufficient, severing most ties with the surface. A mock oil rig was set up underwater, and divers successfully performed several industrial tasks.

SEALAB I, II and III

SEALAB was developed by the United States Navy, primarily to research the physiological aspects of saturation diving.

Tektite I and II



Model of the Tektite I habitat

The Tektite underwater habitat was constructed by General Electric and was funded by NASA, the Office of Naval Research and the Department of Interior.

On February 15, 1969, four U. S. Department of Interior scientists (Ed Clifton, Conrad Mahnken, Richard Waller and John VanDerwalker) descended to the ocean floor in Great Lameshur Bay in the U. S. Virgin Islands to begin an ambitious diving project dubbed "Tektite I". By March 18, 1969, the four aquanauts had established a new world's record for saturated diving by a single team. On April 15, 1969, the aquanaut team returned to the surface with over 58 days of marine scientific studies. More than 19 hours of decompression therapy were needed to accommodate the scientists' return to the surface.

Inspired in part by NASA's budding Skylab program and an interest in better understanding the effectiveness of scientists working under extremely isolated living conditions, Tektite was the first saturation diving project to employ scientists rather than professional divers.

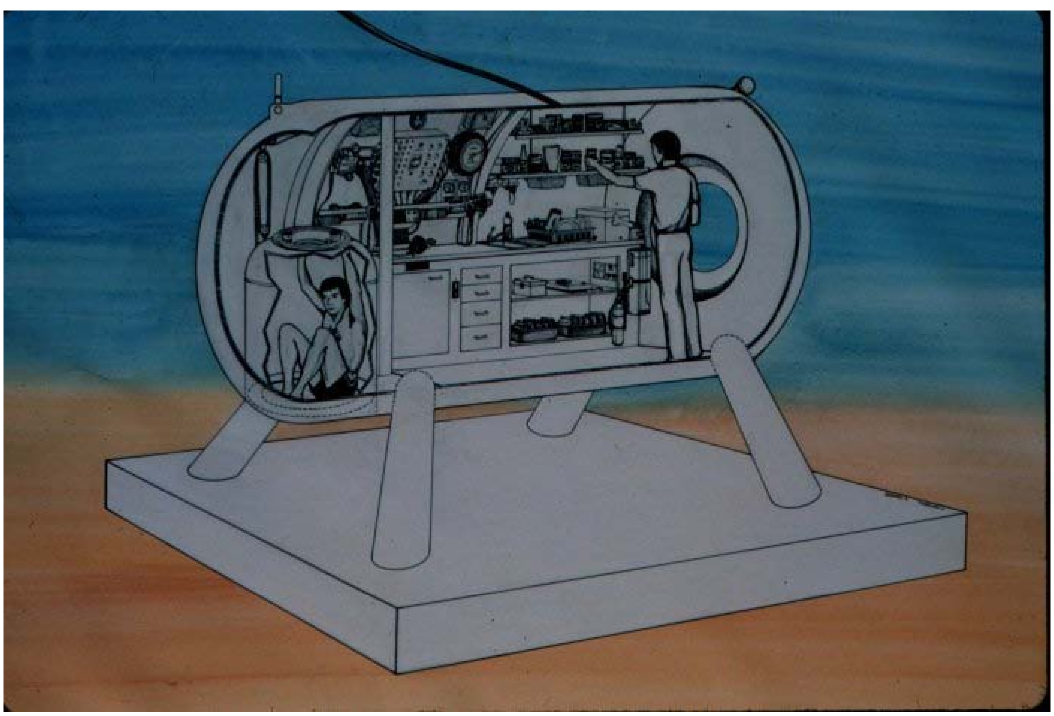
The name Tektite generally refers to a class of meteorites formed by extremely rapid cooling. These include objects of celestial origins that strike the sea surface and come to rest on the bottom (note project Tektite's conceptual origins within the US space program).

The Tektite II missions were carried out in 1970. Tektite II comprised ten missions lasting 10-20 days with four scientists and an engineer on each mission. One of these missions included the first all-female aquanaut team, led by Dr. Sylvia Earle Mead. Other scientists participating in the all-female mission included Dr. Renate True of Tulane, as well as Ann Hartline and Alina Szmant, graduate students at Scripps Institute of Oceanography. The fifth member of the crew was Margaret Ann Lucas, a Villanova engineering graduate, who served as Habitat Engineer. The Tektite II missions were the first to undertake in-depth ecological studies.

Tektite II included 24 hour behavioral and mission observations of each of the missions by a team of observers from the University of Texas at Austin. Selected episodic events and discussions were videotaped using cameras in the public areas of the habitat. Data about the status, location and activities of each of the 5 members of each mission was collected via key punch data cards every 6 minutes during each mission. This information was collated and processed by BellComm and was used for the support of papers written about the research concerning the relative predictability of behavior patterns of mission participants in constrained, dangerous conditions for extended periods of time, such as those that might be encountered in manned spaceflight.

The Tektite habitat was designed and built by General Electric Space Division at the Valley Forge Space Technology Center in King of Prussia, Pennsylvania. The Project Engineer who was responsible for the design of the habitat was Brooks Tenney, Jr. Brooks also served as the underwater Habitat Engineer on the International Mission, the last mission on the Tektite II project. The Program Manager for the Tektite I project at General Electric was Bren Thompson, and the Program Manager for the Tektite II project was Brooks Tenney, Jr. The Tektite Project was led by Dr. Theodore Marton who worked for General Electric.

Hydrolab



Inside Hydrolab

Hydrolab was constructed in 1966 and used as a research station from 1970, the project was in part funded by the National Oceanic and Atmospheric Administration (NOAA). Hydrolab could house 4 people. Approximately 180 Hydrolab missions were conducted; 100 missions in the Bahamas during the early to mid 1970s, and 80 missions in St. Croix, United States Virgin Islands, from 1977 to 1985. These scientific missions are chronicled in the *Hydrolab Journal*.

Dr. William Fife spent 28 days in saturation performing physiology experiments on researchers such as Dr. Sylvia Earle.

The habitat was decommissioned in 1985 and placed on display at the Smithsonian Institution's National History Museum in Washington, D.C.. The habitat is now located at the headquarters of the National Oceanic and Atmospheric Administration (NOAA) in Silver Spring, MD.

Aquarius

Aquarius is presently one of the world's only operational underwater laboratories. It is located adjacent to a coral reef in the Florida Keys National Marine Sanctuary.

MarineLab

The MarineLab underwater laboratory is the longest serving seafloor habitat in history, having operated continuously in an unbroken service since 1984 under the direction of aquanaut Chris Olstad at Key Largo, Florida. The seafloor laboratory has trained hundreds of individuals in that time featuring an extensive array of educational and scientific investigations from US Military investigations to pharmaceutical development.

Beginning with a project initiated in 1973, MarineLab, then known as MEDUSA (Midshipman Engineered & Designed Undersea Systems Apparatus), was designed and built as part of an ocean engineering student program at the United States Naval Academy under the direction of Dr. Neil T. Monney. In 1983, MEDUSA was donated to the Marine Resources Development Foundation (MRDF), and in 1984 was deployed on the seafloor in John Pennekamp Coral Reef State Park, Key Largo, Florida. The 8 X 16 -foot (2.5 X 4.9m) shore-supported habitat supports 3-4 persons and is divided into a laboratory, a wet-room, and a 5' 6" (1.7m) transparent observation sphere. From the beginning, it has been used by students for observation, research, and instruction. In 1985, it was renamed MarineLab and moved to the 30-foot (9.2m) deep mangrove lagoon at MRDF headquarters in Key Largo at a depth of 27 foot (8.3m) with a hatch depth of 20 feet (6.2m). The lagoon contains artifacts and wrecks placed there for education and training. During 1993-95, NASA used MarineLab repeatedly to study Controlled Ecological Life Support Systems (CELLS). These education and research programs qualify MARINE-LAB as the world's most extensively used habitat.

MarineLab is also used as an underwater lab for excursions and underwater lab training for recreational and sport divers who stay under the sea at the Jules Undersea Lodge. MarineLab is currently located right next to the Jules Undersea lodge which is actually the La Chalupa Research Laboratory converted into a luxury underwater habitat, features include a large movie selection and specialty menus, including underwater pizza delivered by a diver. There is a cable running along the bottom of the lagoon that divers can follow at night or in reduced visibility to reach MarineLab which is a short distance from the Jules Underwater Lodge. Basically, MarineLab is set up to do lab work and to serve as an underwater science classroom and the Jules Underwater Lodge is used as an underwater habitat base where the participants can stay over night, rest, relax and dine in comfort.

La Chalupa Research Laboratory

La Chalupa research laboratory, now known as Jules' Undersea Lodge

In the early 1970s, Ian Koblick, president of Marine Resources Development Foundation, developed and operated the La Chalupa research laboratory, which was the largest and most technologically advanced underwater habitat of its time. Koblick, who has continued his work as a pioneer in developing advanced undersea programs for ocean science and education, is the co-author of the book "Living and Working in the Sea" and is considered one of the foremost authorities on undersea habitation.

In the mid 1980s La Chalupa was transformed into Jules Undersea Lodge in Key Largo, Florida. Jules' co-developer Dr. Neil Monney formerly served as Professor and Director of Ocean Engineering at the U.S. Naval Academy, and has extensive experience as a research scientist, aquanaut, and designer of underwater habitats. Jules' has had over 10,000 overnight guests in its 20 years of operation. Today many certified divers who are interested stay in the Jules Underwater Lodge, and some who meet the skill and bottom time requirements and participate in underwater experiments in the MarineLab can elect to receive specialty diver recognition from PADI or NAUI as an AQUANAUT. This is probably the only recreational Aquanaut qualification available worldwide. Today

Aquanaut Hotel guests must scuba dive to get down to the hotel, and a nearby landbase offers diving lessons for people who are unfamiliar with the activity. Years ago non-scuba diving guests were taken down to the lodge breathing air pumped down from the surface through a long hose similar to a garden hose but this practice was discontinued and now all guests must scuba dive to the lodge enterance five fathoms below. The air hose system is often still used by the underwater guides to get back and forth to the lodge without donning scuba gear.

Scott Carpenter Space Analog Station

The Scott Carpenter Space Analog Station was launched near Key Largo on six week missions in 1997 and 1998. The station was a NASA project illustrating the analogous science and engineering concepts common to both undersea and space missions. During the missions, some 20 aquanauts rotated through the undersea station including NASA scientists, engineers and director James Cameron. The SCSAS was designed by NASA engineer Dennis Chamberland.

Lloyd Godson's Biosub

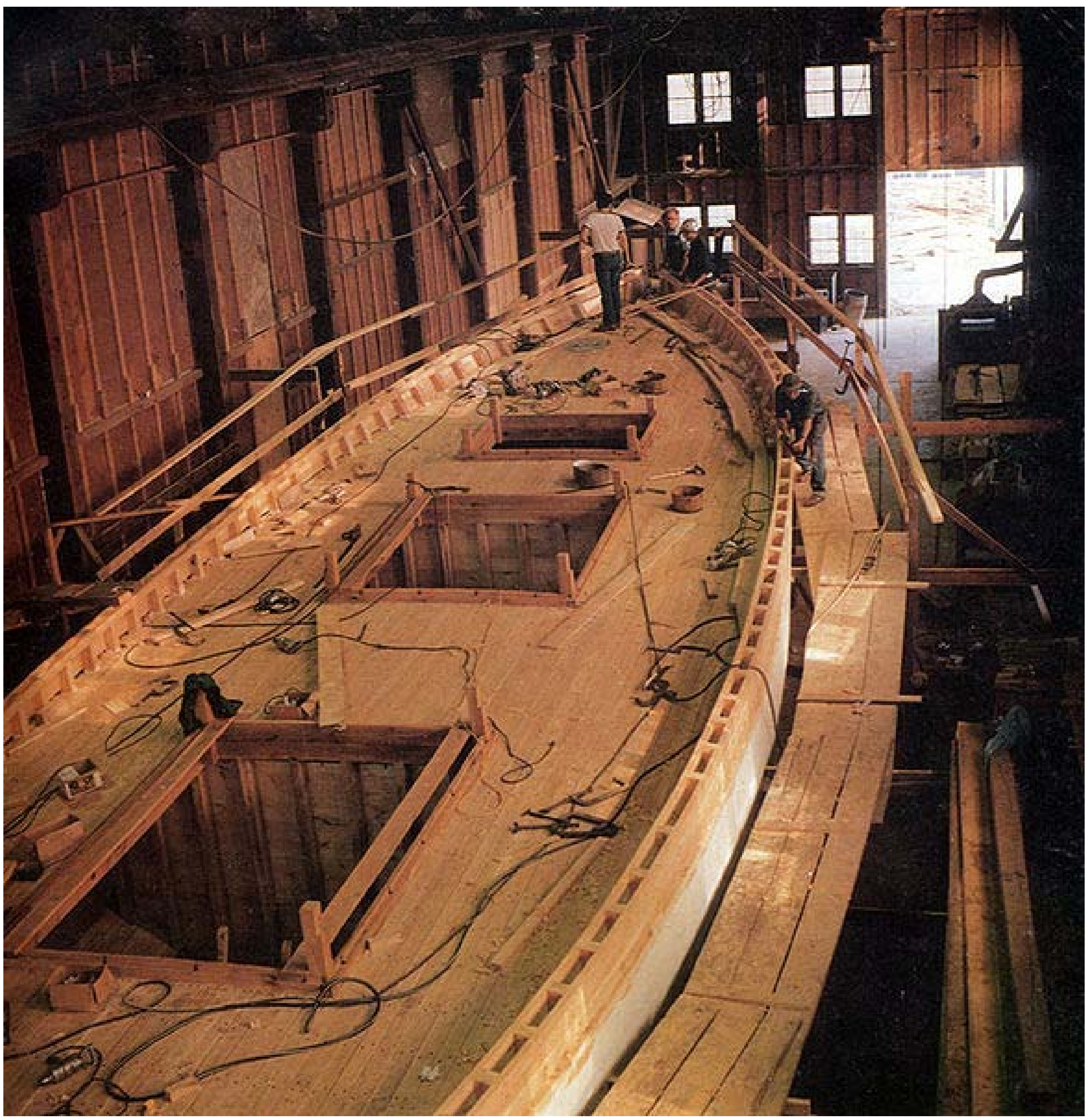
Lloyd Godson's Biosub was an underwater habitat, built in 2007 for a competition by Australian Geographic. The Biosub generated its own electricity (using a bike), its own water, using the Air2Water Dragon Fly M18 system, its own air (using algae that produce O_2). The algae were fed using the Cascade High School Advanced Biology Class Biocoil. The habitat shelf itself was constructed by Trygons Designs.

Atlantica Expedition

On July 4, 2012 a new expedition is scheduled to launch. Called the Atlantica Expedition I & II, it is a new endeavor to once again try to establish a permanent deep-sea underwater human colony with several stages of development. It is being led by Dennis Chamberland. Believing that good preparation and planning will be the key to a thriving community underwater as on land, Chamberland seeks to methodically study and deal with potential problems of a permanent underwater habitat with the establishment of Leviathan, the first underwater module, scheduled to “launch” on July 4, 2012. He believes that it is possible to overcome the problems of humans living underwater by thoroughly researching and studying all aspects of underwater living; from the technical difficulties like producing breathable oxygen and structural integrity to the political ramifications of how the culture would be run. He’s made the jump from temporary underwater research stations to an all encompassing changing human community. Dr. Sarah Jane Pell is also a researcher and scientist who is has worked for toward the establishment and study of permanent colony both in the ocean and in space.

Chapter 9

Boat Building



The schooner *Appledore II* under construction

Boat building, one of the oldest branches of engineering, is concerned with constructing the hulls of boats and, for sailboats, the masts, spars and rigging.

Parts

Boat building in Greece

Side view of the wooden frame

- Bow - the front and generally sharp end of the hull. It is designed to reduce the resistance of the hull cutting through water and should be tall enough to prevent water from easily washing over the top of the hull.
- Bulkhead - the internal walls of the hull
- Chines - are long, longitudinal strips on hydroplaning hulls that deflect downwards the spray that is produced by the hull when it travels at speed in the water. The term also refers to distinct changes in angle of the hull sections, where the bottom blends into the sides of a flat bottomed skiff, for instance. A hull may have 2 or more chines to allow an approximation of a round bottomed shape with flat panels. It also refers to the longitudinal members inside the hull which support the edges of these panels.
- Deck - the top surface of the hull keeps water and weather out of the hull and allows the crew to stand safely and operate the boat more easily. It stiffens an enclosed hull.
- Garboard - the strake immediately adjacent to the keel.
- Gunwale - The upper longitudinal structural member of the hull.
- Keel - the main central member along the length of the bottom of the boat. It is an important part of the boat's structure which also has a strong influence on its turning performance and, in sailing boats, resists the sideways pressure of the wind
- Keelson - an internal beam fixed to the top of the keel to strengthen the joint of the upper members of the boat to the keel
- Rudder - a steering device at the rear of the hull created by a turnable blade on a vertical axis
- Sheer - the generally curved shape of the top of the hull. The sheer is traditionally lowest amidships to maximize freeboard at the ends of the hull. Sheers can be reverse, higher in the middle, to maximize space inside or straight or a combination of shapes.
- Stem - a continuation of the keel upwards at the front of the hull
- Stern - the back of the boat
- Strake - a strip of material running longitudinally along the vessel's side, bilge or bottom
- Transom - a wide, flat, sometimes vertical board at the rear of the hull, which, on small power boats, is often designed to carry an outboard motor. Transoms increase width and also buoyancy at the stern.

Construction materials and methods

Damaged boat mid-reconstruction; carvel planking partially removed

Caulking irons and oakum

Caulking a wooden boat

- Wood - The traditional boat building material that was and is still used for hull and spar construction. It is buoyant, cheap, widely available and easily worked. As such, it is a popular material for amateur builders, especially for small boats (of e.g. 6-metre length; such as dinghies and sharpies). It is not particularly abrasion resistant and it can deteriorate if fresh water or marine organisms are allowed to penetrate the wood. The hull of a wooden boat usually consists of planking fastened to frames and a keel. Keel and frames are traditionally made of hardwoods such as oak while planking can be oak but is more often softwood such as pine, larch or cedar. Plywood is especially popular for amateur construction. More recently introduced tropical woods as mahogany, okoumé, iroko, Keruing, azobe and merbau. are also used. With tropical species, extra attention needs to be taken to ensure that the wood is indeed FSC-certified. Teak or iroko is usually used to create the deck and any superstructure. Glue, screws, rivets and/or nails are used to join the wooden components.

Some types of wood construction include:

-
    - **Carvel**, in which a smooth hull is formed by wooden planks attached to a frame. The planks may be curved in cross section like barrel staves. Carvel planks are generally caulked with oakum or cotton that is driven into the seams between the planks and covered with some waterproof substance. It takes its name from an archaic ship type and is believed to have originated in the Mediterranean.
    - Another method of building wooden boats is **lapstrake**, a technique originally identified with the Vikings in which wooden planks are fixed to each other with a slight overlap that is bevelled for a tight fit. The planks may be mechanically connected to each other with copper rivets, bent over iron nails, screws or with adhesives. Often, steam bent wooden frames are fitted inside the hull. This technique is known as clinker in Britain and also as clench built.
    - Strip planking is yet another type of wooden boat construction. It is a glued construction method which is very popular with amateur boatbuilders as it is quick, avoids complex temporary jig work and does not require shaping of the planks.
    - Another method is called sheet plywood boat building and uses sheets of **plywood panel**s fixed to a frame. Plywood may be laminated into a round hull or used in single sheets. These hulls generally have one or more chines and the method is called Ply on Frame construction. A subdivision of the sheet plywood boat building method is known as the stitch-and-glue method, where pre-shaped panels of plywood are edge glued and reinforced with fibreglass without the use of a frame. Metal or plastic wires pull curved flat panels into three-dimensional curved shapes. These hulls generally have one or more chines. Plywood panels of good quality are often designated "WBP" (which stands for water- and boiled-proof). Both types of plywood construction are very popular with amateur builders, and many dinghies such as the Vaurien (ply on frame

construction) and FJs, FDs and Kolibris (stitch-and-glue method) have been built from it.

- Cold-Molding is a composite method of wooden boat building that uses many different layers of thin wood, called veneers, oriented in all different directions, resulting in a strong monoque structure, similar to a fibreglass hull. Usually composed of a base layer of strip planking followed then by multiple veneers, cold-molding is becoming popular in very large, wooden superyachts.

- Steel (and before that iron) - Either used in sheet or alternatively, plate for all-metal hulls or for isolated structural members. It is strong, but heavy (despite the fact that the thickness of the hull can be les). It is generally about 30% heavier than aluminium and somewhat more heavy than polyester. The material rusts unless protected from water (this is usually done by means of a covering of paint). Modern steel components are welded or bolted together. As the welding can be done very easily (with common welding equipment), and as the material is very cheap, it is a popular material with amateur builders. Also, amateur builders which are not yet well established in building steel ships may opt for DIY construction kits. If steel is used, a zinc layer is often applied to coat the entire hull. It is applied after sandblasting (which is required to have a cleaned surface) and before painting. The painting is usually done with lead paint (Pb_3O_4). Optionally, the covering with the zinc layer may be left out, but it is generally not recommended. Zinc anodes also need to be placed on the ship's hull. Until the mid 1900s, steel sheets were riveted together.

A punt under construction

Wooden boats being built during the Klondike Gold Rush

- Aluminium - either used in sheet for all-metal hulls or for isolated structural members. Many sailing spars are made of aluminium. The material requires special manufacturing techniques, construction tools and construction skills. It is the lightest material for building boats (being 15-20% lighter than polyester and 30% lighter than steel). Aluminium is very expensive and it is usually not used by amateur builders. While it is easy to cut, aluminium is difficult to weld, and also requires heat treatments such as precipitation strengthening for most applications. Corrosion is a concern with aluminium, particularly below the waterline.

- Fiberglass (Glass-reinforced plastic or GRP) - Typically used for production boats because of its ability to reuse a female mold as the foundation for the shape of the boat. The resulting structure is strong in tension but often needs to be either laid up with many heavy layers of resin-saturated fiberglass or reinforced with wood or foam in order to provide stiffness. GRP hulls are largely free of corrosion though not normally fireproof. These can be solid fiberglass or of the sandwich (cored) type, in which a core of balsa, foam or similar material is applied after the outer layer of fiberglass is laid to the mold, but before the inner skin is laid. This is similar to the next type, composite, but is not usually classified as composite, since the core material in this case does not provide much additional strength. It does, however, increase stiffness, which means that less resin and fiberglass cloth can be used in order to save weight. Most fibreglass boats are currently made in an open mold, with fibreglass and resin applied by hand (hand-lay-up method). Some are now constructed by vacuum infusion where the fibres are laid out and resin is pulled into the mold by atmospheric pressure. This can produce stronger parts with more glass and less resin, but takes special materials and more technical knowledge.

