Maritime Steam;

How Steam Revolutionized the World's Shipping

Written for the San Diego Maritime Museum's Exhibit of Maritime Steam

John Forester, M.S., P.E.

1 The Power Revolution

Thousands of years ago man learned to use the power of animals to carry his loads on land and the power of the wind to carry his loads at sea. Animal power didn't work for maritime purposes; even trained rowers were used only for maneuvering in and out of harbors and for sea battles. Man also used water power to grind his grain and to power small factories and textile mills, but watermills are fixed in place and waterpower is unusable for transportation. Those were all the sources and uses of power that man had.

After four thousand years of development, sailing ships carried men and goods to all the shores of the Earth in reasonable safety (the oceans are always dangerous to some extent), along recognized trading routes, and often within the expected voyage durations. The sailing ship, and in particular the sailing navy, exhibited the highest technology and technological organization of its time. Then, two hundred years ago, at the start of the nineteenth century, there started a revolution that in one century swept the commercial and naval sailing ships from the seas, so that, today, sailing vessels are used only for recreation, for training seamen in the ways of the sea, the maritime environment that hasn't changed, and for some small fishing and trading services.

This revolution was created by man's discovery of a new source of power, steam power. When man worked out how to apply the power of steam, he applied it to his existing uses. First, to factories and textile mills, to make them independent of waterpower locations. Second, to ground transportation in the form of railroads. Third, to ocean transportation in the form of steamships. In many ways, development of satisfactory steam power for maritime use was the more difficult problem and took the longest time. This is the story of how that came about.

2 Steam Power Basics

2.1 The Machinery

The basic steam plant consists of:

1. 1: The boiler over its furnace. The boiler is a closed container for the water that the heat from the furnace turns into steam. As the water turns into steam, it expands many times. The steam is both hot and it pushes outward, which we call exerting pressure.
2. 2: The steam engine. The engine uses the heat and pressure of the steam to produce mechanical power. In the early days, all steam engines used pistons working in cylinders to convert the heat power of the steam into mechanical power, either push-and-pull, as on pump rods, or rotating, as on shafts for propellers.
3. 3: The condenser. The condenser accepts the used steam from the engine and cools it off, thus turning it back into water. This does two things. Condensing the water makes it much smaller (the opposite of boiling water). This enables the condenser to operate at substantially vacuum pressure. Condensing the water also makes it available again for use in the boiler, a very important point in marine service, where the surrounding ocean water has much salt in it, which ruins boilers.
4. Auxiliary machinery. There must be several pumps. The condenser pump sucks the water (formerly steam) out of the vacuum in the condenser up to room pressure. The boiler feed pump pumps the water from room pressure up to boiler pressure. The oil pump pumps oil into the steam to lubricate the engine. The circulating pump circulates ocean water through the condenser tubes to cool the steam.

2.2 The Principle

2.2.1 Converting Heat into Mechanical Power

The steam engine is a heat engine. That is, it accepts high-temperature heat, converts some of that heat to mechanical work, and rejects low-temperature heat. Of course, heat does not exist by itself; something has to be hot or cold. For the steam engine, this working fluid is steam. The steam enters the engine at high temperature and high pressure, and leaves the engine at low temperature and low pressure, with the heat difference converted into mechanical power.

2.2.2 Kinetic Theory of Gases

For those of you who remember some elementary physics, heat is the motion of molecules; the higher the temperature, the faster the molecules move. In liquids, the molecules move around each other, but stick to each other. When a liquid is boiled, its molecules, one-by-one, get going fast enough to jump out of the liquid and become a gas. This gas is larger than the liquid, so, if the liquid is in a closed container, the molecules of gas press outward on the walls of the container, which is what is meant by pressure. Temperature and pressure always go together as long as there is both liquid and gas in the container.

The hotter the liquid, the faster the molecules go when they escape the liquid state. The faster each molecule goes, the more force it exerts when it bounces off the wall of the container. Also, the hotter the liquid the more molecules escape from it. The combination of the number of molecules and the speed with which they bounce off the walls of the container is the force exerted by the gas on the container's walls, which we call pressure. However, we reach an equilibrium when as many molecules are attracted back into the liquid as escape. Then the pressure is constant at that temperature. Therefore, as long as we have both liquid and its gas in a container, the higher the temperature the higher the pressure, according to a definite rule for each liquid. For water, water boils at 212 degrees F at room pressure, which is 15 pounds per square inch. Water also boils at 375 deg F when enclosed to a pressure of 180 pounds per square inch, as in the boilers of our ferryboat Berkeley.

2.2.3 The Efficiency Law

No heat engine can be 100% efficient. The maximum efficiency is equal to:

Max Eff = (Heat In - Heat Rejected)/Heat In

Max Eff = (High Temp - Low Temp)/High Temp

1.