- Composite - Originally "composite" referred to a timber carvel skin fastened to iron frame and deck beams. This allowed sheet copper anti-fouling to be employed without the risk of galvanic corrosion of the hull fabric. It was employed for fast cargo vessels so that they were not slowed by marine fouling. While GRP, wood, and even concrete hulls are technically made of composite materials, the term "composite" is often used for plastics reinforced with fibers other than (or in addition to) glass. Cold-molded refers to a type of building one-off hulls using thin strips of wood applied to a series of forms at 45-degree angles to the centerline. This method is often called double-diagonal because a minimum of two layers is recommended, each occurring at opposing 45-degree angles. "Cold-molding" is now a relatively archaic term because the contrasting "hot-molded" method of building boats, which used ovens to heat and cure the resin, has not been widely used since World War II. Now almost all curing is done at room temperature. Other composite types include sheathed-strip, which uses (usually) a single layer of strips laid up parallel to the sheer line. The composite materials in question are then applied to the mold in the form of a thermosetting plastic (usually epoxy, polyester, or vinylester) and some kind of fiber cloth (fiberglass, kevlar, dynel, carbon fiber, etc), hence the finished hull is a "composite" of fiber and resin. These methods often give strength-to-weight ratios approaching that of aluminum, while requiring less specialized tools and skills.

- Steel-reinforced cement (ferrocement) - Strong and long lasting. First developed in the mid 19th Century in France. Used for building warships during the war. Extensively refined in New Zealand shipyards in the 1950s and the material became popular among amateur builders of cruising sailboats in the 1970s and 1980s, because the material cost was cheap although the labour time element was high. The weight of a finished ferrocement boat is comparable to that of a traditionally built wooden boat. As such they are often built for slower, more comfortable sea passages. Hulls built properly of ferrocement are more labor-intensive than steel or fiberglass, so there are few examples of commercial shipyards using this material. The inability to mass produce boats in ferrocement has led there to there being few examples around. Many ferrocement boats built in back yards have a rough, lumpy look, which has helped to give the material a poor reputation. The ferrocement method is easy to do, but it is also easy to do wrong. This has led to some disastrous 'home-built' boats. Properly designed, built and plastered ferrocement boats have smooth hulls with fine lines, and therefore are often mistaken for wooden or fiberglass boats.

Hull types

To build a boat, the type of hull used is of vital importance; for example, going to sea requires a hull which is more stable than a hull used for sailing rivers (which can be more flat/round). Some types include:

- Smooth curve hull - As its name implies, the hulls of these vessels are rounded and don't usually have any chines or corners.
- Chined and hard chined hulls - These are hulls made up of flat panels (commonly made of plywood, or more traditionally with planking) which meet at a sharp angle known as the chine. Chined hulls range from simple flat-bottomed boats where the side and bottom are two distinct pieces (such as banks dories, sharpies and skiffs) to multichine boats. Multichine hulls allow a round hull shape to be approximated.
- Flat-bottomed hull - The flat-bottomed hull has many advantages, such as the ability to travel in shallower water, though it is less stable in choppy waters than other hull types.
- Displacement hulls - These are hulls which have a shape which does not promote planing. They travel through the water at a limited rate which is defined by the waterline length. They are often heavier than planing types, though not always.
- Planing hulls - These are hulls with a shape that allows the boat to rise higher and higher out of the water as the speed increases. They are sometimes flat-bottomed, sometimes V-bottomed and sometimes round-bilged. The most common form is to have at least one chine to allow for stability when cornering and for a supportive surface on which to ride while planing. Planing hulls allow higher speeds to be achieved, and are not limited by the waterline length the way displacement hulls are. They do require more energy to achieve these speeds.

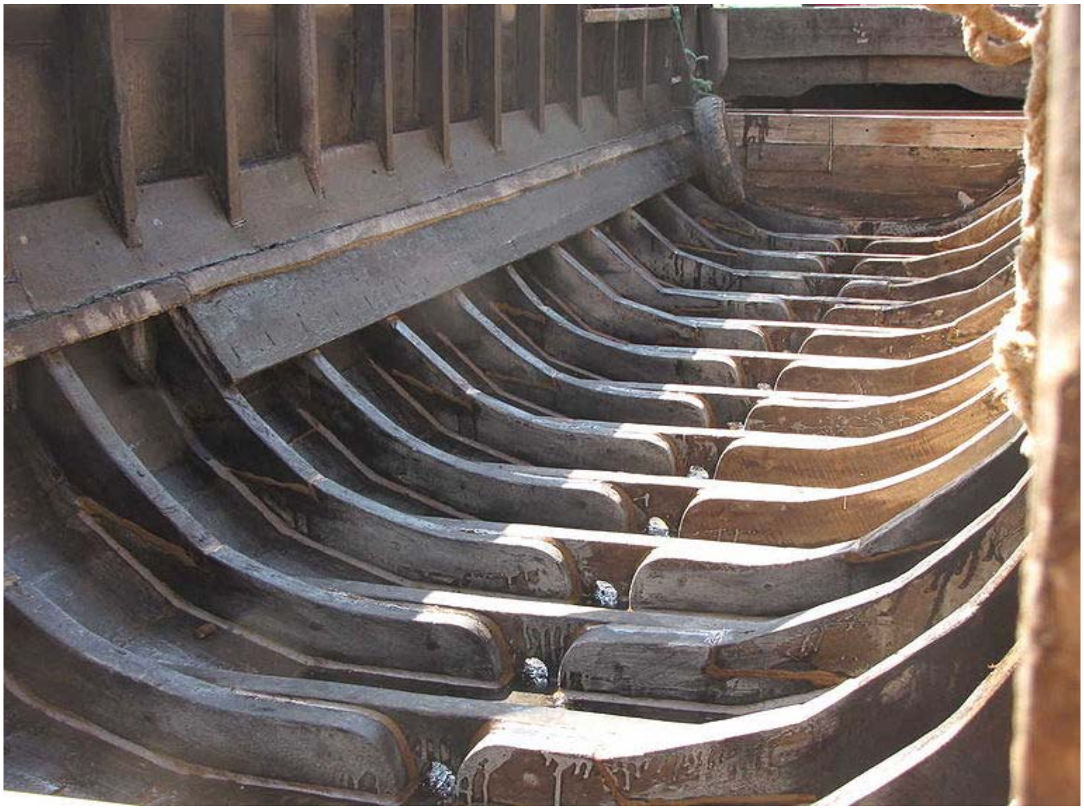
Small boatyard horizontal band saw, Hoi AN

Small boat using the planks first method. Hoi An.

Boat nearing completion with frames added. Hoi An.

Plank on frame construction.Quy Nho'n.

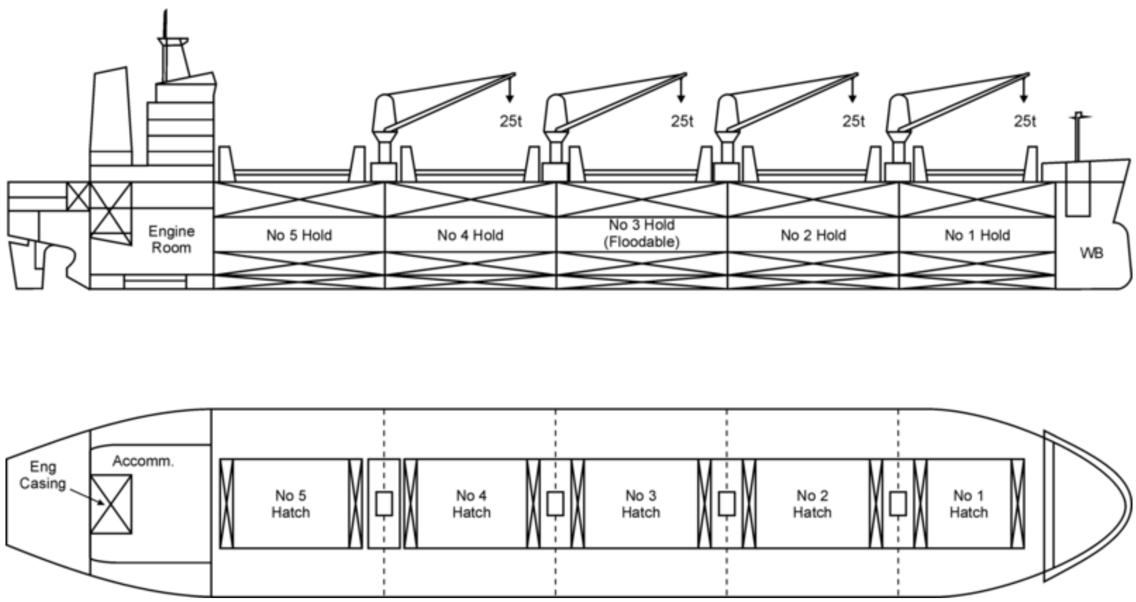
Almost completed offshore fishing hull, Quy Nho'n.



Repaired frames, barge hull. Sa Dec, Mekong Delta.

Chapter 10

Engine Room



Location of a ship's engine room.

Main engine deck of a cargo vessel

On a ship, the **engine room**, or **ER**, commonly refers to the machinery spaces of a vessel. To increase the safety and damage survivability of a vessel, the machinery necessary for operations may be segregated into various spaces, the engine room is one of these spaces, and is generally the largest physical compartment of the machinery space. The engine room houses the vessel's prime mover, usually some variations of a heat engine - diesel engine, gas or steam turbine. On some ships, the machinery space may comprise more than one engine room, such as forward and aft, or port or starboard engine rooms, or may be simply numbered.

On a large percentage of vessels, ships and boats, the engine room is located near the bottom, and at the rear, or aft, end of the vessel, and usually comprises few compartments. This design maximizes the cargo carrying capacity of the vessel and situates the prime mover close to the propeller, minimizing equipment cost and problems posed from long shaft lines. The engine room on some ships may be situated mid-ship, especially on vessels built from 1900 to the 1960s. With the increase use of diesel electric propulsion packages, the engine room(s) may be located well forward, low or high on the vessel, depending on the vessel use.

The engine compartment of a locomotive may be described as an engine room.

Equipment

Engines

The engine room of a Severn class lifeboat

The engine room of a motor vessel typically contains several engines for different purposes. Main, or propulsion engines are used to turn the ship's propeller and move the ship through the water. They typically burn diesel oil or heavy fuel oil, and may be able to switch between the two. There are many propulsion arrangements for motor vessels, some including multiple engines, propellers, and gearboxes.

Large engines drive electrical generators that provide power for the ship's electrical systems. Large ships typically have three or more synchronized generators to ensure smooth operation. The combined output of a ship's generators is well above the actual power requirement to accommodate maintenance or the loss of one generator.

On a steamship, power for both electricity and propulsion is provided by a large boiler. Superheated steam from the boiler is used to spin powerful turbines for propulsion and turbo generators for electricity. Besides propulsion and auxiliary engines, a typical engine room contains many smaller engines, including generators, air compressors, feed pumps, and fuel pumps. Today, these machines are usually powered by small diesel engines or electric motors, but may also use low-pressure steam.

Engine cooling

The engine(s) get required cooling from liquid-to-liquid heat exchangers connected to fresh seawater or divertible to recirculate through tanks of seawater in the engine room. Both supplies draw heat from the engines via the coolant and oil lines. Heat exchangers are plumbed in so that oil is represented by a yellow mark on the flange of the pipes, and relies on paper type gaskets to seal the mating faces of the pipes. Sea water or brine, is represented by a green mark on the flanges and internal coolant is represented by blue marks on the flanges.

Thrusters

In addition to this array of equipment is the ships thruster system, typically operated by electric motors controlled from the bridge. These thrusters are laterally mounted propellers that can suck or blow water from port to starboard (i.e. left to right) or vice versa. They are normally used only in maneuvering, e.g. docking operations, and are often banned in tight confines, e.g. drydocks.

Thrusters, like main propellers, are reversible by hydraulic operation. Small embedded hydraulic motors rotate the blades up to 180 degrees to reverse the direction of the thrust.

Safety

Fire precautions

Engine rooms are hot, noisy, sometimes dirty, and potentially dangerous. The presence of flammable fuel, high voltage (HV) electrical equipment and internal combustion engines (ICE) means that a serious fire hazard exists in the engine room, which is monitored continuously by the ship's engineering staff and various monitoring systems.

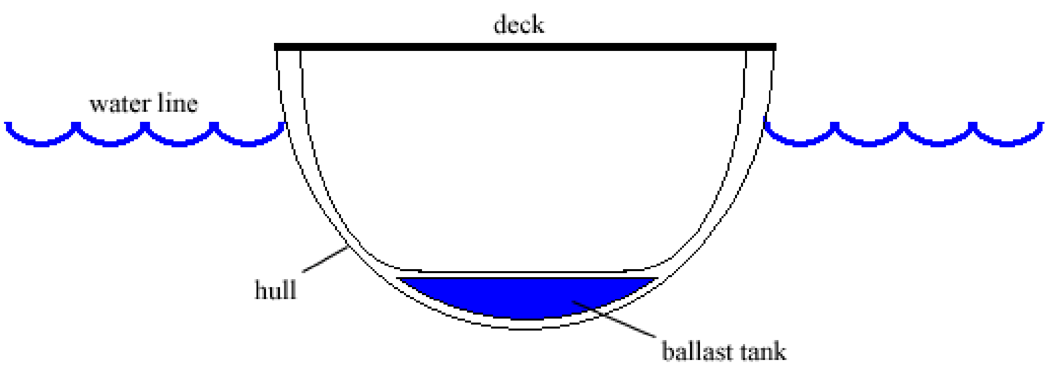
Ventilation

Engine room of the SS Shieldhall

If equipped with internal combustion or turbine engines, engine rooms employ some means of providing air for the operation of the engines and associated ventilation. If individuals are normally present in these rooms, additional ventilation should be available to keep engine room temperatures to acceptable limits. If personnel are not normally in the engine space, as in many pleasure boats, the ventilation need only be sufficient to supply the engines with intake air. This would require an unrestricted hull opening of the same size as the intake area of the engine itself assuming the hull opening is in the engine room itself. Commonly screens are placed over such openings and if this is done, airflow is reduced by approximately 50% so the opening area is increased appropriately. The requirement for general ventilation and the requirement for sufficient combustion air are quite different. A typical arrangement might be to make the opening large enough to provide intake air plus 1000 Cubic Feet per Minute (CFM) for additional ventilation. Engines pull sufficient air into the engine room for their own operation. However, additional airflow for ventilation usually requires intake and exhaust blowers.

Chapter 11

Ballast Tank



Cross section of a vessel with a single ballast tank at the bottom.

A **ballast tank** is a compartment within a boat, ship or other floating structure that holds water.

History

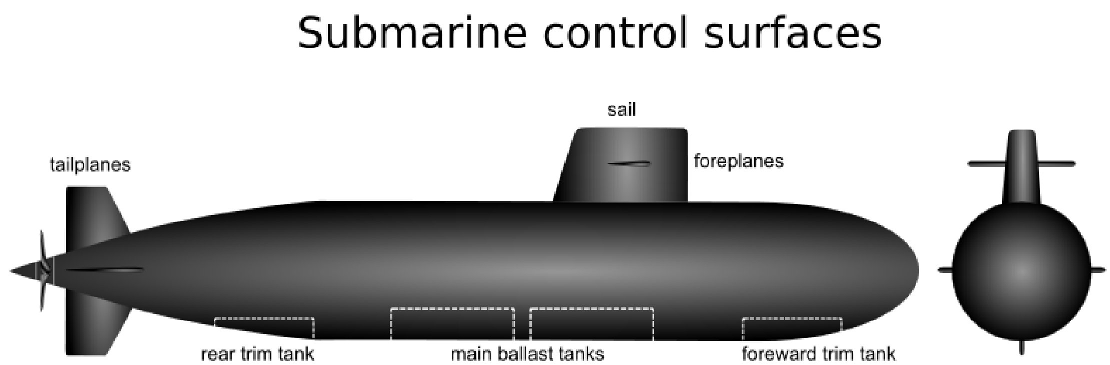
The basic concept behind the ballast tank can be seen in many forms of aquatic life, such as the blowfish or argonaut octopus, and the concept has been invented and reinvented many times by humans to serve a variety of purposes. For example, in 1849 Abraham Lincoln, then an Illinois attorney, patented a ballast-tank system to enable cargo vessels to pass over shoals in North American rivers.

Ships

A vessel may have a single ballast tank near its center or multiple ballast tanks typically on either side. A large vessel typically will have several ballast tanks including double bottom tanks, wing tanks as well as forepeak and aftpeak tanks. Adding ballast to a vessel lowers its center of gravity, and increases the draft of the vessel. Increased draft may be required for proper propeller immersion.

A ballast tank can be filled or emptied in order to adjust the amount of ballast force. Ships designed for carrying large amounts of cargo must take on ballast water for proper stability when travelling with light loads and discharge water when heavily laden with cargo. Small sailboats designed to be light weight for being pulled behind automobiles on trailers are often designed with ballast tanks that can be emptied when the boat is removed from the water.

Submarines



Ballast locations on a submarine.

In submarines ballast tanks are used to allow the vessel to submerge, water being taken in to alter the vessel's buoyancy and allow the submarine to dive. When the submarine surfaces, water is blown out from the tanks using compressed air, and the vessel becomes positively buoyant again, allowing it to rise to the surface. A submarine may have several types of ballast tank: the main ballast tanks, which are the main tanks used for diving and surfacing, and trimming tanks, which are used to adjust the submarine's attitude (its 'trim') both on the surface and when underwater.

Floating structures

Ballast tanks are also integral to the stability and operation of deepwater offshore oil platforms and floating wind turbines. The ballast facilitates "hydrodynamic stability by moving the center-of-mass as low as possible, placing [it] beneath the [air-filled] buoyancy tank."

Wakeboard Boats

Most wakeboard specific inboard boats have multiple integrated ballast tanks that are filled with ballast pumps controlled from the helm with rocker switches. Typically the configuration is based on a three tank system with a tank in the center of the boat and two more in the rear of the boat on either side of the engine compartment. Just like larger ships when adding water ballast to smaller wakeboard boats the hull has a lower center of gravity, and increases the draft of the boat. Most wakeboard boat factory ballast systems can be upgraded with larger capacities by adding soft structured ballast bags.

Environmental concerns

Ballast water taken in to a tank from one body of water and discharged in another body of water can introduce invasive species of aquatic life. The taking in of water from ballast tanks has been responsible for the introduction of species that cause environmental and economic damage. For example, zebra mussels in the Great Lakes of Canada and the United States.

Chapter 12

Strength of Ships

The **strength of ships** is a topic of key interest to naval architects and shipbuilders. Ships which are built too strong are heavy, slow, and cost extra money to build and operate since they weigh more, whilst ships which are built too weakly suffer from minor hull damage and in some extreme cases catastrophic failure and sinking.

Loads on ship hulls

The hulls of ships are subjected to a number of loads.

- Even when sitting at dockside or at anchor, the pressure of surrounding water displaced by the ship presses in on its hull.
- The weight of the hull, and of cargo and components within the ship bears down on the hull.
- Wind blows against the hull, and waves run into it.
- When a ship moves, there is additional hull drag, the force of propellors, water driven up against the bow.
- When a ship is loaded with cargo, it may have many times its own empty weight of cargo pushing down on the structure.

If the ship's structure, equipment, and cargo are distributed unevenly there may be large point loads into the structure, and if they are distributed differently than the distribution of buoyancy from displaced water then there are bending forces on the hull.

When ships are drydocked, and when they are being built, they are supported on regularly spaced posts on their bottoms.

Primary hull loads, strength, and bending

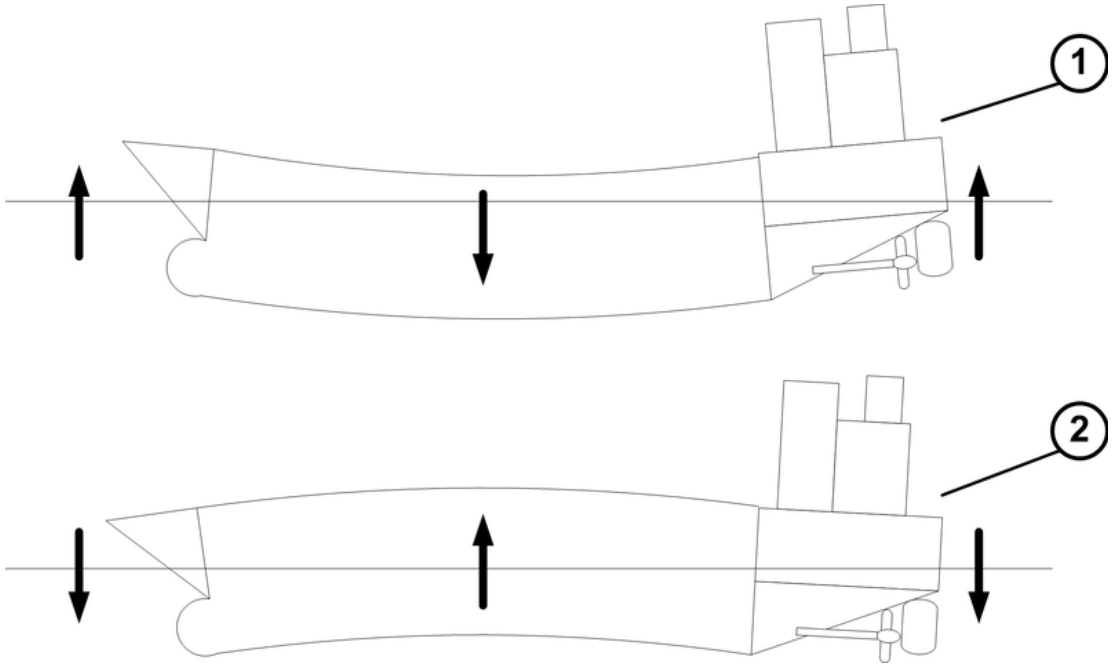


Diagram of ship hull (1) Sagging and (2) Hogging under loads. Bending is exaggerated for illustration purposes.

The primary strength, loads, and bending of a ship's hull are the loads that affect the whole hull, viewed from front to back and top to bottom. Though this could be considered to include overall transverse loads (from side to side within the ship), generally it is applied to longitudinal loads (from end to end) only. The hull, viewed as a single beam, can bend

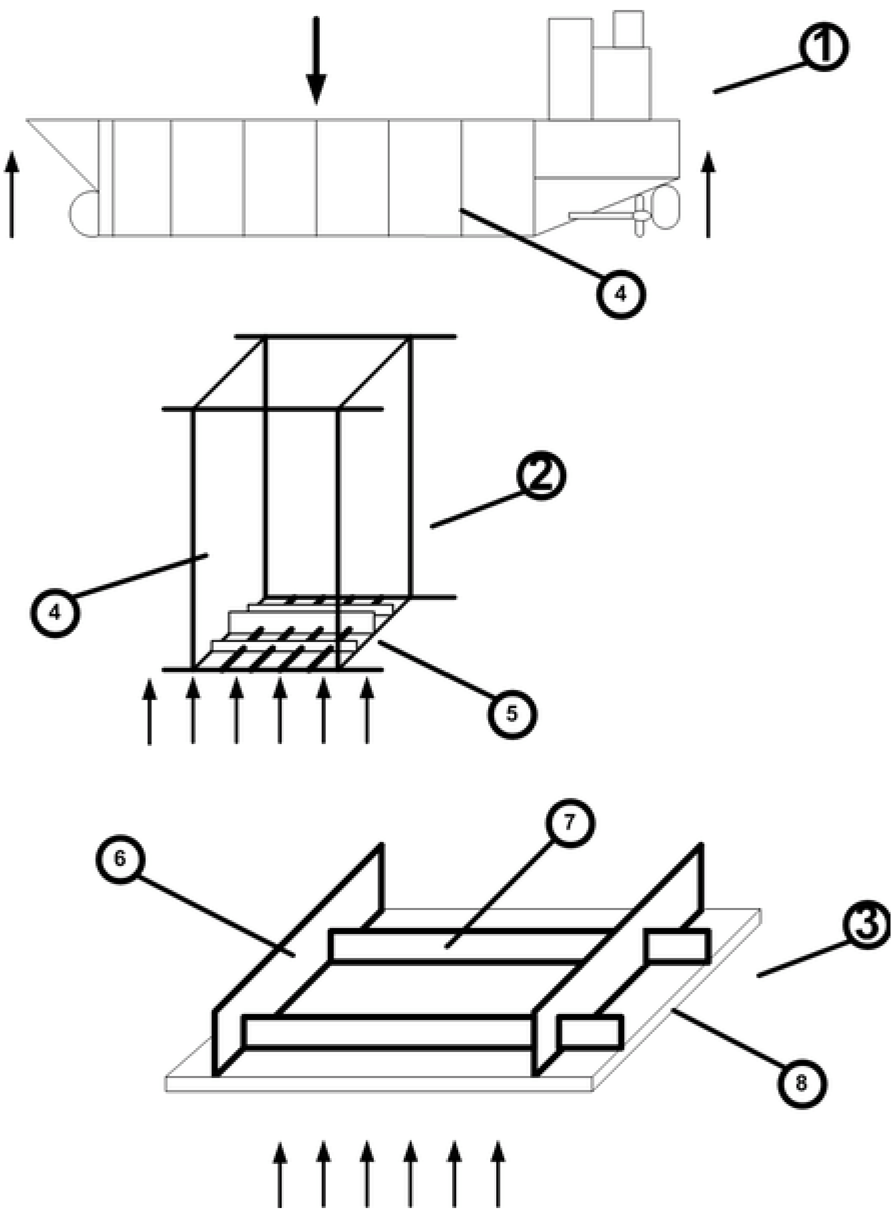
1. down in the center, known as sagging
2. up in the center, known as hogging.

This can be due to:

- hull, machinery, and cargo loads
- wave loads, with the worst cases of:
  - sagging, due to a wave with length equal to the ship's length, and peaks at the bow and stern and a trough amidships
  - hogging, due to a wave with length equal to the ship's length, and a peak amidships (right at the middle of the length)

Primary hull bending loads are generally highest near the middle of the ship, and usually very minor past halfway to the bow or stern.

Primary strength calculations generally consider the midships cross section of the ship. These calculations treat the whole ships structure as a single beam, using the simplified Euler-Bernoulli beam equation to calculate the strength of the beam in longitudinal bending. The moment of inertia (technically, second moment of area) of the hull section is calculated by finding the neutral or central axis of the beam and then totaling up the quantity $I_y = \frac{bh^3}{12} + Ad^2$ for each section of plate or girder making up the hull, with I_y being the moment of inertia of that section of material, *b* being the width (horizontal dimension) of the section, *h* being the height of the section (vertical dimension), *A* being the area of the section and *d* being the vertical distance of the center of that section from the neutral axis.



Primary (1), Secondary (2), and Tertiary (3) structural analysis of a ship hull. Depicted internal components include a watertight bulkhead (4) at the primary and secondary level, the ship's hull bottom structure including keel, keelsons, and transverse frames between two bulkheads (5) at the secondary level, and transverse frames (6), longitudinal stiffeners (7), and the hull plating (8) at the tertiary level.

Primary strength loads calculations usually total up the ships weight and buoyancy along the hull, dividing the hull into manageable lengthwise sections such as one compartment, arbitrary ten foot segments, or some such manageable subdivision. For each loading condition, the displaced water weight or buoyancy is calculated for that hull section based on the displaced volume of water within that hull section. The weight of the hull is similarly calculated for that length, and the weight of equipment and systems. Cargo weight is then added in to that section depending on the loading conditions being checked.

The total **still water bending moment** is then calculated by integrating the difference between buoyancy and total weight along the length of the ship.

For a ship in motion, additional bending moment is added to that value to account for waves it may encounter. Standard formulas for wave height and length are used, which take ship size into account. The worst possible waves are, as noted above, where either a wave crest or trough is located exactly amidships.

Those total bending loads, including still water bending moment and wave loads, are the forces that the overall hull primary beam has to be capable of withstanding.

Secondary hull loads, strength, and bending

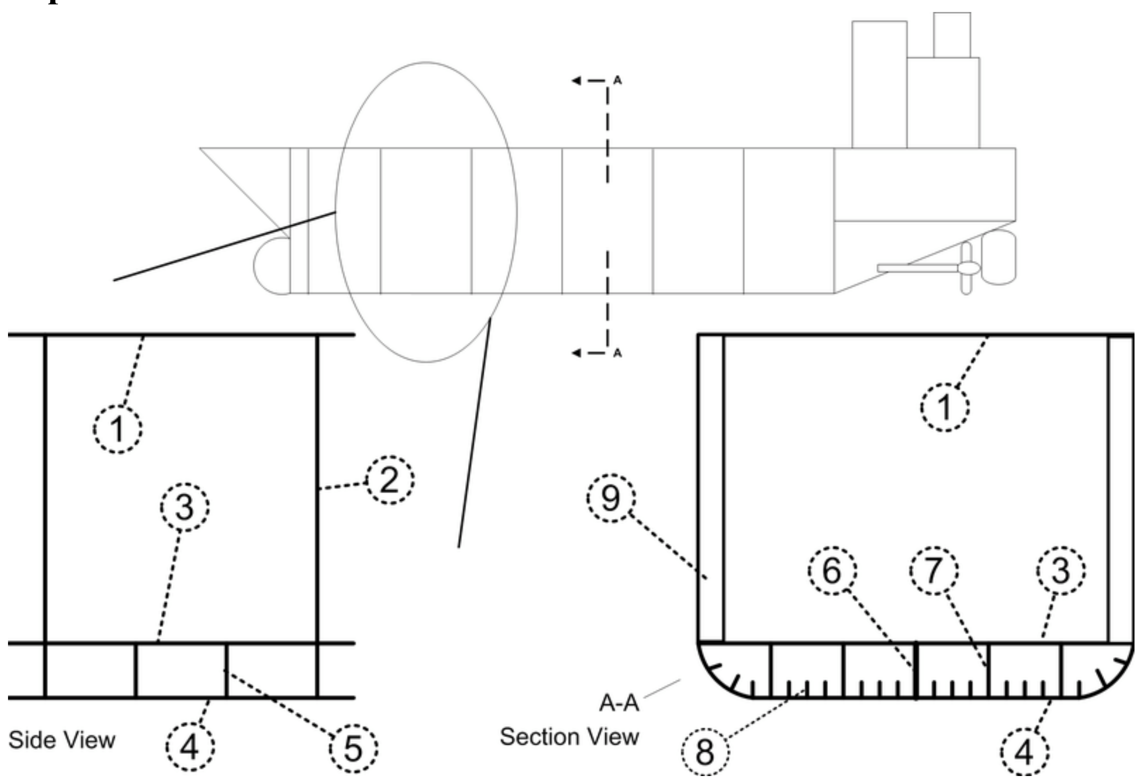
The secondary hull loads, bending, and strength are those loads that happen to the skin structure of the ship (sides, bottom, deck) between major lengthwise subdivisions or bulkheads. For these loads, we are interested in how this shorter section behaves as an integrated beam, under the local forces of displaced water pushing back on the hull, cargo and hull and machinery weights, etc. Unlike primary loads, secondary loads are treated as applying to a complex composite panel, supported at the sides, rather than as a simple beam.

Secondary loads, strength, and bending are calculated similarly to primary loads: you determine the point and distributed loads due to displacement and weight, and determine local total forces on each unit area of the panel. Those loads then cause the composite panel to deform, usually bending inwards between bulkheads as most loads are compressive and directed inwards. Stress in the structure is calculated from the loads and bending.

Tertiary hull loads, strength, and bending

Tertiary strength and loads are the forces, strength, and bending response of individual sections of hull plate between stiffeners , and the behaviour of individual stiffener sections. Usually the tertiary loading is simpler to calculate: for most sections, there is a simple, maximum hydrostatic load or hydrostatic plus slamming load to calculate. The plate is supported against those loads at its edges by stiffeners and beams. The deflection of the plate (or stiffener), and additional stresses, are simply calculated from those loads and the theory of plates and shells.

Ship hull structure elements



Structural Elements of a Ship's Hull

This diagram shows the key structural elements of a ship's main hull (excluding the bow, stern, and deckhouse).

1. Deck plating (a.k.a. Main Deck, Weatherdeck or Strength Deck)
2. Transverse bulkhead
3. Inner bottom shell plating
4. Hull bottom shell plating
5. Transverse frame (1 of 2)
6. Keel frame
7. Keelson (longitudinal girder) (1 of 4)
8. Longitudinal stiffener (1 of 18)
9. Hull side beam

The depicted hull is a sample small double bottom (but not double hull) oil tanker.

Total loads, bending, and strength

The total load on a particular section of a ship's hull is the sum total of all primary, secondary, and tertiary loads imposed on it from all factors. The typical test case for quick calculations is the middle of a hull bottom plate section between stiffeners, close to or at the midsection of the ship, somewhere midways between the keel and the side of the ship.

Standard rules

Ship classification societies such as Det Norske Veritas, American Bureau of Shipping, and Lloyd's Register have established standard calculation forms for hull loads, strength requirements, the thickness of hull plating and reinforcing stiffeners, girders, and other structures. These methods often give a quick and dirty way to estimate strength requirements for any given ship. Almost always those methods will give conservative, or stronger than precisely required, strength values. However, they provide a detailed starting point for analyzing a given ship's structure and whether it meets industry common standards or not.

Material response

Modern ships are, almost without exception, built of steel. Generally this is fairly standard steel with yield strength of around 32,000 to 36,000 psi (220 to 250 MPa), and tensile strength or **ultimate tensile strength (UTS)** over 50,000 psi (340 MPa).

Shipbuilders today use steels which have good corrosion resistance when exposed to seawater, and which do not get brittle at low temperatures (below freezing) since many ships are at sea during cold storms in wintertime, and some older ship steels which were not tough enough at low temperature caused ships to crack in half and sink during World War II in the Atlantic.

The benchmark steel grade is ABS A, specified by the American Bureau of Shipping. This steel has a yield strength of at least 34,000 psi (230 MPa), ultimate tensile strength of 58,000 to 71,000 psi (400 to 490 MPa), must elongate at least 19% in an 8-inch (200 mm) long specimen before fracturing and 22% in a 2-inch (50 mm) long specimen.

A safety factor above the yield strength has to be applied, since steel regularly pushed to its yield strength will suffer from metal fatigue. Steels typically have a **fatigue limit**, below which any quantity of stress load cycles will not cause metal fatigue and cracks/failures. Ship design criteria generally assume that all normal loads on the ship, times a moderate safety factor, should be below the fatigue limit for the steel used in their construction. It is wise to assume that the ship will regularly operate fully loaded, in heavy weather and strong waves, and that it will encounter its maximum normal design operating conditions many times over its lifetime.

Designing underneath the fatigue limit coincidentally and beneficially gives large (factor of up to 6 or more) total safety factors from normal maximum operating loads to ultimate tensile failure of the structure. But those large ultimate safety margins are not the intent: the intent is that the basic operational stress and strain on the ship, throughout its intended service life, should not cause serious fatigue cracks in the structure. Very few ships ever see ultimate load conditions anywhere near their gross failure limits. It is likely that, without fatigue concerns, ship strength requirements would be somewhat lower.

Numerical modeling

While it is possible to develop fairly accurate analyses of ship loads and responses by hand, or using minimal computer help such as spreadsheets, modern CAD computer programs are usually used today to generate much more detailed and powerful computer models of the structure. Finite element analysis tools are used to measure the behaviour in detail as loads are applied. These programs can handle much more complex bending and point load calculations than human engineers are able to do in reasonable amounts of time.

However, it is still important to be able to manually calculate rough behaviour of ship hulls. Engineers do not trust the output of computer programs without some general reality checking that the results are within the expected order of magnitude. And preliminary designs may be started before enough information on a structure is available to perform a computer analysis.

Chapter 13

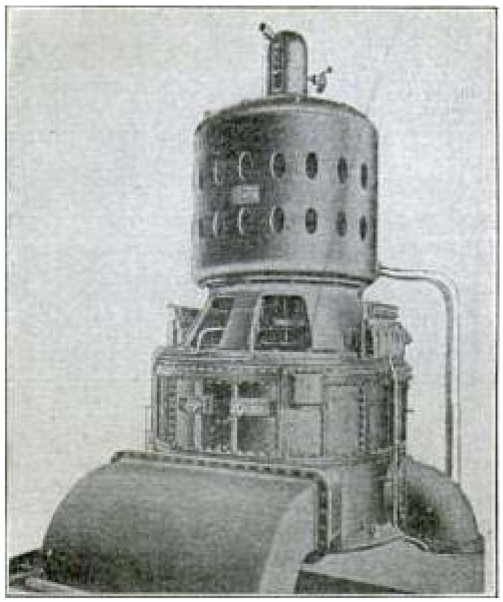
Steam Turbine

A rotor of a modern **steam turbine**, used in a power plant

A **steam turbine** is a mechanical device that extracts thermal energy from pressurized steam, and converts it into rotary motion. Its modern manifestation was invented by Sir Charles Parsons in 1884.

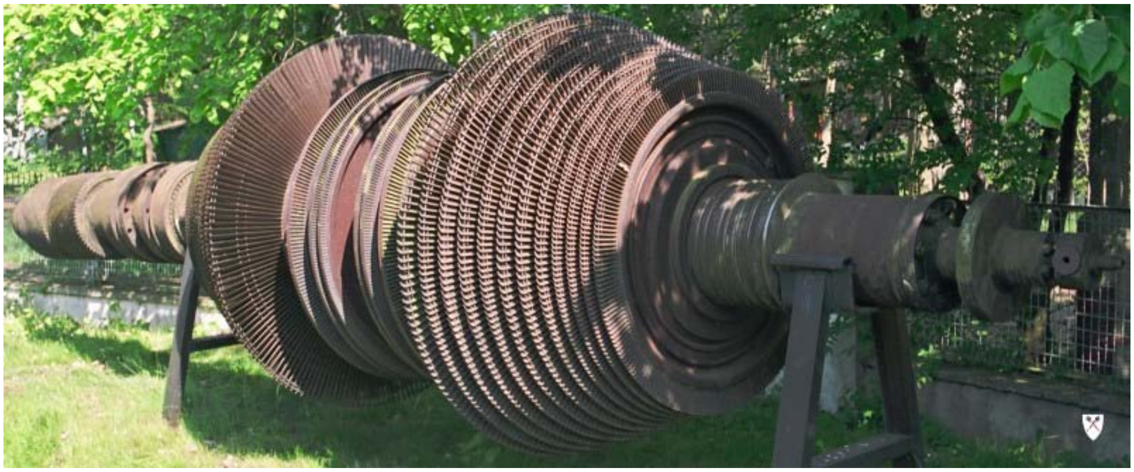
It has almost completely replaced the reciprocating piston steam engine primarily because of its greater thermal efficiency and higher power-to-weight ratio. Because the turbine generates rotary motion, it is particularly suited to be used to drive an electrical generator – about 80% of all electricity generation in the world is by use of steam turbines. The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency through the use of multiple stages in the expansion of the steam, which results in a closer approach to the ideal reversible process.

History



2000 KW Curtis steam turbine circa 1905.

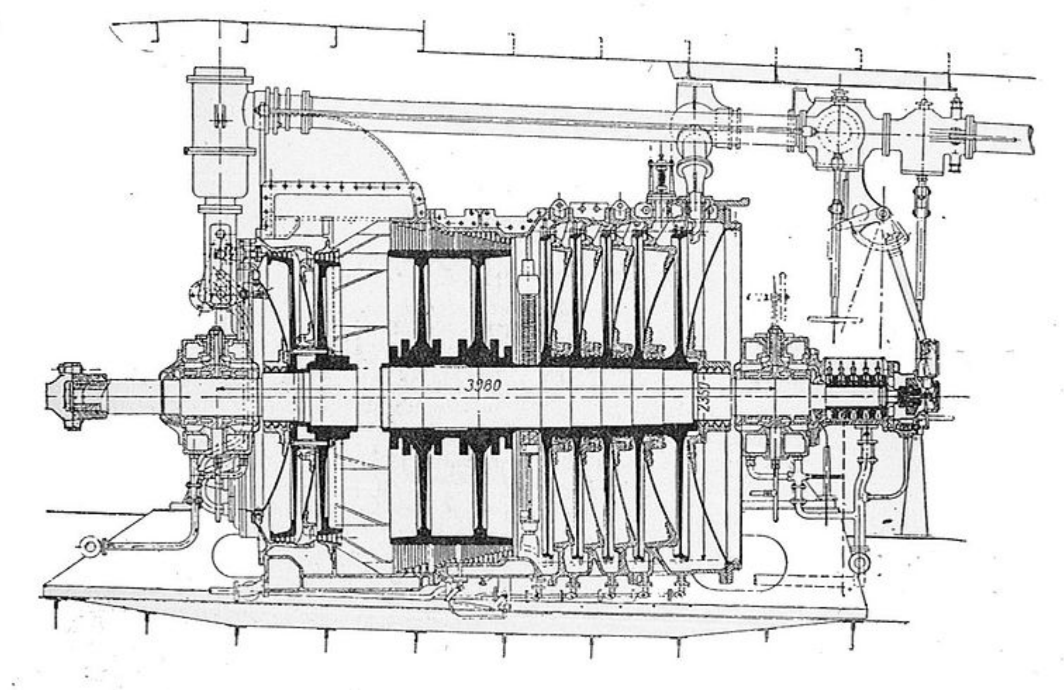
The first device that may be classified as a reaction steam turbine was little more than a toy, the classic Aeolipile, described in the 1st century by Greek mathematician Hero of Alexandria in Roman Egypt. More than a thousand years later, in 1543, Spanish naval officer Blasco de Garay used a primitive steam machine to move a ship in the port of Barcelona. In 1551, Taqi al-Din in Ottoman Egypt described a steam turbine with the practical application of rotating a spit. Steam turbines were also described by the Italian Giovanni Branca (1629) and John Wilkins in England (1648). The devices described by al-Din and Wilkins are today known as steam jacks.



Parsons turbine from the Polish destroyer ORP *Wicher*.

The modern steam turbine was invented in 1884 by the Englishman Sir Charles Parsons, whose first model was connected to a dynamo that generated 7.5 kW (10 hp) of electricity. The invention of Parson's steam turbine made cheap and plentiful electricity possible and revolutionised marine transport and naval warfare. His patent was licensed and the turbine scaled-up shortly after by an American, George Westinghouse. The Parson's turbine also turned out to be easy to scale up. Parsons had the satisfaction of seeing his invention adopted for all major world power stations, and the size of generators had increased from his first 7.5 kW set up to units of 50,000 kW capacity. Within Parson's lifetime the generating capacity of a unit was scaled up by about 10,000 times, and the total output from turbo-generators constructed by his firm C. A. Parsons and Company and by their licensees, for land purposes alone, had exceeded thirty million horse-power.

A number of other variations of turbines have been developed that work effectively with steam. The *de Laval turbine* (invented by Gustaf de Laval) accelerated the steam to full speed before running it against a turbine blade. Hence the (impulse) turbine is simpler, less expensive and does not need to be pressure-proof. It can operate with any pressure of steam, but is considerably less efficient.

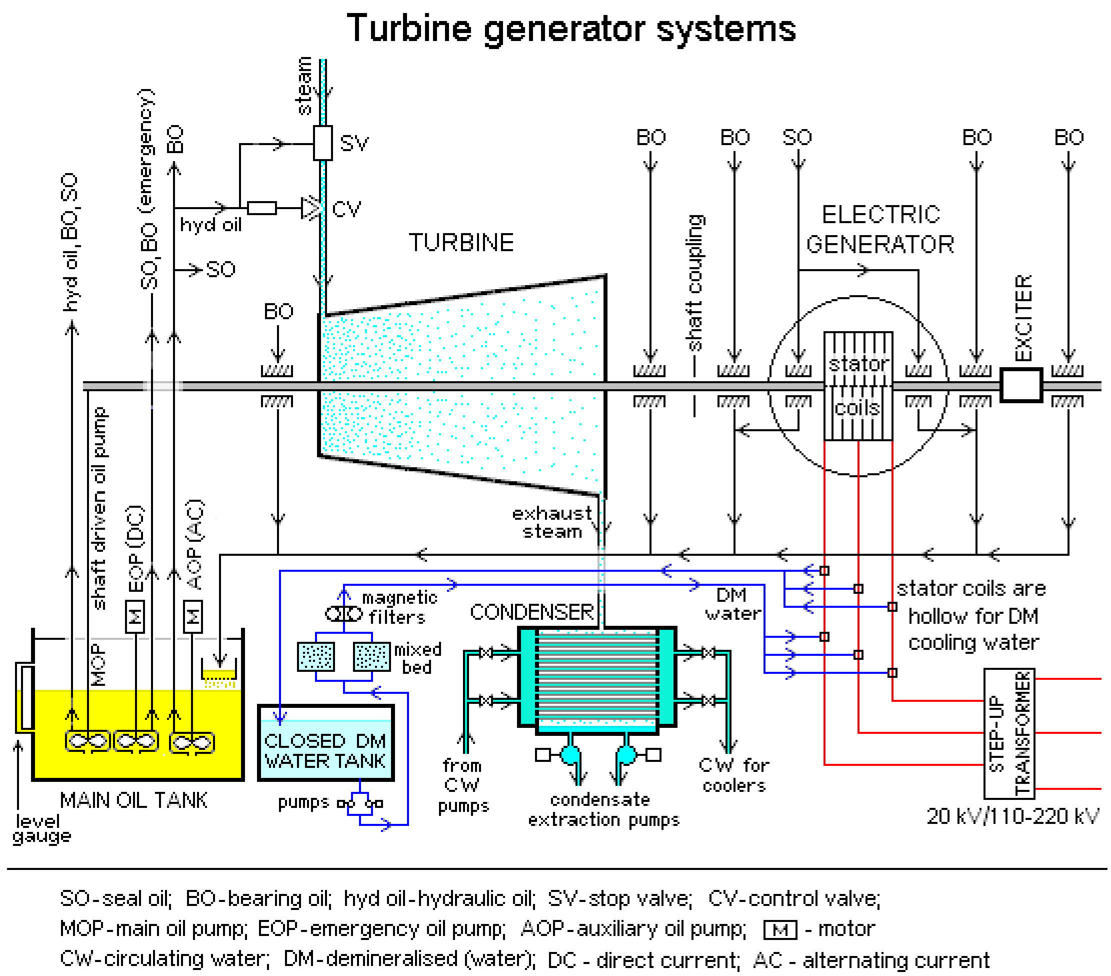


Cut away of an AEG marine steam turbine circa 1905

One of the founders of the modern theory of steam and gas turbines was also Aurel Stodola, a Slovak physicist and engineer and professor at Swiss Polytechnical Institute (now ETH) in Zurich. His mature work was *Die Dampfturbinen und ihre Aussichten als Wärmekraftmaschinen* (English The Steam Turbine and its perspective as a Heat Energy Machine) which was published in Berlin in 1903. In 1922, in Berlin, was published another important book *Dampf und Gas-Turbinen* (English Steam and Gas Turbines).