This means two things. The efficiency can never be as high as 100%. The higher the high temperature and the lower the low temperature, the greater the difference between high and low temperatures, the more efficient the engine can be. Of course, this is only the highest theoretical efficiency, that no engine can exceed. No engine can be designed to be perfect; every practical engine falls below the highest theoretical efficiency for its temperature span.

2.2.4 The Course of Development

One very significant problem for marine steam is the amount of power that can be produced from each pound of fuel. Not only does fuel cost money, but each pound of fuel that must be carried prevents a pound of cargo from being carried. An inefficient engine not only costs more to operate, it reduces the earning power as well. It is not practical to reduce the low-temperature end of the cycle below the temperature of the ocean water in which the vessel floats. Therefore, the course of development of marine steam has been the search for ways to employ steam of higher pressure and higher temperature, so that fuel consumption is reduced to a level supportable by the trading that is available. Naturally, the high-value trades employed steamships early, because they could afford to use engines that were inefficient. The low-value trades acquired steam later, because they could not afford it until it became more efficient.

2.3 Steam Engine Development

2.3.1 General

The development of any technology depends on learning the science of it, applying that science through engineering that is based on the science, and discovering ways to overcome all the other limitations that cause problems.

Steam engines existed long before the science was understood. That meant that they were crude, inefficient machines. Once the science became understood, bit by bit, it became possible to build engines that were reasonably designed. Then engineers had to develop all the bits and pieces of the technology. For instance, there had to be a standard for power, and there had to be instruments to measure the power of an engine. This short essay concentrates on only those things that enabled the design of engines that would fit into ships and the methods of increasing their efficiency.

2.3.2 Newcomen's Engine

The first successful steam engine was built by Newcomen in 1712. It operated between the temperature of boiling water at almost room pressure, say 220F, and room temperature, say 60F. It was used only to pump water out of coal mines, because it burned so much coal that it was uneconomic anywhere else. It had a separate boiler and cylinder, but the cylinder also was the condenser. The cylinder was vertical with an open top, down into which the piston worked. The piston pulled down a chain, connected to one end of a rocking beam. The other end of the beam held up the pump rod with its buckets down in the well. The pump rod and buckets were so heavy that the engine rested with the pump end of the beam down and the piston at the top of the cylinder.

To operate the engine, the operator opened two cocks, the drain cock to drain the bottom of the cylinder and the steam cock to let steam from the boiler fill the cylinder with steam. When the cylinder was hot enough to fill with steam at room pressure, the operator closed both the steam and the drain cocks and opened another cock to let cold water from an overhead tank spray into the cylinder. The cold water condensed the steam, producing almost a vacuum (as good a vacuum you could get with water, and maybe a bit of air, in the system). The vacuum inside the cylinder allowed the normal pressure of the atmosphere on the top of the piston to push it down, thus lifting the pump rod with its buckets.

The operator then closed off the water cock, opened the steam cock to allow the cylinder to fill with steam, so that the weight of the falling pump rod would pull the piston up to the top of the cylinder, and then opened the drain cock to drain off the water from the bottom of the cylinder, and start the cycle again.

It was some years before one of the young boys who worked the cocks figured out a system of cords from the working beam to operate the cocks automatically.

Because this engine was driven by the pressure of the atmosphere (the steam didn't drive the piston, just provided the opportunity to form a vacuum by condensing it) it wasn't called a steam engine at all, but Newcomen's Atmospheric Engine, colloquially called a fire engine.

The parts of the typical Newcomen engine were so crudely machined that pistons didn't fit cylinders. The rim of the piston was stuffed with greased cloth, and the top of the piston was flooded with water, so that air could not leak in. Such was the state of the art.

2.3.3 Watt's Separate Condenser Engine

When Newcomen's engines had been at work for fifty years, there was a working model of one at the University of Edinburgh, where Professor Black had been working on the science of heat. The model didn't work very well, as might be expected. Making the model work better was assigned to the university mechanic, James Watt, who had studied under Black.

Watt figured out that one reason that the Newcomen engine used so much steam, and hence required so much fuel, was that the entire cylinder and piston had to be heated up to the temperature of the steam at the start of every stroke, after being cooled by the cold water that was necessary to condense the steam. Watt provided a separate cold chamber, called the condenser, to condense the steam, so that the cylinder could always be kept hot. That required a different valving system, and, of course, a pump to suck the water out of the condenser. Since water occupied so much less volume than steam (approximately 1/1600 of the volume), the condensate pump could be small and required little of the total power.

Watt's engine used much less fuel than Newcomen's, and Watt is regarded as the inventor of the steam engine.

The vacuum provided by the separate condenser enabled the cylinder to be built with a closed top (except for the tight gland through which the piston rod operated). This allowed the piston to provide power in both directions, because one side always had steam pressure while the opposite side always had vacuum from the condenser.