The *Brown-Curtis turbine* which had been originally developed and patented by the U.S. company International Curtis Marine Turbine Company was developed in the 1900s in conjunction with John Brown & Company. It was used in John Brown's merchant ships and warships, including liners and Royal Navy warships.

Types



Schematic operation of a steam turbine generator system

Steam turbines are made in a variety of sizes ranging from small <1 hp (<0.75 kW) units (rare) used as mechanical drives for pumps, compressors and other shaft driven equipment, to 2,000,000 hp (1,500,000 kW) turbines used to generate electricity. There are several classifications for modern steam turbines.

Steam supply and exhaust conditions

These types include condensing, noncondensing, reheat, extraction and induction.

Noncondensing or backpressure turbines are most widely used for process steam applications. The exhaust pressure is controlled by a regulating valve to suit the needs of the process steam pressure. These are commonly found at refineries, district heating units, pulp and paper plants, and desalination facilities where large amounts of low pressure process steam are available.

Condensing turbines are most commonly found in electrical power plants. These turbines exhaust steam in a partially condensed state, typically of a quality near 90%, at a pressure well below atmospheric to a condenser.

Reheat turbines are also used almost exclusively in electrical power plants. In a reheat turbine, steam flow exits from a high pressure section of the turbine and is returned to the boiler where additional superheat is added. The steam then goes back into an intermediate pressure section of the turbine and continues its expansion.

Extracting type turbines are common in all applications. In an extracting type turbine, steam is released from various stages of the turbine, and used for industrial process needs or sent to boiler feedwater heaters to improve overall cycle efficiency. Extraction flows may be controlled with a valve, or left uncontrolled.

Induction turbines introduce low pressure steam at an intermediate stage to produce additional power.

Mounting of a steam turbine produced by Siemens

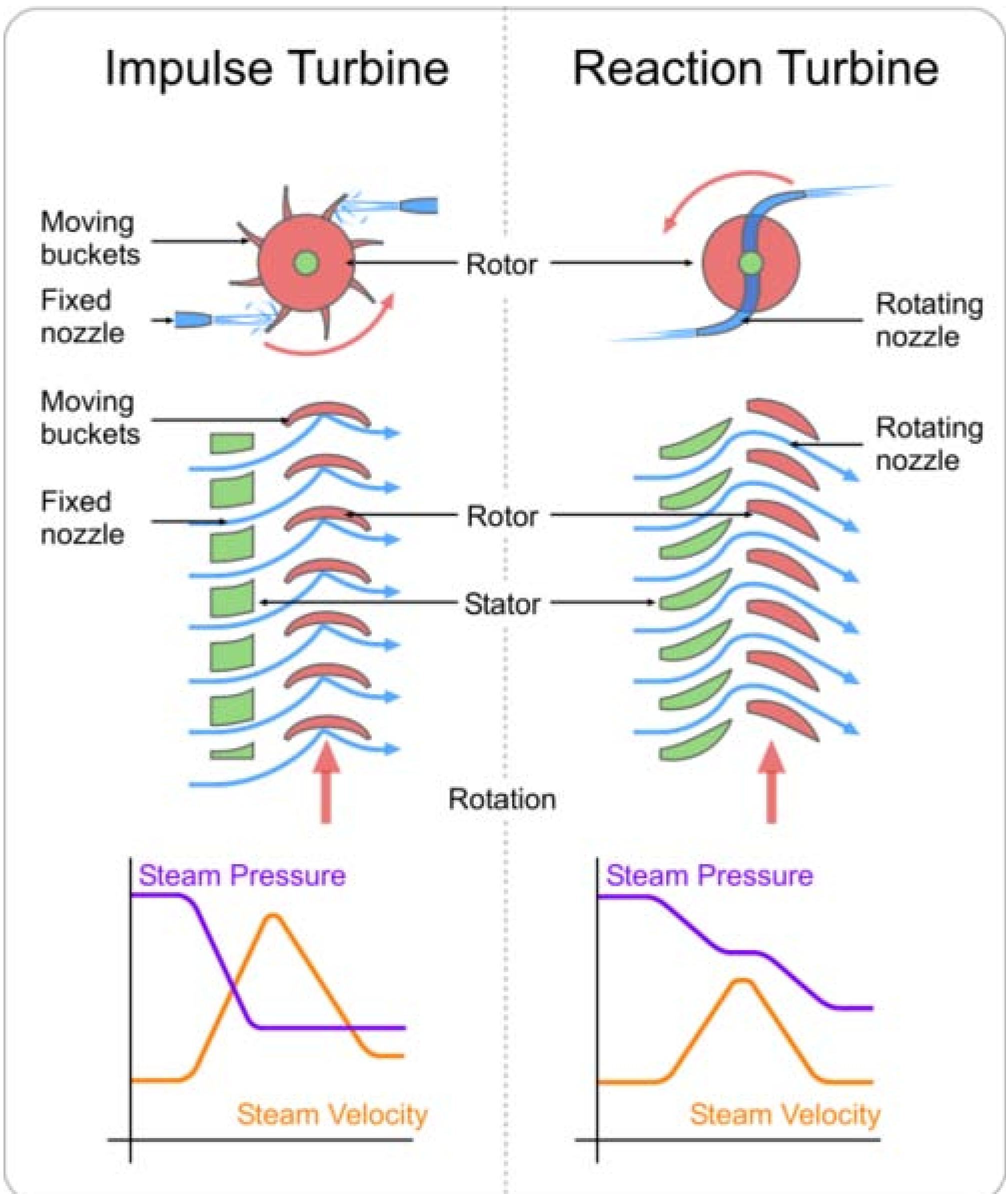
Casing or shaft arrangements

These arrangements include single casing, tandem compound and cross compound turbines. Single casing units are the most basic style where a single casing and shaft are coupled to a generator. Tandem compound are used where two or more casings are directly coupled together to drive a single generator. A cross compound turbine arrangement features two or more shafts not in line driving two or more generators that often operate at different speeds. A cross compound turbine is typically used for many large applications.

Principle of operation and design

An ideal steam turbine is considered to be an isentropic process, or constant entropy process, in which the entropy of the steam entering the turbine is equal to the entropy of the steam leaving the turbine. No steam turbine is truly "isentropic", however, with typical isentropic efficiencies ranging from 20%-90% based on the application of the turbine. The interior of a turbine comprises several sets of blades, or "buckets" as they are more commonly referred to. One set of stationary blades is connected to the casing and one set of rotating blades is connected to the shaft. The sets intermesh with certain minimum clearances, with the size and configuration of sets varying to efficiently exploit the expansion of steam at each stage.

Turbine efficiency



Schematic diagram outlining the difference between an impulse and a reaction turbine

To maximize turbine efficiency the steam is expanded, generating work, in a number of stages. These stages are characterized by how the energy is extracted from them and are known as either impulse or reaction turbines. Most steam turbines use a mixture of the reaction and impulse designs: each stage behaves as either one or the other, but the overall turbine uses both. Typically, higher pressure sections are impulse type and lower pressure stages are reaction type.

Impulse turbines

An **impulse turbine** has fixed nozzles that orient the steam flow into high speed jets. These jets contain significant kinetic energy, which the rotor blades, shaped like buckets, convert into shaft rotation as the steam jet changes direction. A pressure drop occurs across only the stationary blades, with a net increase in steam velocity across the stage.

As the steam flows through the nozzle its pressure falls from inlet pressure to the exit pressure (atmospheric pressure, or more usually, the condenser vacuum). Due to this higher ratio of expansion of steam in the nozzle the steam leaves the nozzle with a very high velocity. The steam leaving the moving blades has a large portion of the maximum velocity of the steam when leaving the nozzle. The loss of energy due to this higher exit velocity is commonly called the "carry over velocity" or "leaving loss".

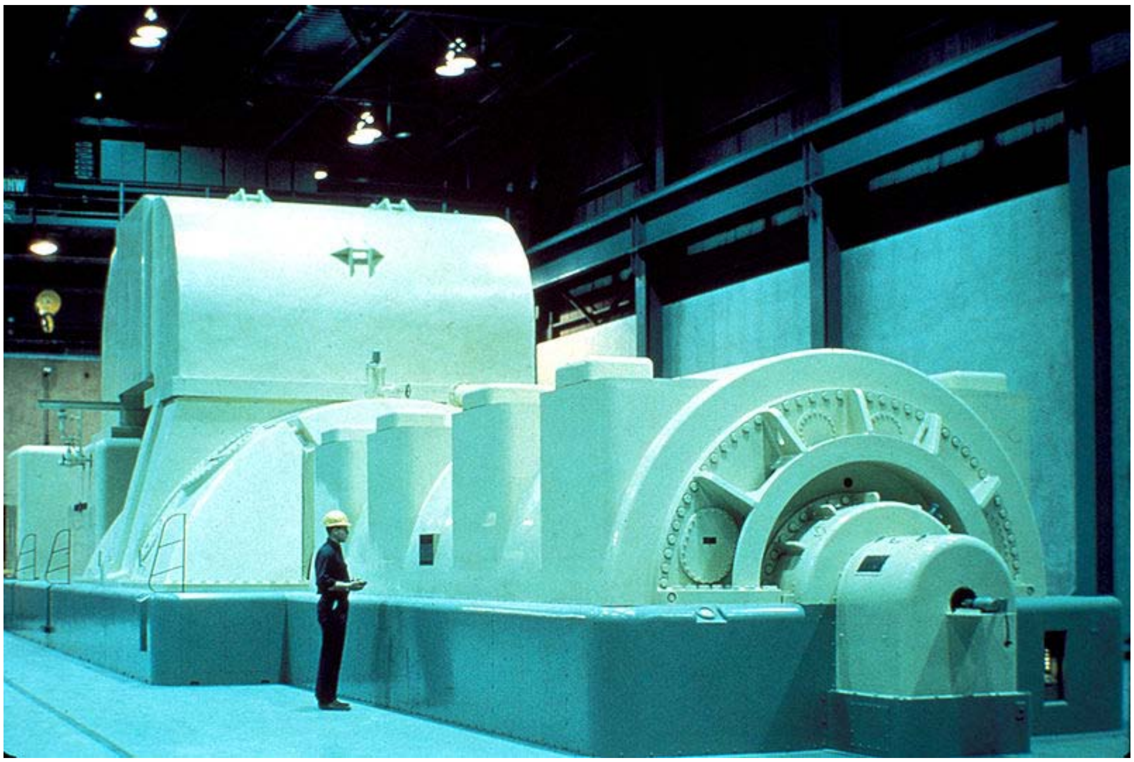
A selection of turbine blades

Reaction turbines

In the *reaction turbine*, the rotor blades themselves are arranged to form convergent nozzles. This type of turbine makes use of the reaction force produced as the steam accelerates through the nozzles formed by the rotor. Steam is directed onto the rotor by the fixed vanes of the stator. It leaves the stator as a jet that fills the entire circumference of the rotor. The steam then changes direction and increases its speed relative to the speed of the blades. A pressure drop occurs across both the stator and the rotor, with steam accelerating through the stator and decelerating through the rotor, with no net change in steam velocity across the stage but with a decrease in both pressure and temperature, reflecting the work performed in the driving of the rotor.

Operation and maintenance

When warming up a steam turbine for use, the main steam stop valves (after the boiler) have a bypass line to allow superheated steam to slowly bypass the valve and proceed to heat up the lines in the system along with the steam turbine. Also, a turning gear is engaged when there is no steam to the turbine to slowly rotate the turbine to ensure even heating to prevent uneven expansion. After first rotating the turbine by the turning gear, allowing time for the rotor to assume a straight plane (no bowing), then the turning gear is disengaged and steam is admitted to the turbine, first to the astern blades then to the ahead blades slowly rotating the turbine at 10 to 15 RPM to slowly warm the turbine.



A modern steam turbine generator installation

Problems with turbines are now rare and maintenance requirements are relatively small. Any imbalance of the rotor can lead to vibration, which in extreme cases can lead to a blade letting go and punching straight through the casing. It is, however, essential that the turbine be turned with dry steam - that is, superheated steam with a minimal liquid water content. If water gets into the steam and is blasted onto the blades (moisture carryover) rapid impingement and erosion of the blades can occur, possibly leading to imbalance and catastrophic failure. Also, water entering the blades will likely result in the destruction of the thrust bearing for the turbine shaft. To prevent this, along with controls and baffles in the boilers to ensure high quality steam, condensate drains are installed in the steam piping leading to the turbine.

Speed regulation

The control of a turbine with a governor is essential, as turbines need to be run up slowly, to prevent damage while some applications (such as the generation of alternating current electricity) require precise speed control. Uncontrolled acceleration of the turbine rotor can lead to an overspeed trip, which causes the nozzle valves that control the flow of steam to the turbine to close. If this fails then the turbine may continue accelerating until it breaks apart, often spectacularly. Turbines are expensive to make, requiring precision manufacture and special quality materials. During normal operation in synchronization with the electricity network, power plants are governed with a five percent droop speed control. This means the full load speed is 100% and the no-load speed is 105%. This is required for the stable operation of the network without hunting and drop-outs of power plants. Normally the changes in speed are minor. Adjustments in power output are made by slowly raising the droop curve by increasing the spring pressure on a centrifugal governor. Generally this is a basic system requirement for all power plants because the older and newer plants have to be compatible in response to the instantaneous changes in frequency without depending on outside communication.

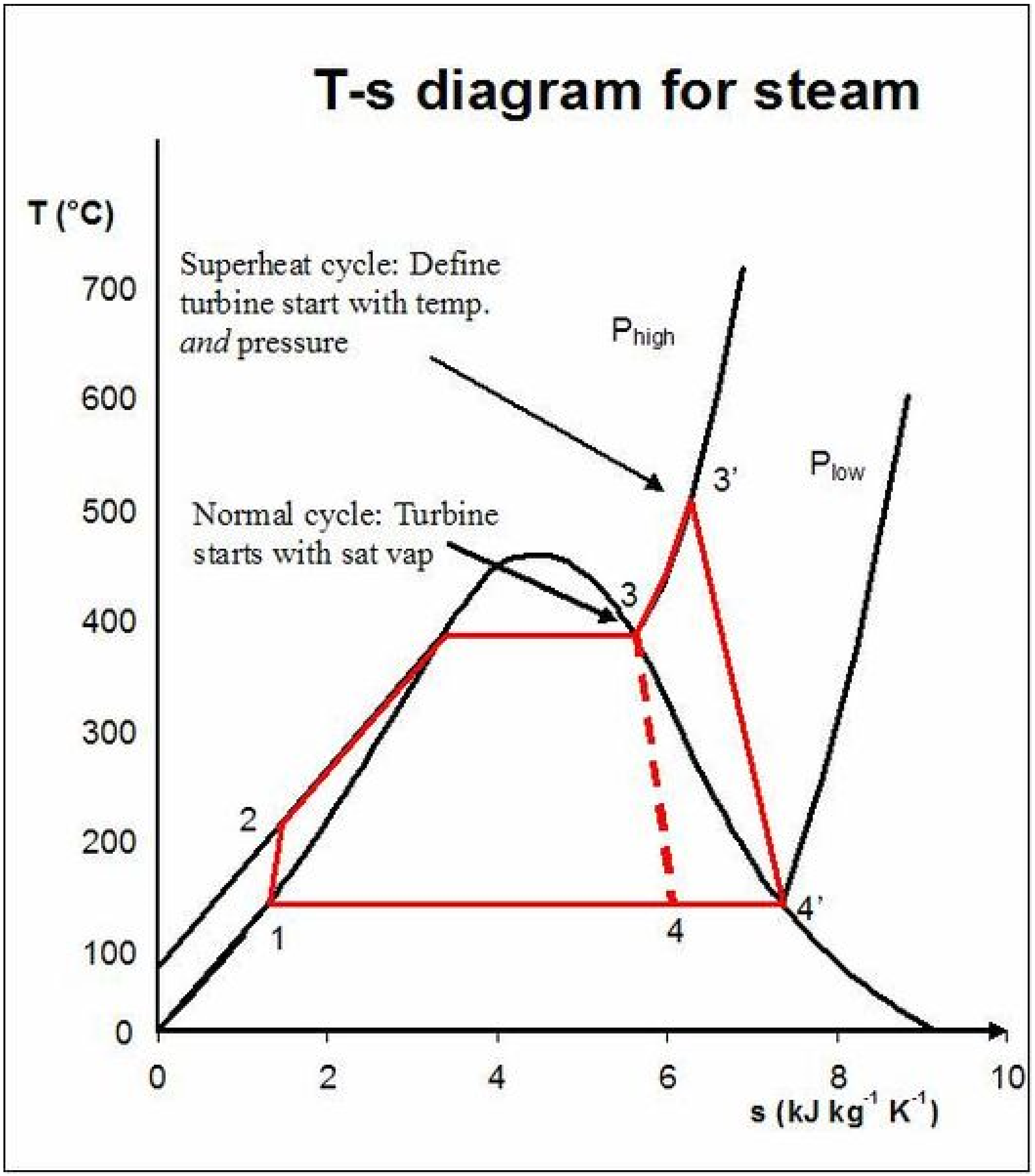
Thermodynamics of steam turbines

The steam turbine operates on basic principles of thermodynamics using the part of the Rankine cycle. Superheated vapor (or dry saturated vapor, depending on application) enters the turbine, after it having exited the boiler, at high temperature and high pressure. The high heat/pressure steam is converted into kinetic energy using a nozzle (a fixed nozzle in an impulse type turbine or the fixed blades in a reaction type turbine). Once the steam has exited the nozzle it is moving at high velocity and is sent to the blades of the turbine. A force is created on the blades due to the pressure of the vapor on the blades causing them to move. A generator or other such device can be placed on the shaft and the energy that was in the vapor can now be stored and used. The gas exits the turbine as a saturated vapor (or liquid-vapor mix depending on application) at a lower temp and pressure than it enter with and is sent to the condenser to be cooled. If we look at the first law we can find an equation comparing the rate at which work is developed per unit mass. Assuming there is no heat transfer to the surrounding environment and that the change in kinetic and potential energy is negligible when compared to the change in specific entropy we come up with the following equation

$$\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$$

- $\dot{\mathbf{W}}_t$ is the rate at which work is developed per unit time
- $\dot{\mathbf{m}}$ is the rate of mass flow through the turbine

Isentropic turbine efficiency



Rankine cycle with superheat
Process 1-2: The working fluid is pumped from low to high pressure.
Process 2-3: The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor.
Process 3-3': The vapour is superheated.
Process 3-4 and 3'-4': The dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur.
Process 4-1: The wet vapor then enters a condenser where it is condensed at a constant pressure to become a saturated liquid.

To measure how well a turbine is performing we can look at the isentropic efficiency. Isentropic efficiencies involve a comparison between the actual performance of a device and the performance that would be achieved under idealized circumstances. When calculating the isentropic efficiency heat to the surroundings is assumed to be zero. The starting pressure and temperature is the same for both the isentropic and actual efficiency. Since state 1 is the same for both efficiencies, the specific enthalpy h_1 is known. The specific entropy for the isentropic process is greater than the specific entropy for the actual process due to irreversibility in the process. The specific entropy is evaluated at the same pressure for the actual and isentropic processes in order to give a good comparison between the two.

The isentropic efficiency is given to us as the actual work divided by the maximum work that could be achieved if there were no irreversibly in the process.

$$\eta_t = \frac{\dot{W}_{cv}/\dot{m}}{\dot{W}_{cv}/\dot{m}} = \frac{h_1 - h_2}{h_1 - h_{2s}}.$$

- h_1 is the specific enthalpy at state one
- h_2 is the specific enthalpy at state two for an actual process
- h_{2s} is the specific enthalpy at state two for an isentropic process

Calculating turbine efficiency

The efficiency of the steam turbine can be calculated by using the Kelvin statement of the Second law of Thermodynamics.

$$\eta = \frac{W_{cycle}}{Q_H}.$$

- W_{cycle} is the Work done during one cycle
- Q_H is the Heat transfer received from the heat source

If we look at the Carnot cycle the maximum efficiency of a steam turbine can be calculated. This efficiency can never be achieved in the real world due to irreversibility during the process, but it does give a good measure as to how a particular turbine is performing.

$$\eta = 1 - \frac{T_L}{T_H}.$$

- T_L is the absolute temperature of the vapor moving out of the turbine
- T_H is the absolute temperature of the vapor coming from the boiler

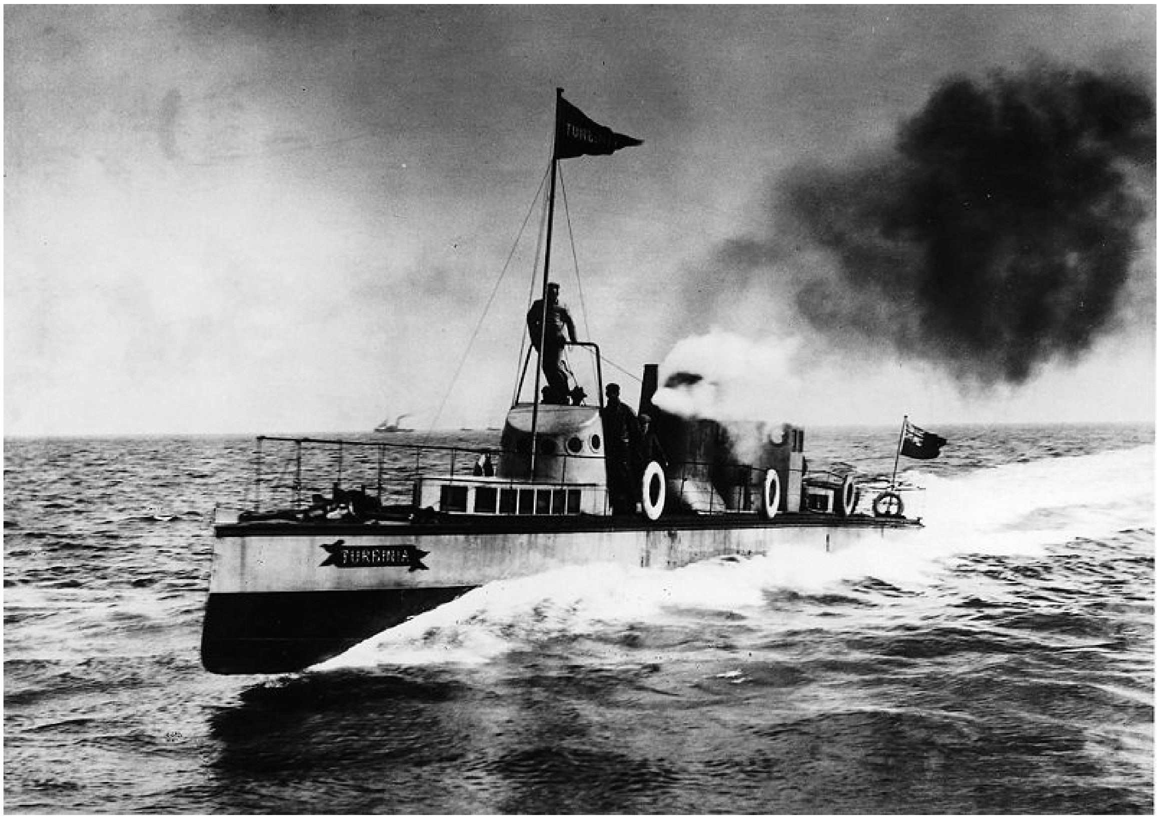
Direct drive

A small industrial steam turbine (right) directly linked to a generator (left). This turbine generator set of 1910 produced 250 kW of electrical power.

Electrical power stations use large steam turbines driving electric generators to produce most (about 80%) of the world's electricity. The advent of large steam turbines made central-station electricity generation practical, since reciprocating steam engines of large rating became very bulky, and operated at slow speeds. Most central stations are fossil fuel power plants and nuclear power plants; some installations use geothermal steam, or use concentrated solar power (CSP) to create the steam. Steam turbines can also be used directly to drive large centrifugal pumps, such as feedwater pumps at a thermal power plant.

The turbines used for electric power generation are most often directly coupled to their generators. As the generators must rotate at constant synchronous speeds according to the frequency of the electric power system, the most common speeds are 3000 RPM for 50 Hz systems, and 3600 RPM for 60 Hz systems. Since nuclear reactors have lower temperature limits than fossil-fired plants, with lower steam quality, the turbine generator sets may be arranged to operate at half these speeds, but with four-pole generators, to reduce erosion of turbine blades.

Marine propulsion



The *Turbinia*, 1894, the first steam turbine-powered ship

In ships, compelling advantages of steam turbines over reciprocating engines are smaller size, lower maintenance, lighter weight, and lower vibration. A steam turbine is only efficient when operating in the thousands of RPM, while the most effective propeller designs are for speeds less than 100 RPM; consequently, precise (thus expensive) reduction gears are usually required, although several ships, such as *Turbinia*, had direct drive from the steam turbine to the propeller shafts. Another alternative is turbo-electric drive, where an electrical generator run by the high-speed turbine is used to run one or more slow-speed electric motors connected to the propeller shafts; precision gear cutting may be a production bottleneck during wartime. The purchase cost is offset by much lower fuel and maintenance requirements and the small size of a turbine when compared to a reciprocating engine having an equivalent power. However, diesel engines are capable of higher efficiencies: propulsion steam turbine cycle efficiencies have yet to break 50%, yet diesel engines routinely exceed 50%, especially in marine applications.

Nuclear-powered ships and submarines use a nuclear reactor to create steam. Nuclear power is often chosen where diesel power would be impractical (as in submarine applications) or the logistics of refuelling pose significant problems (for example, icebreakers). It has been estimated that the reactor fuel for the Royal Navy's Vanguard class submarine is sufficient to last 40 circumnavigations of the globe – potentially sufficient for the vessel's entire service life. Nuclear propulsion has only been applied to a very few commercial vessels due to the expense of maintenance and the regulatory controls required on nuclear fuel cycles.

Locomotives

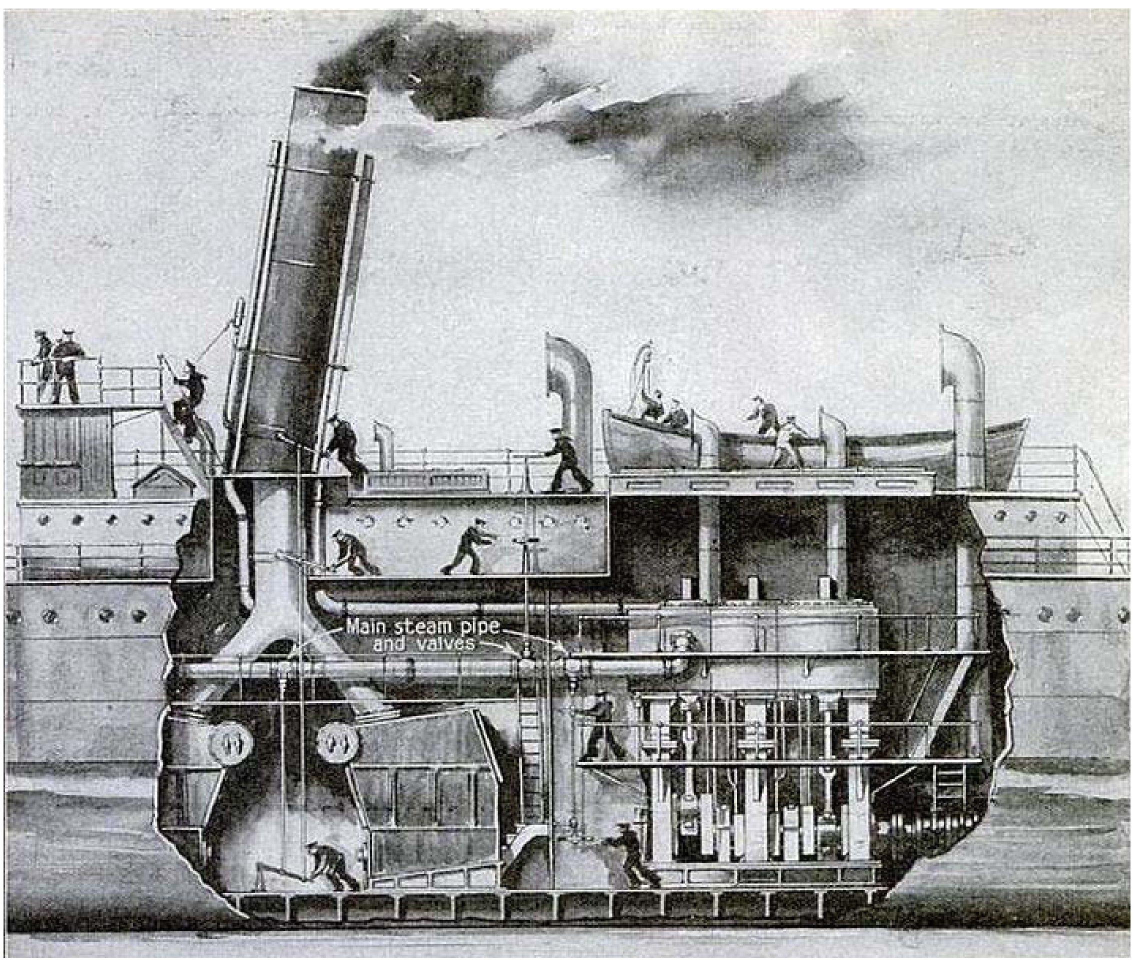
A steam turbine locomotive engine is a steam locomotive driven by a steam turbine.

The main advantages of a steam turbine locomotive are better rotational balance and reduced hammer blow on the track. However, a disadvantage is less flexible power output power so that turbine locomotives were best suited for long-haul operations at a constant output power.

The first steam turbine rail locomotive was built in 1908 for the Officine Meccaniche Miani Silvestri Grodona Comi, Milan, Italy. In 1924 Krupp built the steam turbine locomotive T18 001, operational in 1929, for Deutsche Reichsbahn.

Chapter 14

Marine Steam Engine



Period cut away diagram of a triple expansion steam engine installation, circa 1918

A **marine steam engine** is a reciprocating steam engine that is used to power a ship or boat. Steam turbines and diesel engines largely replaced reciprocating steam engines in marine applications during the 20th century, so this chapter describes the more common types of marine steam engine in use from their inception in the early 19th century to their last years of large-scale manufacture during World War II.

History

The first commercially successful steam engine was developed by Thomas Newcomen in 1712. However, successful adaptation of the steam engine to marine applications would have to wait until almost a century later, when Scottish engineer William Symington built the world's "first practical steamboat", the *Charlotte Dundas*, in 1802. In 1807, the American Robert Fulton built the world's first commercially successful steamboat, simply known as the *North River Steamboat*.

Following Fulton's success, steamboat technology developed rapidly on both sides of the Atlantic. Steamboats initially had a short range and were not particularly seaworthy due to their weight, lack of horsepower, and tendency to break down, but they were employed successfully along rivers and canals, and for short journeys along the coast. The first successful transatlantic crossing by a steamship occurred in 1819 when *Savannah* sailed from Savannah, Georgia to Liverpool, England. The first steamship to make regular transatlantic crossings was the sidewheel steamer *Great Western* in 1838.

As the 19th century progressed, marine steam engine and steamship technology developed alongside it. Paddle propulsion gradually gave way to the screw propeller, and the introduction of iron and later steel hulls to replace the traditional wooden hull allowed ships to grow ever larger, necessitating steam power plants that were increasingly complex and powerful.

Types of marine steam engine

A wide variety of reciprocating marine steam engines was developed over the course of the 19th century. The two main methods of classifying such engines are by *connection mechanism* and *cylinder technology*.

Most early marine engines had the same cylinder technology but a number of different methods of supplying power to the crankshaft (i.e. connection mechanism) were in use. Thus, early marine engines are classified mostly according to their connection mechanism. Some common connection mechanisms were side-lever, steeple, walking beam and direct-acting.

However, steam engines can also be classified according to their cylinder technology (simple expansion, compound, annular etc.). One can therefore sometimes find examples of engines which were classified under both methods, such as the compound walking beam (*compound* being the cylinder technology and *walking beam* being the connection method). Over time, as most engines became direct-acting but cylinder technologies were growing more complex, engines began to be classified solely according to their cylinder technology instead.

Some of the more commonly encountered types of marine steam engine are listed in the following sections. Note that not all of these terms may have been used exclusively in relation to marine applications.

Engines classified by connection mechanism

Side-lever

The side-lever engine was the first type of steam engine to be widely adopted for marine use in Europe. In the early years of steam navigation, the side-lever was the most common type of marine engine for inland waterway and coastal service in Europe, and it remained for many years the preferred engine for oceangoing service on both sides of the Atlantic.

The side-lever was an adaptation of the earliest form of steam engine, the beam engine. Each cylinder of a side-lever engine operated a pair of heavy horizontal iron beams, known as side levers, located on each side of the cylinder near the cylinder base. The side levers were each secured by a pin in the centre which acted as a fulcrum. The far end of each lever was attached to a connecting rod which rotated the crankshaft as the levers rocked up and down around the central pin.

The main disadvantages of the side-lever engine were that it was large and heavy, and for inland waterway and coastal service, it was soon replaced by lighter and more efficient designs. It remained the dominant engine type for oceangoing service through much of the first half of the 19th century however, due to its relatively low centre of gravity which gave ships more stability in heavy seas. It was also a common early engine type for warships, since its relatively low height made it less susceptible to battle damage.

The side-lever engine was a paddlewheel engine and was not suitable for driving screw propellers. The last ship built for transatlantic service to be fitted with a side-lever engine was the Cunard Line's paddle steamer RMS *Scotia*, considered an anachronism when it entered service in 1862.

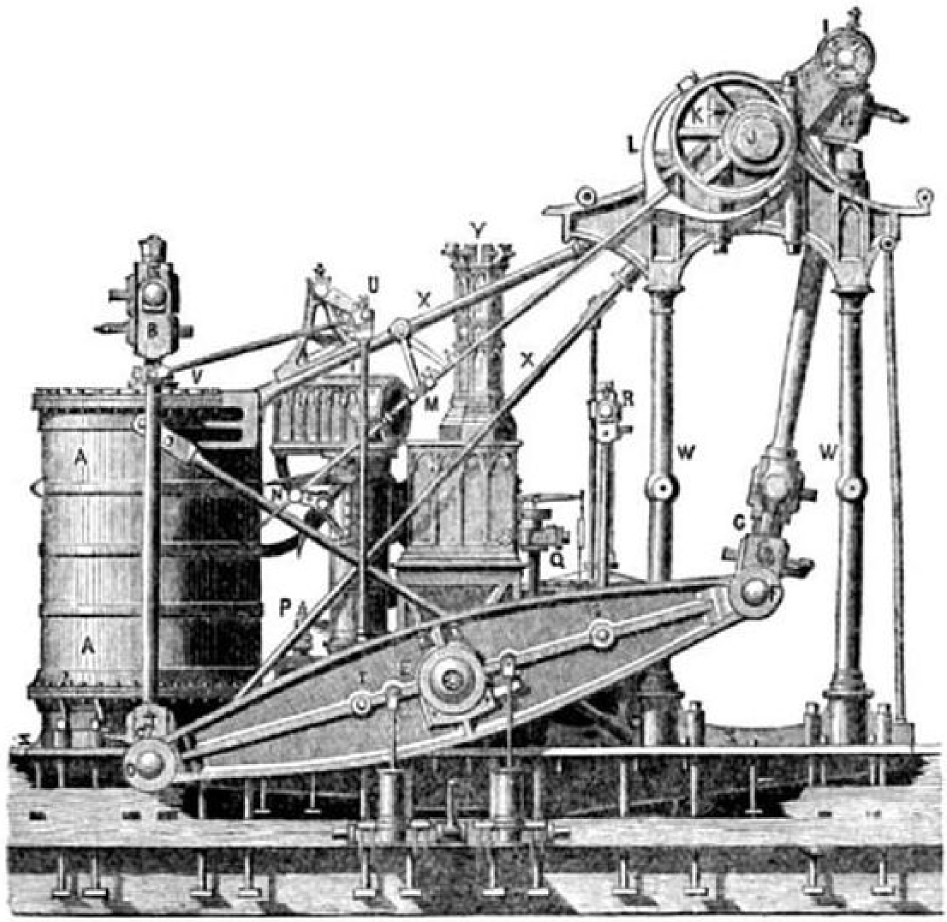
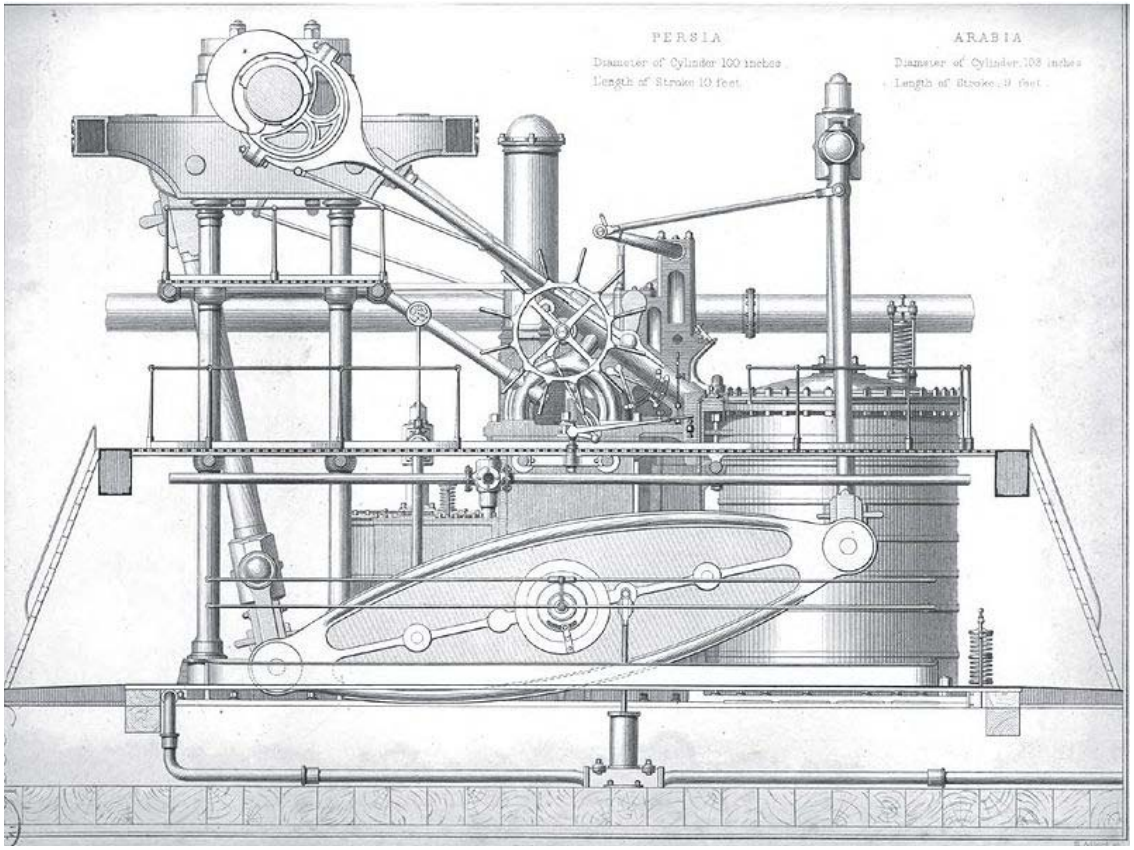


FIG. 92.—The Side-Lever Engine, 1849.

Side-lever engine of SS *Pacific* (1849)



Side-lever engine of RMS *Persia* (1855)

Early Napier side-lever engine from PS *Leven*, on display at Dumbarton, Scotland

Grasshopper

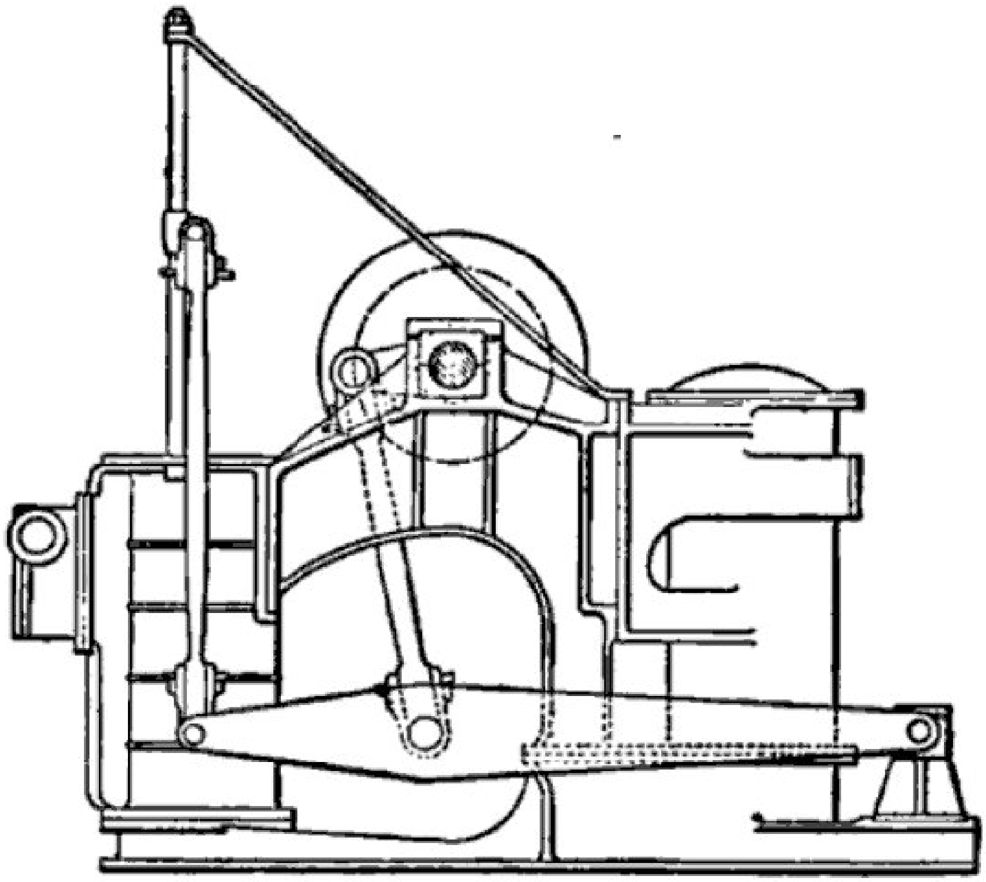


Fig. 3.—" Grasshopper " Engine.

Diagram of a grasshopper engine

The **grasshopper** engine was a variant of the side-lever engine. The grasshopper engine differs from the conventional side-lever in that the location of the lever fulcrum and connecting rod are more or less reversed, with the fulcrum located at one end of the lever instead of the centre, while the connecting rod is attached to the lever between the cylinder at one end and the fulcrum at the other.

Chief advantages of the grasshopper engine were cheapness of construction and robustness, with the type said to require less maintenance than any other type of marine steam engine. Another advantage is that the engine could be easily started from any crank position. Like the conventional side-lever engine however, grasshopper engines were disadvantaged by their weight and size. They were mainly used in small watercraft such as riverboats and tugs.

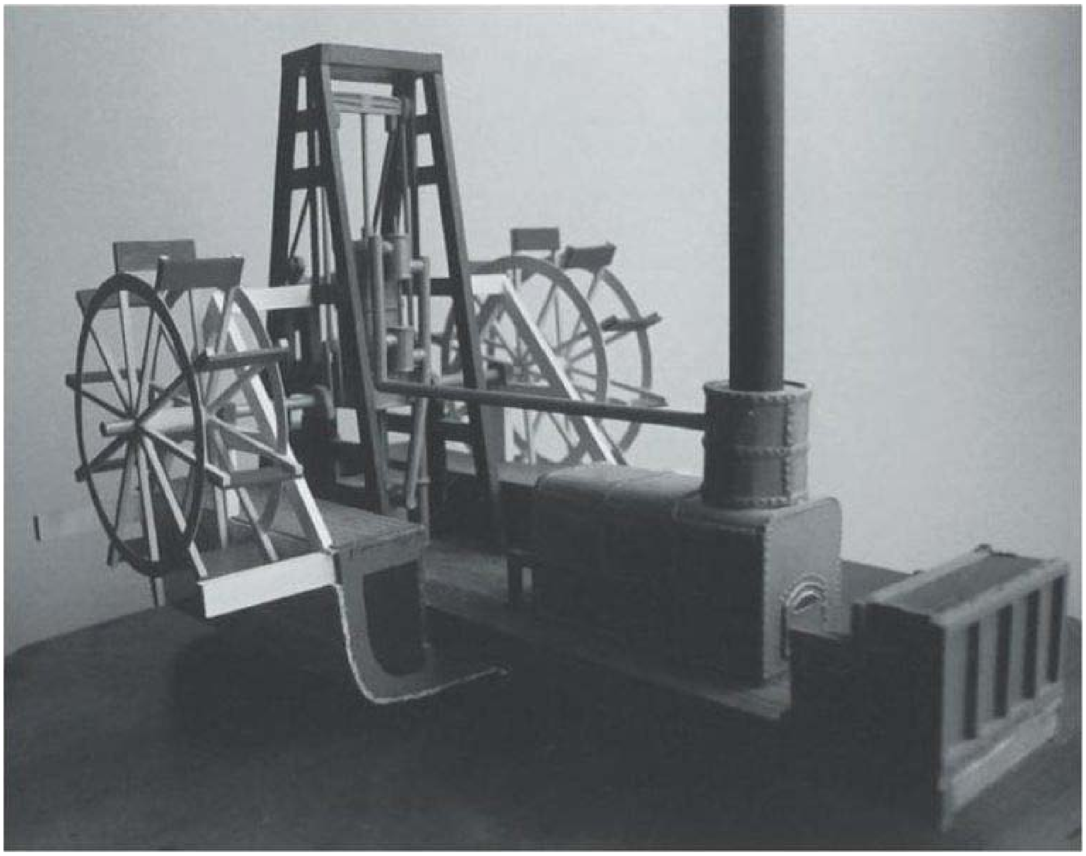
Crosshead (square)

The crosshead engine, also known as a **square**, **sawmill** or **A-frame** engine, was a type of paddlewheel engine used in the United States. It was the most common type of engine in the early years of American steam navigation.

The crosshead engine is described as having a vertical cylinder above the crankshaft, with the piston rod secured to a horizontal crosshead, from each end of which, on opposite sides of the cylinder, extended a connecting rod which rotated its own separate crankshaft. The crosshead operated within vertical guides that enabled the assembly to maintain the correct path as it moved. The engine's alternative name "A-frame" presumably derived from the shape of the frames supporting these guides. Some crosshead engines had more than one cylinder, in which case the piston rods were usually all connected to the same crosshead. An unusual feature of early examples of this type of engine was the installation of flywheels—geared to the crankshafts—which were thought necessary to ensure smooth operation. These gears could apparently be very noisy in operation.

Because the cylinder was placed above the crankshaft in this type of engine, it had a high center of gravity and was therefore deemed unsuitable for oceangoing service, so that its use was largely confined to vessels plying inland waterways. As marine engines grew steadily larger and heavier through the course of the century, the high center of gravity of square crosshead engines became increasingly impractical, leading to their abandonment by the 1840s in favor of the walking beam engine.

The name of this engine can sometimes lead to confusion as "crosshead" is also an alternative name for the steeple engine (see below). Many sources thus prefer to refer to it by its informal name of "square" engine to avoid confusion. Additionally, the marine crosshead or square engine described in this section should not be confused with the term "square engine" as applied to combustion engines, which in the latter case refers to an engine whose bore is equal to its stroke.



Model of a crosshead or "square" engine, showing location of engine cylinder above the crankshaft; also piston rod, crosshead, connecting rods and paddlewheels

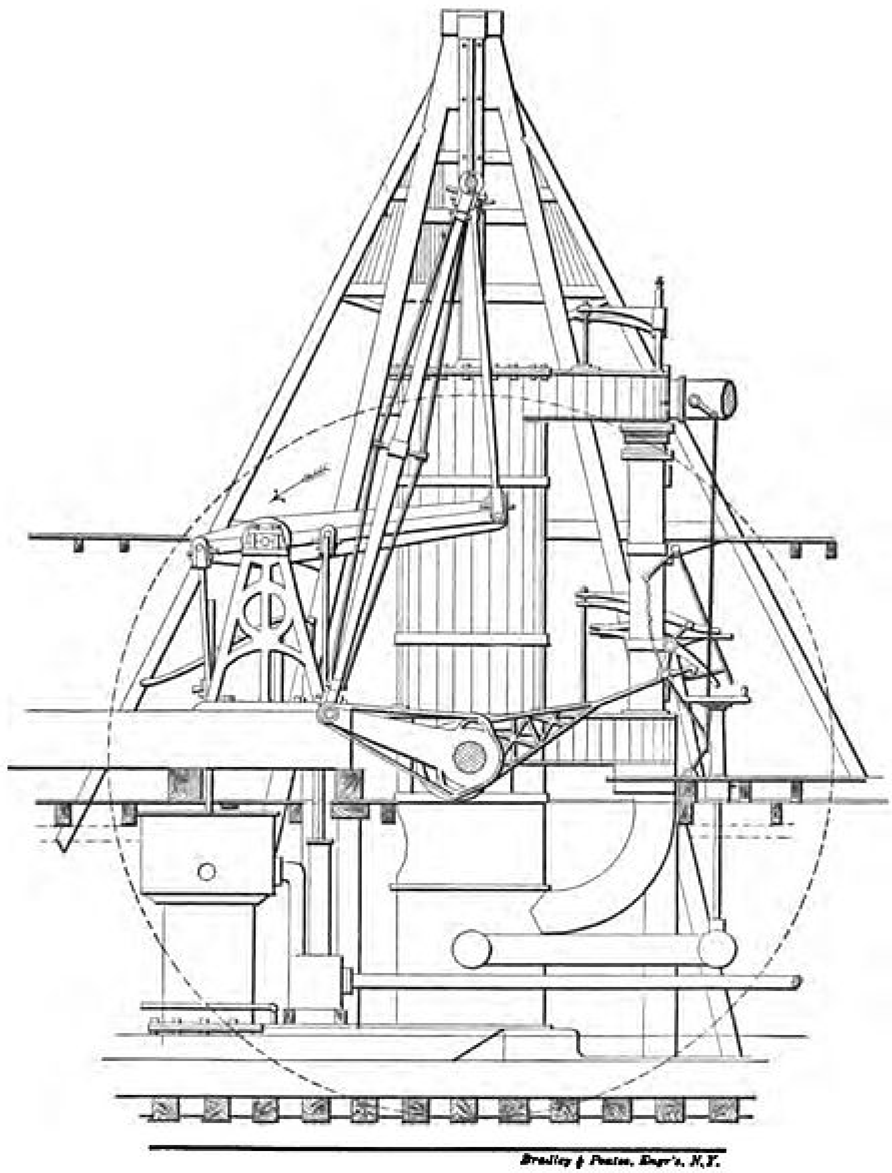
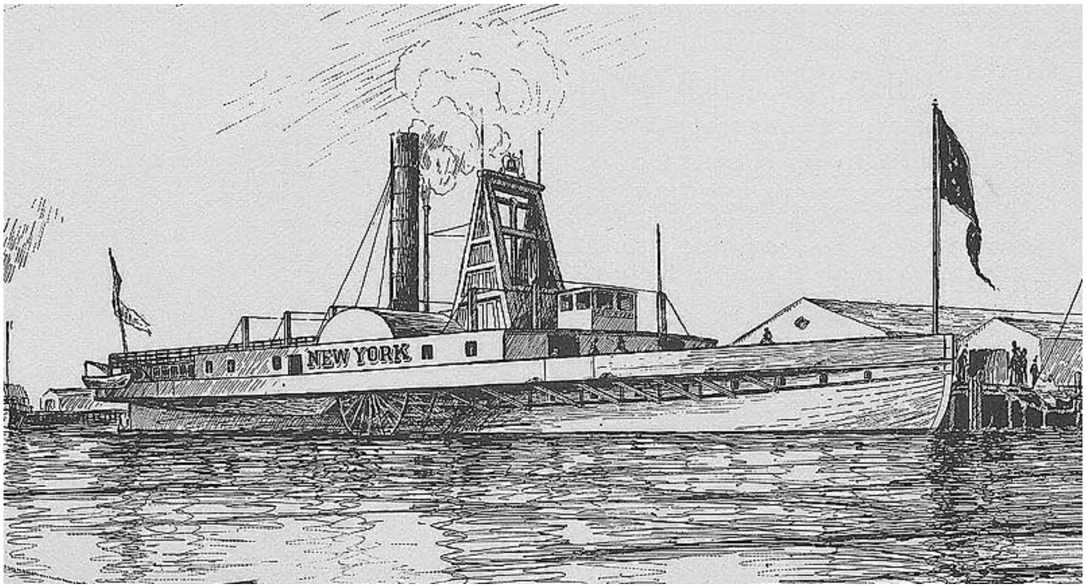


Diagram of a typical Hudson River steamboat crosshead engine (side view)



The 1836 paddle steamer *New York*. Between the paddlewheels is the tall square or "A-frame" engine, within which can be seen the long piston rod, near the top of its stroke, making a "T" with the horizontal crosshead

Walking beam

The walking beam, also known as a "vertical beam", "overhead beam", or simply "beam", was another early adaptation of the beam engine, but its use was confined almost entirely to the United States. After its introduction, the walking beam quickly became the most popular engine type in America for inland waterway and coastal service, and the type proved to have remarkable longevity, with walking beam engines still being occasionally manufactured as late as the 1940s. In marine applications, the beam itself was generally reinforced with iron struts that gave it a characteristic diamond shape, although the supports on which the beam rested were often built of wood. The adjective "walking" was applied because the beam, which rose high above the ship's deck, could be seen operating, and its rocking motion was (somewhat fancifully) likened to a walking motion.

Walking beam engines were a type of paddlewheel engine and were rarely used for powering propellers. They were used primarily for ships and boats working in rivers, lakes and along the coastline, but were a less popular choice for seagoing vessels because the great height of the engine made the vessel less stable in heavy seas. They were also unsuitable for military use, because the engine was exposed to enemy fire and could thus be easily disabled. Their popularity in the United States was due primarily to the fact that the walking beam engine was well suited for the shallow-draft boats which operated in America's shallow coastal and inland waterways.

Walking beam engines remained popular with American shipping lines right to the end of the 19th century. The Philadelphian shipbuilder Charles H. Cramp blamed America's general lack of competitiveness with the British shipbuilding industry in the mid-to-late 19th century upon the conservatism of American domestic shipbuilders and shipping line owners, who doggedly clung to outdated technologies like the walking beam and its associated paddlewheel long after they had been abandoned in other parts of the world.

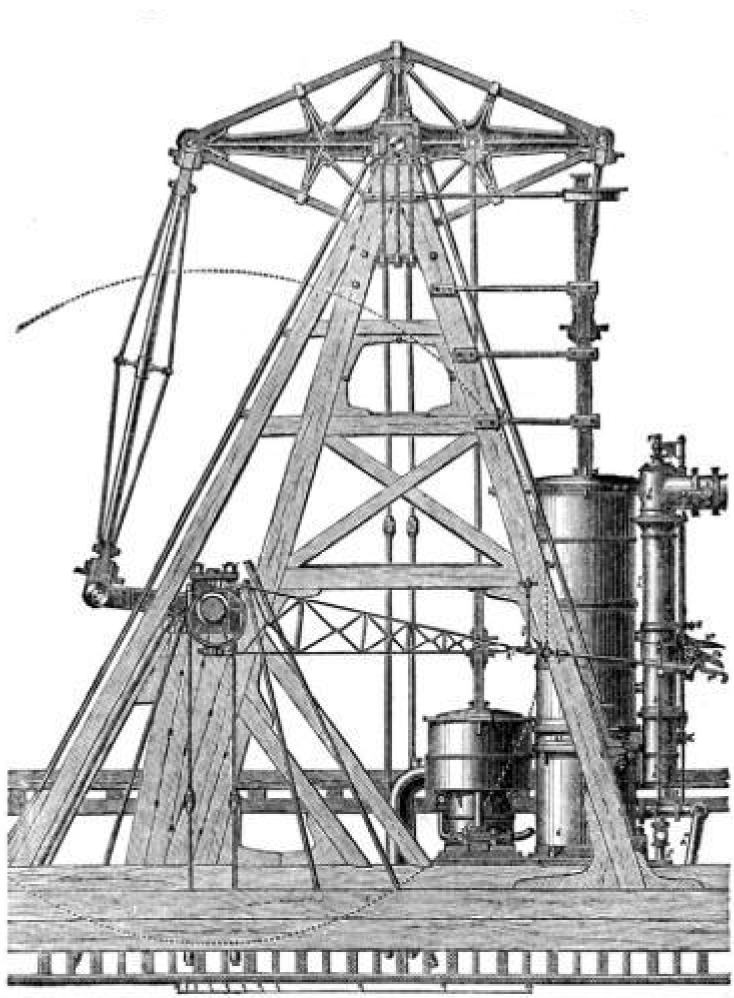
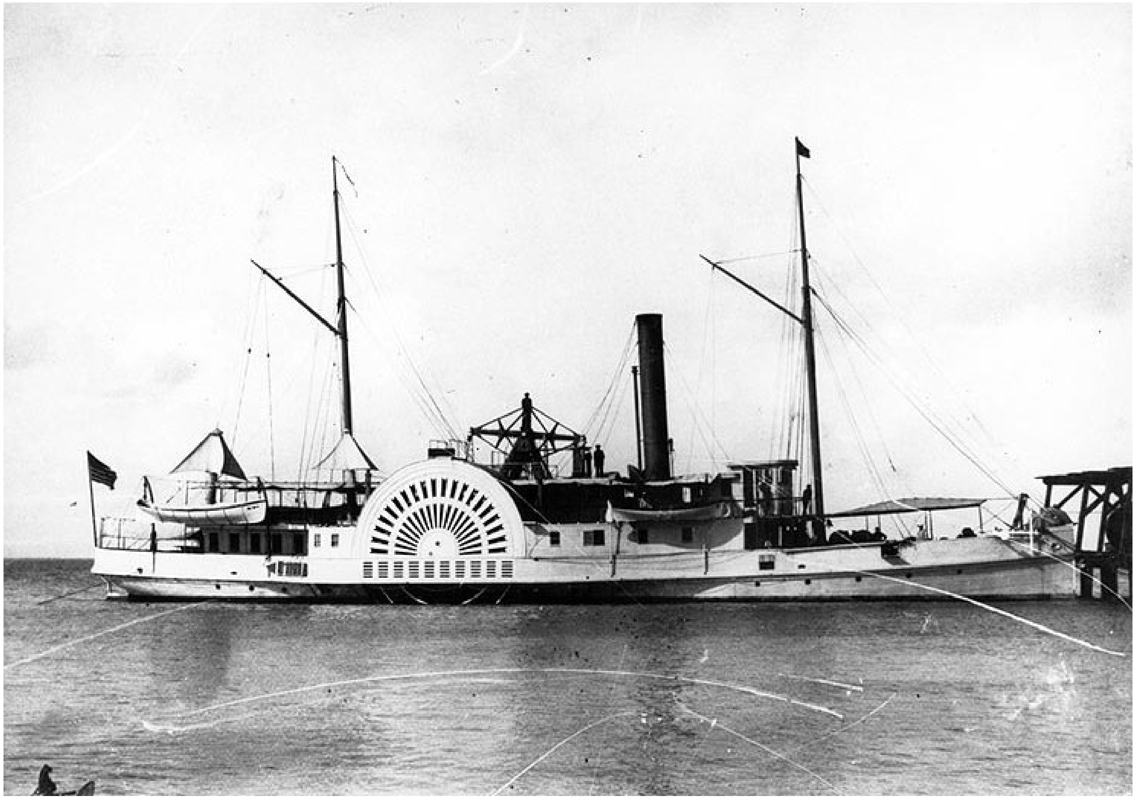


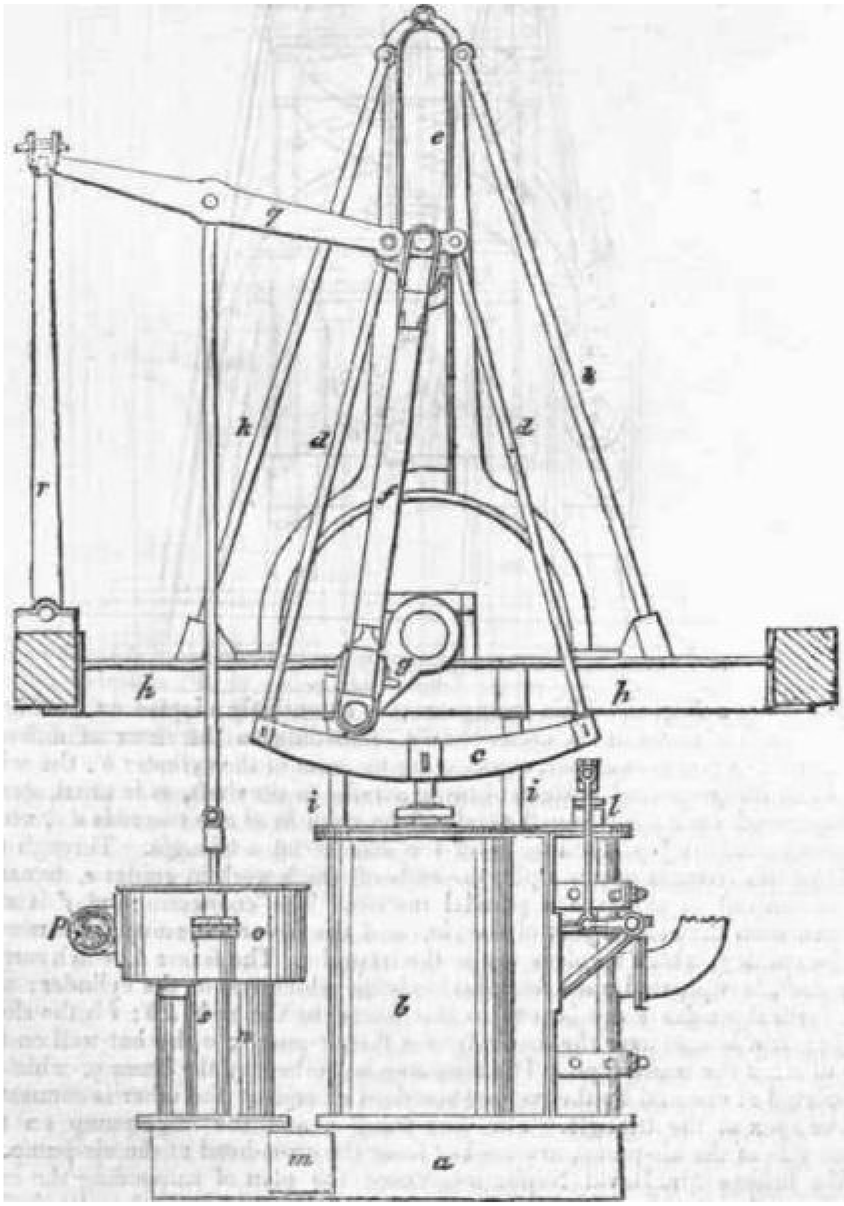
Fig. 180.—Beam-Engine.

Basic diagram of a walking beam engine



USS *Delaware* (1861). The vessel's diamond shaped "walking beam" can clearly be seen amidships

Steeple



Steeple engine

The steeple engine, sometimes referred to as a "crosshead" engine, was an early attempt to break away from the beam concept common to both the walking beam and side-lever types, and come up with a smaller, lighter, more efficient design. In a steeple engine, the vertical oscillation of the piston is not converted to a horizontal rocking motion as in a beam engine, but is instead used to move an assembly, composed of a crosshead and two rods, through a vertical guide at the top of the engine which in turn rotates the crankshaft connecting rod below. In early examples of the type, the crosshead assembly was rectangular in shape, but over time it was refined into an elongated triangle. The triangular assembly above the engine cylinder gives the engine its characteristic "steeple" shape, hence the name.

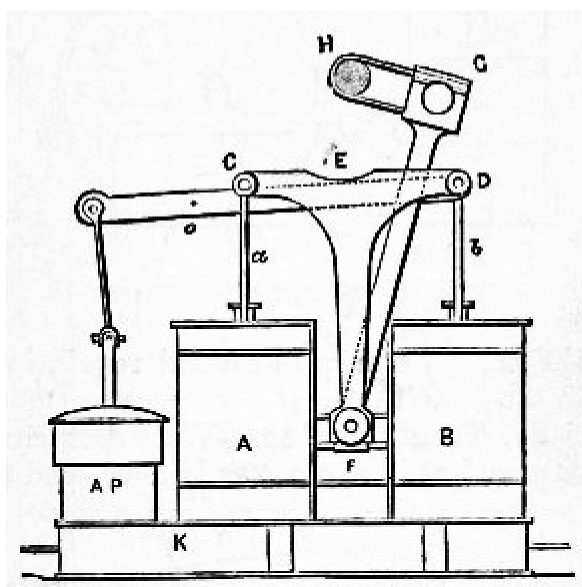
Steeple engines were tall, though not as tall as walking beams, but much narrower laterally, saving both space and weight. Because of their height and high centre of gravity, they were, like walking beams, considered to be less appropriate for oceangoing service, but they remained highly popular for several decades, especially in Europe, for inland waterway and coastal vessels.

Steeple engines began to appear in steamships in the 1830s and the type was perfected in the early 1840s by the British shipbuilder David Napier. The steeple engine was gradually superseded by the various types of direct-acting engine.

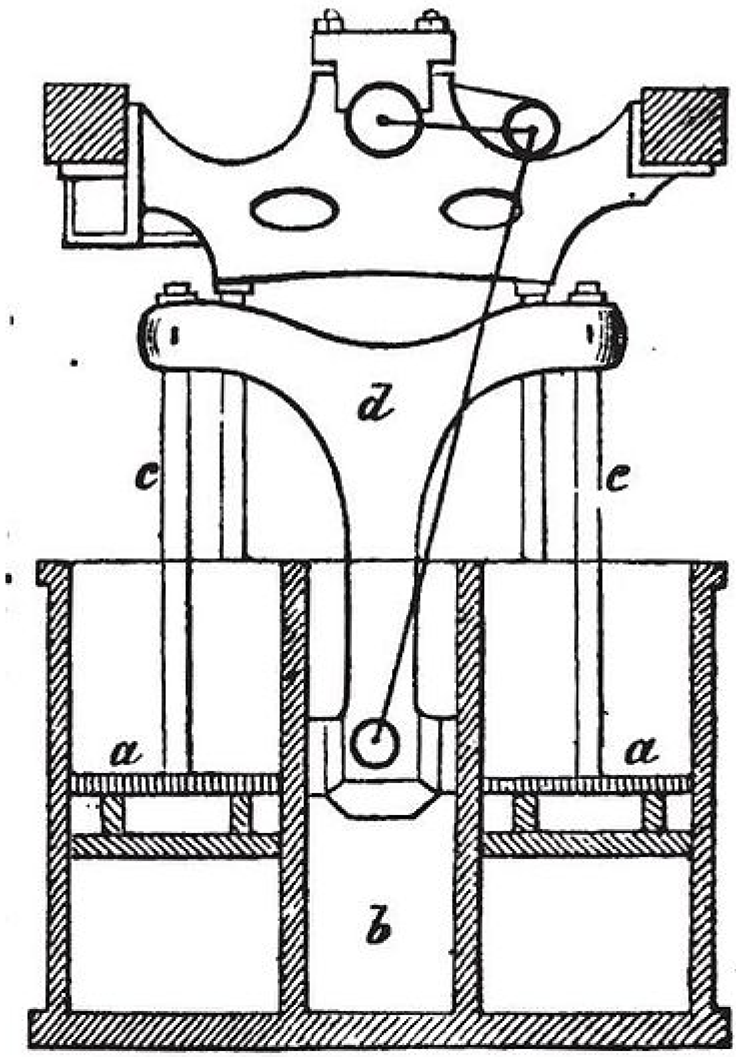
Siamese

The Siamese engine, also referred to as the "double cylinder" or "twin cylinder" engine, was another early alternative to the beam or side-lever engine. This type of engine had two identical, vertical engine cylinders arranged side-by-side, whose piston rods were attached to a common, T-shaped crosshead. The vertical arm of the crosshead extended down between the two cylinders and was attached at the bottom to both the crankshaft connecting rod and to a guide block that slid between the vertical sides of the cylinders, enabling the assembly to maintain the correct path as it moved.

The Siamese engine was invented by British engineer Joseph Maudslay (son of Henry), but although he invented it after his oscillating engine (see below), it failed to achieve the same widespread acceptance, as it was only marginally smaller and lighter than the side-lever engines it was designed to replace. It was however used on a number of mid-century warships, including the first warship fitted with a screw propeller, HMS *Rattler*.

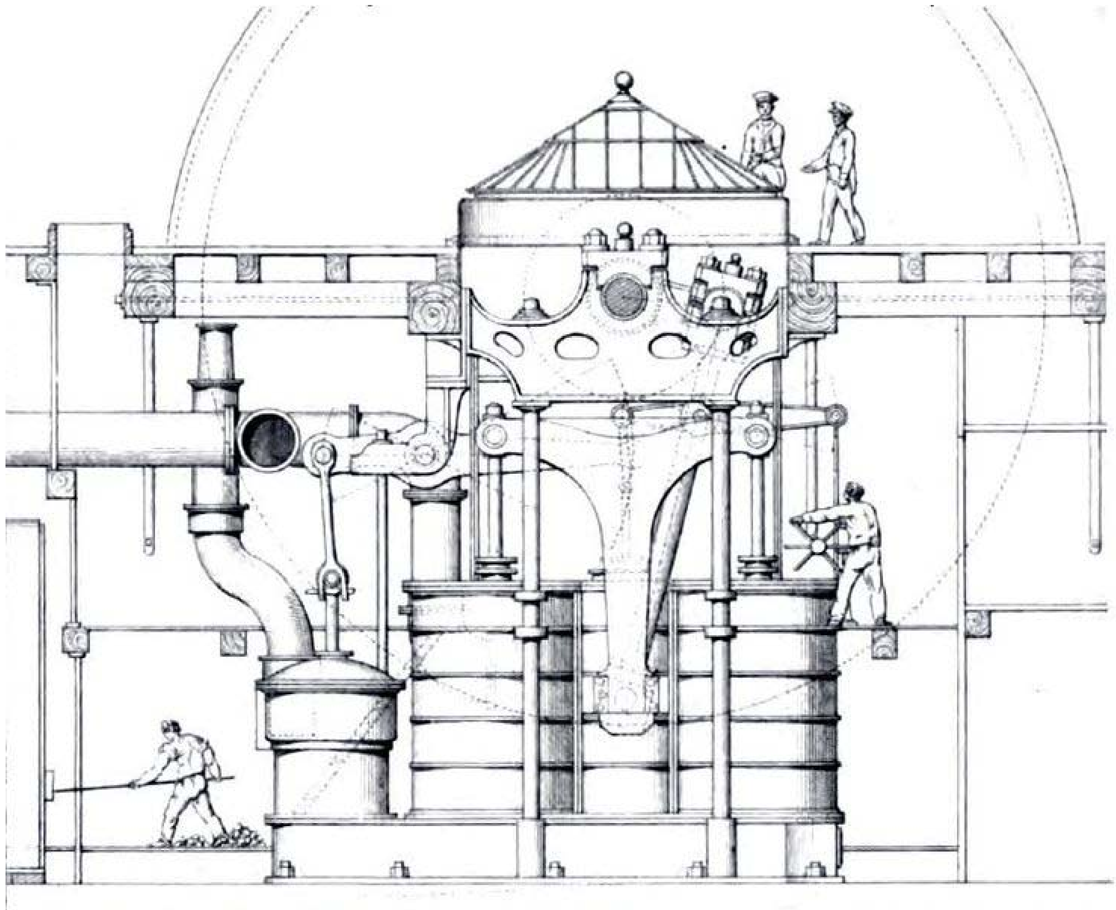


Basic diagram of a Siamese engine



Annular Engine.

Diagram of an annular engine (see below) with Siamese connection mechanism



Siamese engine of HMS *Retribution* (1844)

Direct acting

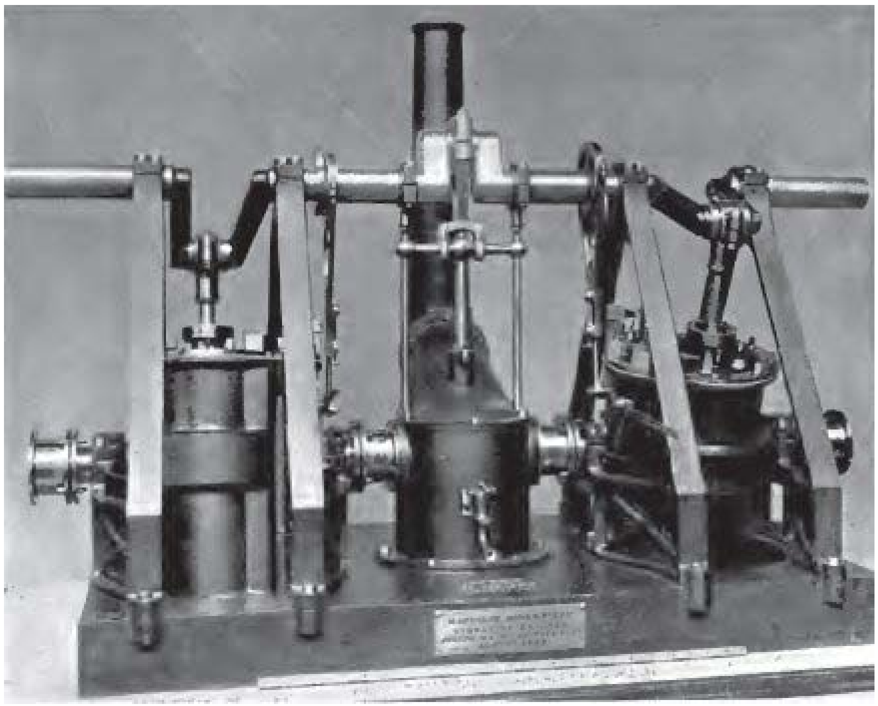
There are two definitions of a direct-acting engine encountered in 19th-century literature. The earlier definition applies the term "direct-acting" to any type of engine other than a beam (i.e. walking beam, side-lever or grasshopper) engine. The later definition only uses the term for engines which apply their power directly to the crankshaft via the piston rod and/or connecting rod. Unless otherwise noted.

Unlike the side-lever or beam engine, a direct-acting engine could be readily adapted to power either paddlewheels or a propeller. As well as offering a lower profile, direct-acting engines had the advantage of being smaller and weighing considerably less than beam or side-lever engines. The Royal Navy found that on average a direct-acting engine (early definition) weighed 40% less and required an engine room only two thirds the size of that for a side-lever of equivalent power. One disadvantage of such engines is that they were more prone to wear and tear and thus required more maintenance.

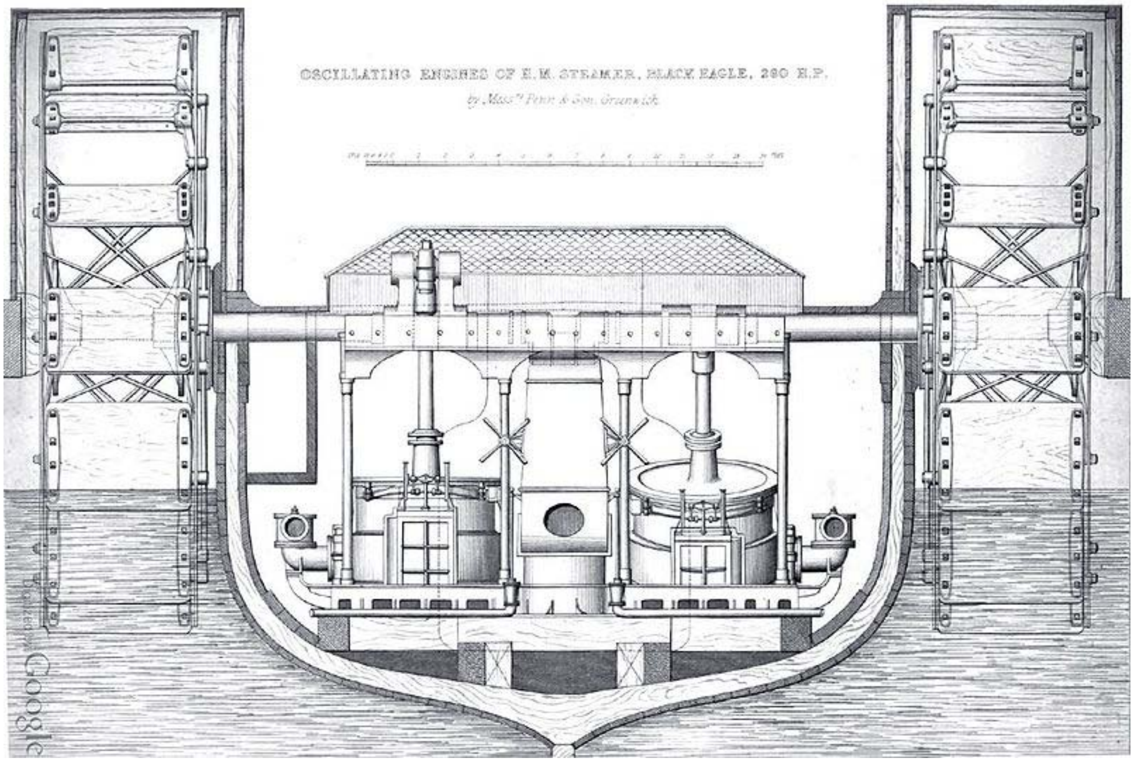
Oscillating

An oscillating engine was a type of direct-acting engine that was designed to achieve further reductions in engine size and weight. Oscillating engines had the piston rods connected directly to the crankshaft, dispensing with the need for connecting rods. In order to achieve this aim, the engine cylinders were not immobile as in most engines, but secured in the middle by trunnions which allowed the cylinders themselves to pivot back and forth as the crankshaft rotated, hence the term *oscillating*. Steam was supplied and exhausted through the trunnions.

The first patented oscillating engine was built by Joseph Maudslay in 1827, but the type is considered to have been perfected by John Penn. Oscillating engines remained a popular type of marine engine for much of the 19th century.



Model of a Maudslay oscillating engine



Oscillating paddlewheel engines of HMS *Black Eagle*. Oscillating engines could be used to drive either paddlewheels or propellers.

Oscillating engine built in 1853 by J. & A. Blyth of London for the Austrian paddle steamer *Orsova*

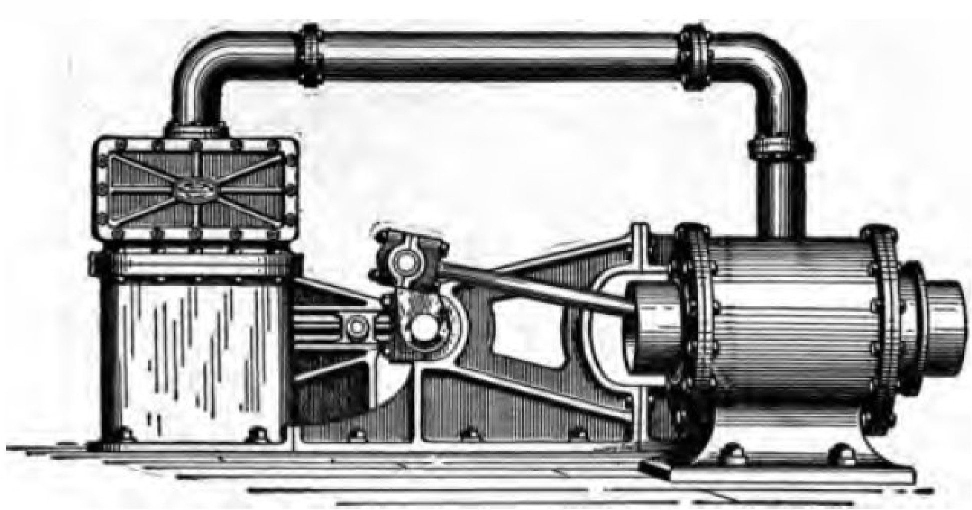
Trunk

The trunk engine, another type of direct-acting engine, was originally developed as a means of reducing an engine's height while retaining a long stroke. Early examples of such engines had vertical cylinders; however, it was quickly realized that the type was compact enough to be laid horizontally across the keel. In this configuration, it was very useful to navies, as it had a profile low enough to fit entirely below a ship's waterline, where it would be as safe as possible from enemy fire. The type was generally produced for military service by John Penn.

This type of engine had a horizontal cylinder, through the centre of which passed a cylindrical "trunk" or passage containing the connecting rod. The walls of the trunk were either bolted to the piston or cast as one piece with it, and moved back and forth with it. The working portion of the cylinder was annular or ring-shaped, with the trunk passing through the centre of the cylinder itself.

Trunk engines were quite common on mid-19th century warships, and were also to be found in commercial vessels, where though valued for their compact size and low centre of gravity, they proved expensive to operate. Trunk engines however proved poorly adapted to the higher boiler pressures that became prevalent in the latter half of the 19th century, and were abandoned in favour of other solutions.

Normally large engines, a small mass-produced, high-revolution, high-pressure version was produced for the Crimean War. In being quite effective, the type persisted in later gunboats. An original trunk engine of the gunboat type exists in the Western Australian Museum in Fremantle. After sinking in 1872, it was raised in 1985 from the SS *Xantho* and can now be turned over by hand. The Trunk Engine's mode of operation, illustrating its compact nature can be viewed on the *Xantho* project's website.



Trunk Engine

Trunk engine illustration

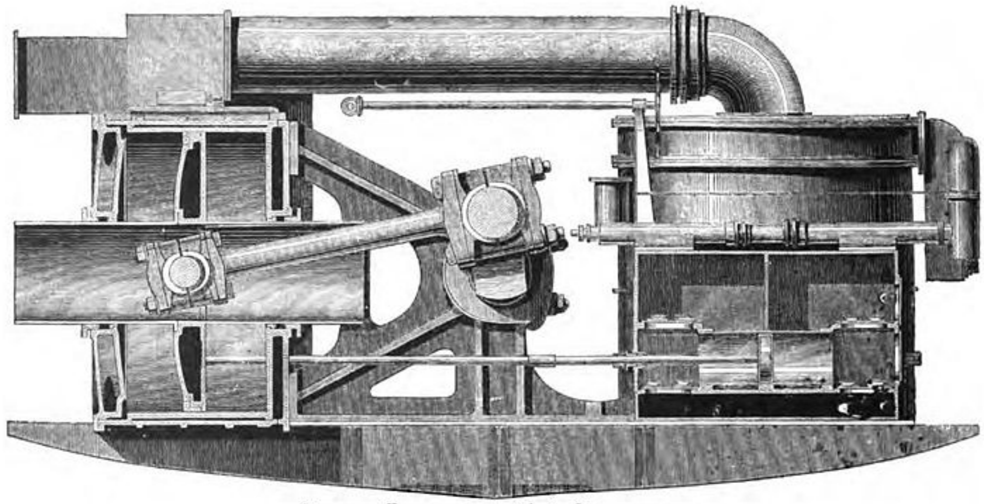
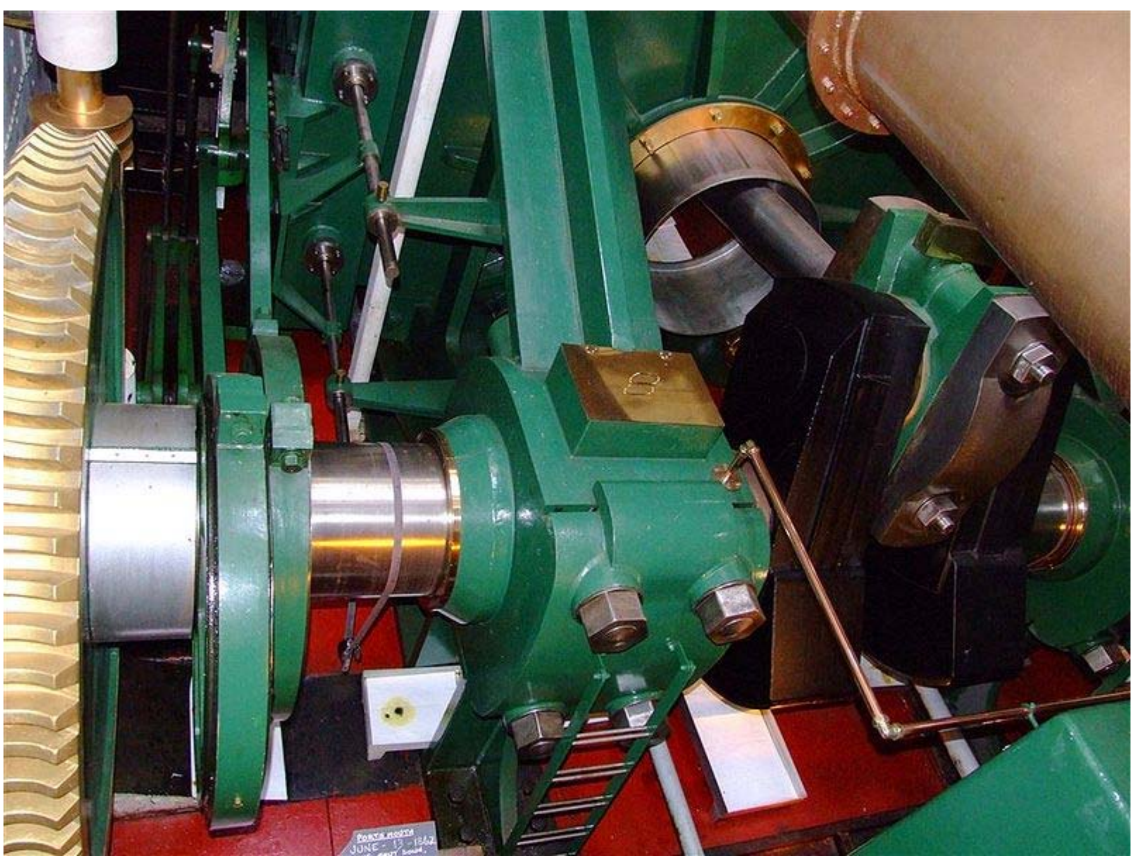


FIG. 10.—ENGINE OF H. M. S. BELLEROPHON.

Cutaway view of trunk engine of HMS *Bellerophon*, showing (on the left) engine cylinder, annular piston and trunk assembly, and connecting rod inside trunk



Looking down at the trunk engine of HMS *Warrior* (1860). The connecting rod can be seen emerging from the trunk at right.

Vibrating lever

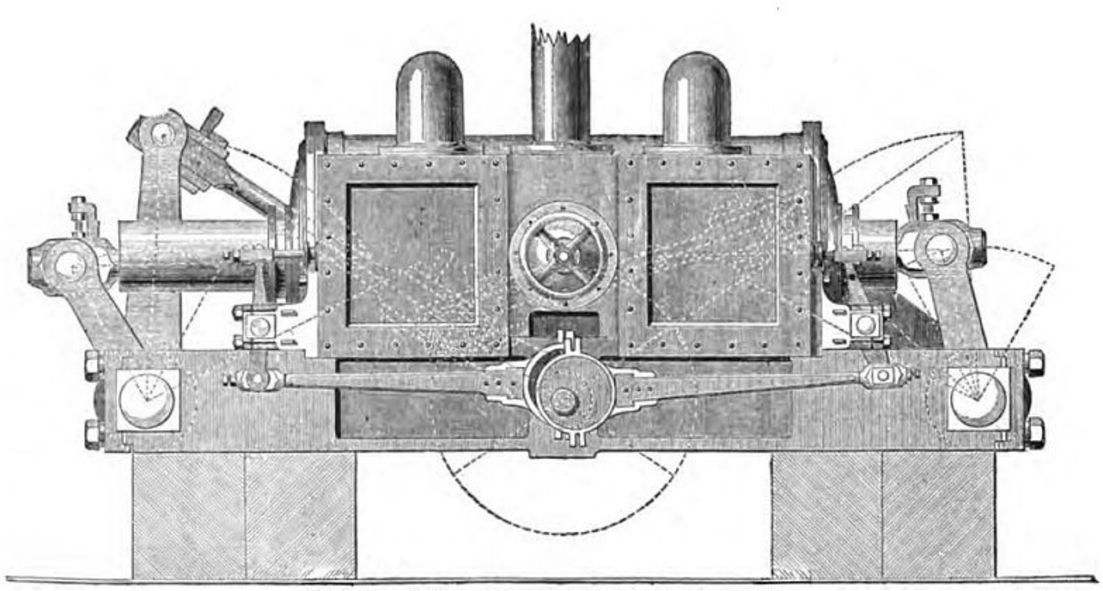


FIG. 38.—ENGINE OF U. S. MONITOR MONADNOCK.

Vibrating-lever engine of USS *Monadnock* (1863) - front view

The vibrating lever, or **half-trunk** engine, was a development of the conventional trunk engine conceived by Swedish-American engineer John Ericsson. Ericsson needed a small, low-profile engine like the trunk engine to power the U.S. Federal government's monitors, a type of warship developed during the American Civil War that had very little space for a conventional powerplant. The trunk engine itself was however unsuitable for this purpose because the preponderance of weight was on the side of the engine containing the cylinder and trunk, a problem which could not be compensated for on the small monitor warships.

Ericsson resolved this problem by placing two horizontal cylinders back-to-back in the middle of the engine, working two "vibrating levers", one on each side, which by means of shafts and additional levers rotated a centrally located crankshaft. Vibrating lever engines were later used in some other warships and merchant vessels, but their use was confined to ships built in the United States and in Ericsson's native country of Sweden, and as they had few advantages over more conventional engines, were soon supplanted by other types.

Back acting

The back-acting engine, also known as the **return connecting rod engine**, was another engine designed to have a very low profile. A back-acting engine can be thought of as something like a steeple engine, but laid horizontally across the keel of a ship rather than standing vertically above it. Instead of the triangular crosshead assembly found in a typical steeple engine however, the back-acting engine generally utilized a set of two or more elongated, parallel piston rods terminating in a crosshead to perform the same function. The term "back-acting" or "return connecting rod" derives from the fact that the connecting rod "returns" or comes back from the side of the engine opposite the engine cylinder to rotate a centrally located crankshaft.

Back-acting engines were another type of engine popular in both warships and commercial vessels in the mid-19th century, but like many other engine types in this era of rapidly changing technology, they were eventually abandoned for other solutions. There is only one back-acting engine known to be still in existence—that of the TV *Emery Rice* (formerly USS *Ranger*), now the centerpiece of a display at the American Merchant Marine Museum.

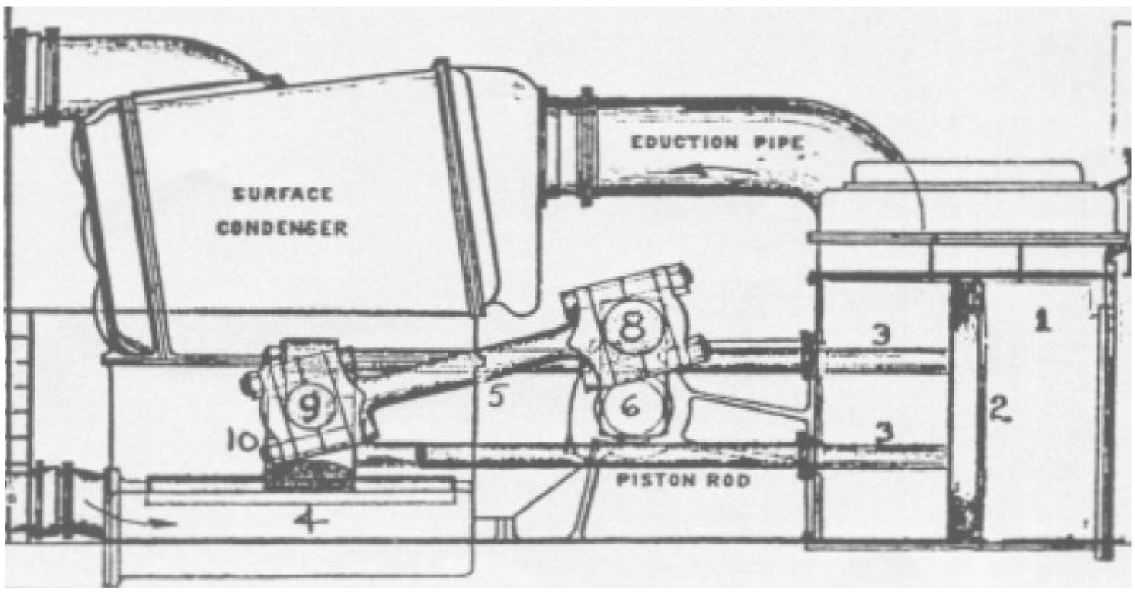


Diagram of back-acting engine of USS *Ranger*

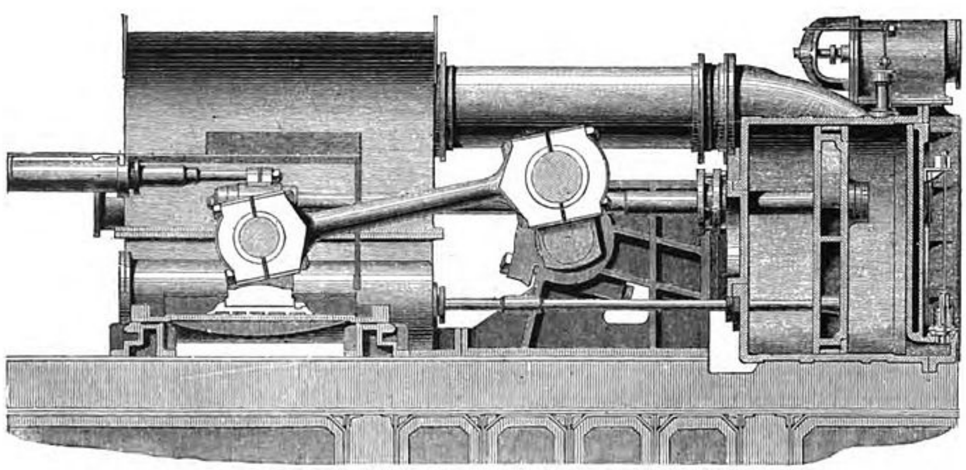


FIG. 12.—ENGINE OF H. M. S. AGINCOURT.

Return connecting rod engine of HMS *Agincourt* (1865)

Vertical

As steamships grew steadily in size and tonnage through the course of the 19th century, the need for low profile, low centre-of-gravity engines correspondingly declined. Freed increasingly from these design constraints, engineers were able to revert to simpler, more efficient and more easily maintained designs. The result was the growing dominance of the so-called "vertical" engine (more correctly known as the **vertical inverted direct acting** engine).

In this type of engine, the cylinders are located directly above the crankshaft, with the piston rod/connecting rod assemblies forming a more or less straight line between the two. The configuration is similar to that of a modern internal combustion engine (one notable difference being that the steam engine is double acting, see below, whereas an internal combustion engine generates power only in the downward stroke). Vertical engines are sometimes referred to as "hammer", "forge hammer" or "steam hammer" engines, due to their roughly similar appearance to another common 19th-century steam technology, the steam hammer.

Vertical engines came to supersede almost every other type of marine steam engine toward the close of the 19th century. Because they became so common, vertical engines are not usually referred to as such, but are instead referred to based upon their cylinder technology, i.e. as compound, triple expansion, quadruple expansion etc. It should be noted that the term "vertical" for this type of engine is imprecise, since technically any type of steam engine is "vertical" if the cylinder is vertically orientated. An engine described as "vertical" should therefore not be assumed to be of the vertical inverted direct-acting type unless the term "vertical" is unqualified.

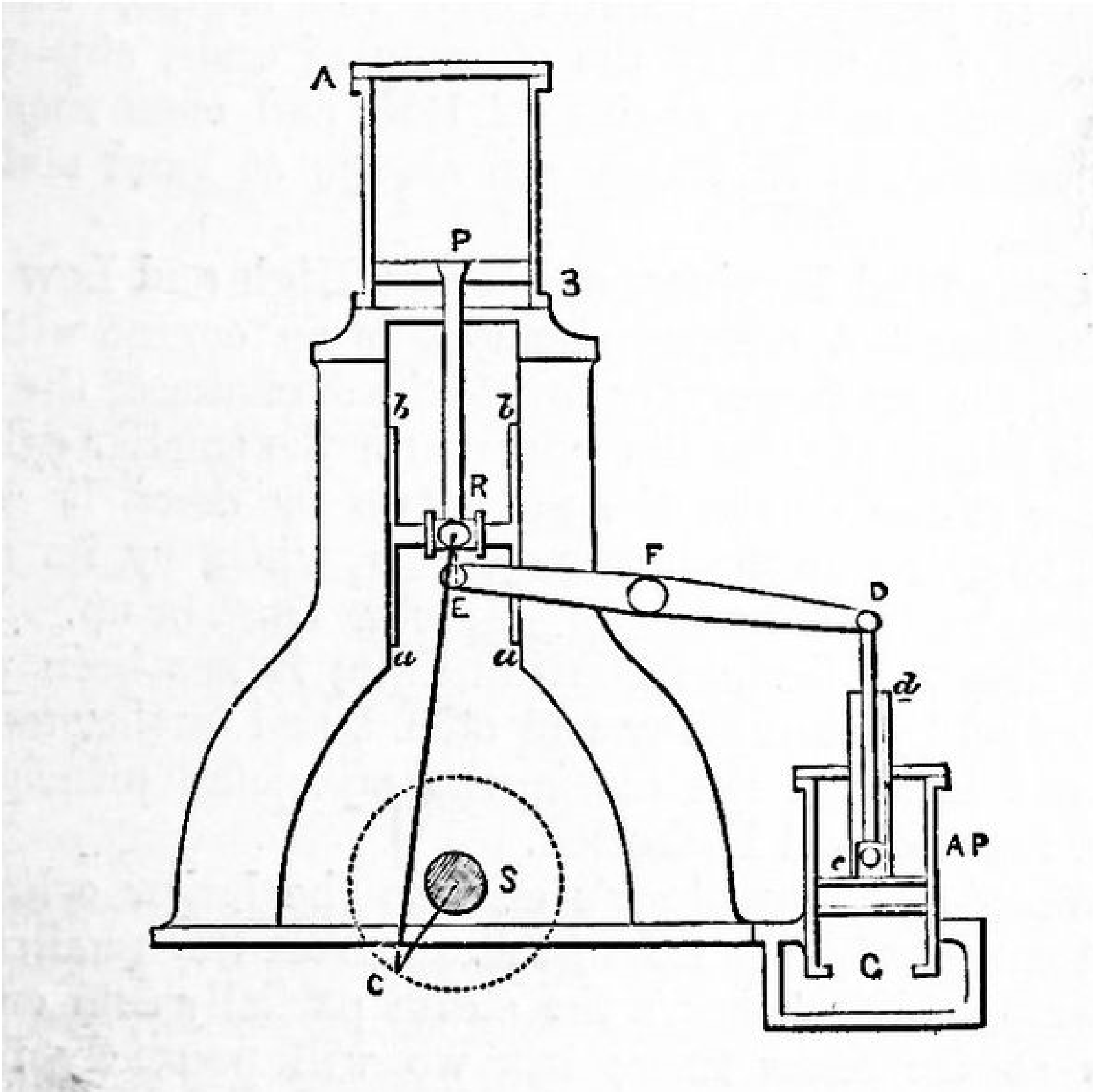
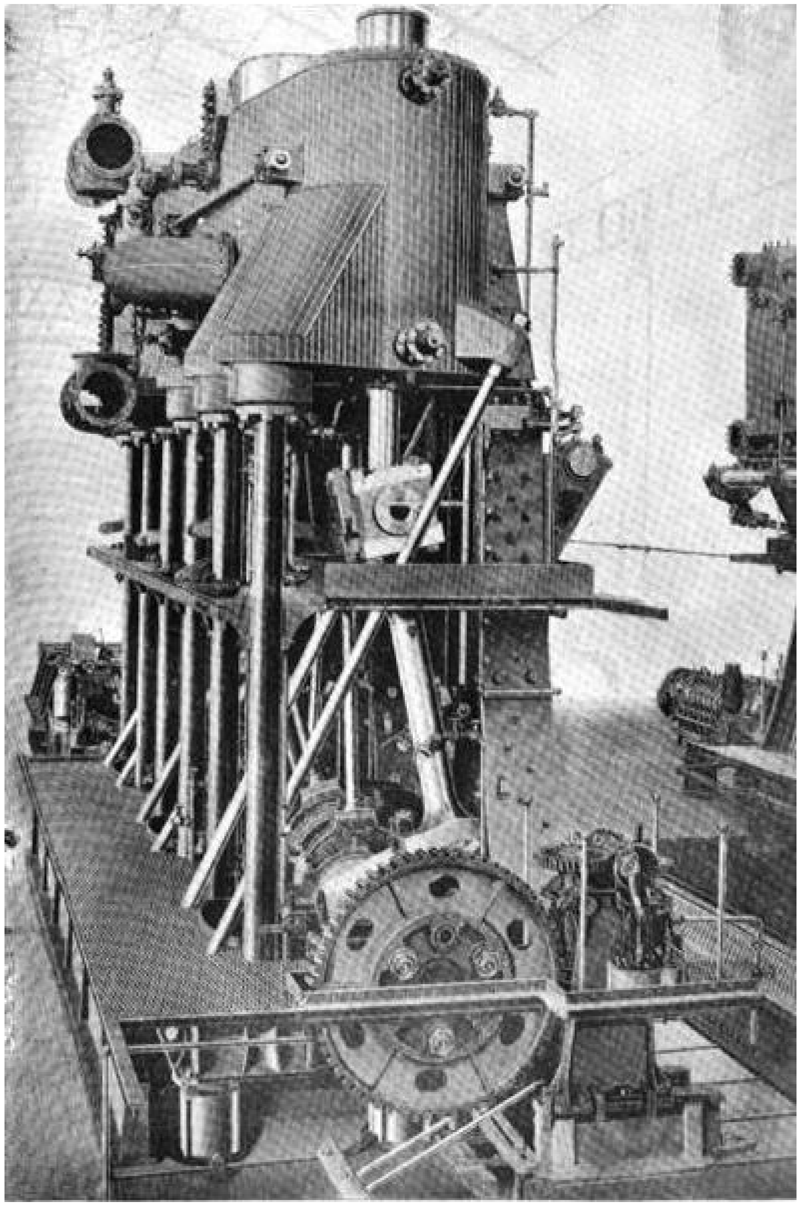


Diagram of a simple "hammer" engine



Vertical triple expansion engine of USS *Wisconsin* (BB-9). The typical vertical engine arrangement of cylinder, piston rod, connecting rod and crankshaft can clearly be seen in this photo.

Engines classified by cylinder technology

Simple expansion

A simple expansion engine is a steam engine that expands the steam through only one stage, which is to say, all its cylinders are operated at the same pressure. Since this was by far the most common type of engine in the early period of marine engine development, the term "simple expansion" is rarely encountered; rather, an engine is assumed to be simple expansion unless otherwise stated.

Compound

A compound engine is a steam engine which operates cylinders through more than one stage, i.e., at different pressure levels. Compound engines were a method of improving efficiency. Up until the development of compound engines, steam engines used the steam only once before being recycled back to the boiler, but a compound engine recycles the steam into one or more larger, lower pressure second cylinders first, in order to utilize more of its heat energy. Compound engines could be configured to either increase a ship's economy or its speed. Although broadly speaking a compound engine can refer to a steam engine with any number of different-pressure cylinders, the term usually refers to engines which expand steam through only two stages, i.e. those which operate cylinders at only two different pressures (or "double expansion" engines).

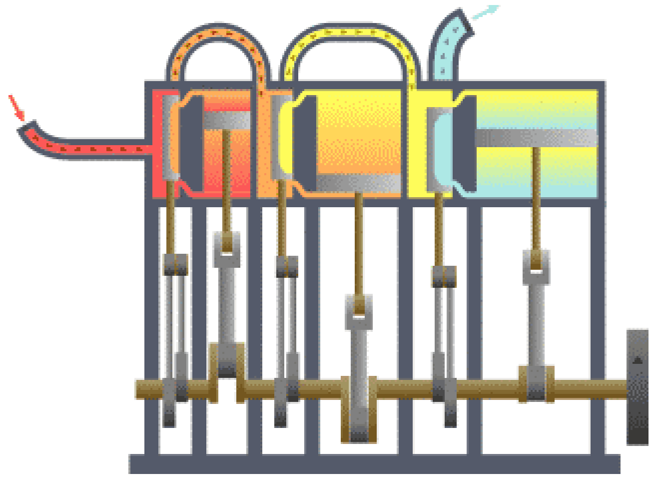
Note that a compound engine (including multiple expansion engines, see below) can have more than one *set* of variable-pressure cylinders. For example, an engine might have two cylinders operating at pressure x and two operating at pressure y, or one cylinder operating at pressure x and three operating at pressure y. What makes it compound (or double expansion) as opposed to multiple expansion is that there are only two *pressures*, x and y.

The first compound engine believed to have been installed in a ship was that fitted to *Henry Eckford* by the American engineer James P. Allaire in 1824. However, many sources attribute the "invention" of the marine compound engine to Glasgow's John Elder in the 1850s. Elder made improvements to the compound engine that made it safe and economical for transcontinental voyages for the first time.

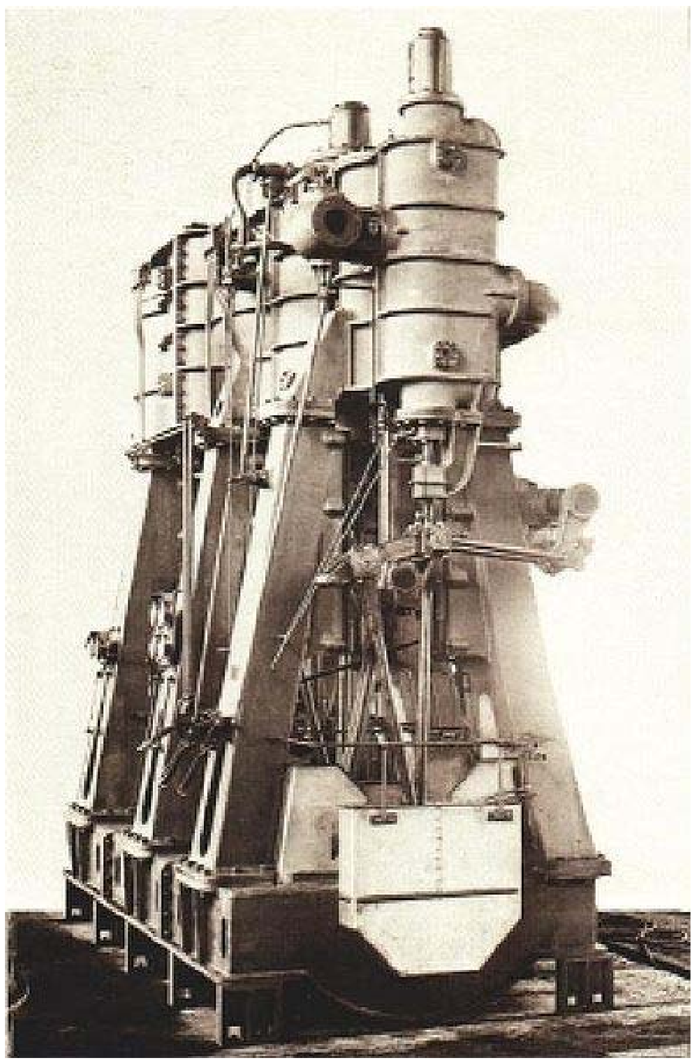
Triple or multiple expansion

A triple expansion engine is a compound engine that expands the steam in three stages, i.e. an engine which has cylinders operating at three different pressures. A quadruple expansion engine expands the steam in four stages, and so on.

Multiple expansion engines survived well into the 20th century. All 2,700 Liberty ships built by the United States during World War II were powered by triple-expansion engines, because the capacity of the US to manufacture steam turbines was still limited. The biggest manufacturer of triple expansion engines during the war was the Joshua Hendy Iron Works. Toward the end of the war, turbine-powered Victory ships were manufactured in increasing numbers.



A typical vertical triple-expansion engine



A Joshua Hendy triple expansion engine

A triple expansion engine on the Lydia Eva (steam drifter)

Annular

An annular engine is an unusual type of engine that has an annular (ring-shaped) cylinder. Some of American pioneering engineer James P. Allaire's early compound engines were of the annular type, with a smaller, high pressure cylinder placed in the centre of a larger, ring-shaped low-pressure cylinder. Trunk engines were another type of annular engine. A third type of annular marine engine which was sometimes produced utilized the Siamese engine connecting mechanism, but instead of two separate cylinders, had a single annular-shaped cylinder wrapped around the vertical arm of the crosshead (see diagram).

Other terms

Some other terms are encountered in marine engine literature of the period. These terms, listed below, are usually used in conjunction with one or more of the basic engine classification terms listed above.

Simple

A simple engine is an engine with only one cylinder. Up until about the mid-19th century, most ships had engines with only one cylinder (although some vessels had more than one engine). Simple engines are always also simple expansion engines by necessity.

Double acting

A double acting engine is an engine where steam is applied to both the up and down stroke of the piston. Earlier steam engines applied steam in only one direction, allowing momentum or gravity to return the piston to its starting place, but a double acting engine uses steam to force the piston in both directions, thus increasing RPM and power. Like the term "simple expansion", the term "double acting" is infrequently encountered in the literature since almost all marine engines were of the double acting type.

Vertical, horizontal, inclined, inverted

These terms refer to the orientation of the engine cylinder. A vertical cylinder stands vertically with its piston rod operating above it. An inverted cylinder (or "vertical inverted" cylinder) can be thought of as a vertical cylinder positioned upside down. With an inclined or horizontal type, the cylinder and piston are positioned at an incline or horizontally. An inclined inverted cylinder is an inverted cylinder operating at an incline. These terms are all generally used in conjunction with the engine types above. Thus, one may have a horizontal direct-acting engine, or an inverted walking beam, and so on.

Inclined and horizontal cylinders could be very useful in naval vessels as their orientation kept the engine profile as low as possible and thus less susceptible to damage. They could also be used in a low profile ship or to keep a ship's centre of gravity lower. In addition, inclined or horizontal cylinders had the advantage of reducing the amount of vibration by comparison with a vertical cylinder.

Geared

A geared engine or "geared screw" turns the propeller at a different rate to the engine's RPM. Early marine propeller engines were geared upward, which is to say the propeller was geared to run at a higher RPM than the engine itself. As engines became faster and more powerful through the latter part of the 19th century, gearing was often dispensed with and the propeller ran at the same RPM as the engine.