Based on Watt's invention of the separate condenser, Boulton and Watt established the first modern factory to build the new engines, the real start of modern industry.

Watt's early engines were closely derived from the Newcomen pumping engine, with a rocking beam on a pedestal, the upright cylinder under one end and the other end the power end. However, the power end of the rocking beam, instead of lifting the pump rod, became connected by a connecting rod to a crank (not Watt's invention; there was a patent squabble over that) to provide rotating power that was more useful in a factory. Watt made many other detail improvements, also.

The greater complexity of the machinery, and its productivity, both required and enabled it to be built with better technique. The birth of the steam engine created the machine tool industry to make the machines that could make better steam engines.

The new design of engine enabled it to use steam at higher than atmospheric pressure. The higher the pressure and the temperature, the better it would work, and the more power could be produced by a given size (and cost) of engine, although the quality of workmanship had to be better. However, Watt was conservative in this matter, and never went to significantly higher pressures. He was greatly concerned about the probability of boiler explosions, a reasonable fear considering the quality of material available and the frequency with which explosions occurred in other applications that used higher pressures.

A model of the typical early Watt Beam Engine is in the History of Steam Exhibit. It is the green engine, and is the only beam engine in the exhibit. The marine version of the beam engine often drove the early paddle steamers. Such an engine drove the Orizaba, a model of which is also in the exhibit.

2.3.4 The Slide Valve

Every steam engine cylinder has to have valves to control the admission of the steam to the proper end of the cylinder when the piston is at the start of its stroke, and the release of the expanded steam to exhaust when the piston reaches the end of the stroke. The first successful valve system was the slide valve, and its principles underlie all later valve systems.

Alongside each cylinder, the casting is machined to a flat face. In this face are three rectangular ports, near the center of that face. The two ports nearest each end of the cylinder communicate, through passages in the casting, with the end of the cylinder nearest that port. The center port communicates with a channel that goes out the side to the exhaust pipe. Bolted over each flat face is a steamtight box, the steam chest, that is filled with steam from the boiler. The boiler steam would go directly to the exhaust port, except that it is stopped by the slide valve. This is like a smaller box with its open face long enough to cover two, but not all three, of the valve ports. When the valve is at one end of its motion, the steam enters the uncovered port and goes to that end of the cylinder. At the same time the box covers both the port to the other end of the cylinder and the exhaust port. Therefore, the steam that was in the other end of the cylinder escapes through the inside of the box to the exhaust port.

The slide valve is made to move back and forth, opening each cylinder port first to steam and then to exhaust, while doing the opposite to the other cylinder port. The valve is driven by a mechanism that works like a cam on the main crankshaft (the eccentric on most engines, but on most locomotives an actual small crank, called the return crank). For the valve to have its action timed to control the steam, this eccentric as to be set about 90 degrees ahead of the crank.

The dimensions of the ports and the lips of the slide valve and the length of its motion have to be very carefully designed so that the proper amount of steam enters the cylinder at each piston stroke.

To reverse the engine, another eccentric must be engaged, this one set about 90 degrees in the other direction from the crank. The motion of each eccentric on the crank is transmitted to the valve, which is alongside the cylinder, by its eccentric rod. The ends of the two eccentric rods are connected by a curved slotted bar (Stephenson link) that actually drives the valve rod, so that as one rod moves to the active position the other moves away, so the valve moves smoothly.

2.3.5 Using the Expansion of Steam

We never fill the whole cylinder with steam at boiler pressure. If we did so, when the exhaust port opened the energy represented by that pressure and temperature would blast out and be lost. We set the valve operation so that the steam supply is cut off early in the piston stroke, say at 25% of full stroke.

After that, the steam still pushes against the piston, but with gradually diminishing force as the pressure and temperature fall. We get less power from the engine, but more power from each pound of steam, which means from each pound of fuel.

We still lose the power represented by the pressure and temperature of the steam when the exhaust port opens. We cannot expand the steam in the cylinder to zero pressure, although the condenser is at substantially zero pressure, because that would require an infinitely-sized cylinder. So there always is some loss at the release into exhaust.

It is more efficient to control the power of the engine by changing the position in the piston stroke at which the steam port closes (cutoff point) than it is to reduce the pressure of the steam going to the engine by partly closing the throttle valve. Connecting the Ahead and the Astern eccentric rods by the Stephenson link enables the cutoff to be changed easily. As the link moves from the Ahead position halfway (Mid Gear) to the Astern position, the steam port closes earlier and earlier in the stroke, until at Mid Gear the steam port doesn't open at all. As the link moves further, from Mid Gear toward Astern, the steam port starts to open and close early in the stroke when the piston is moving in the opposite direction. At the Astern position, the steam port closes as late in the stroke as it did in the Ahead position, but when the piston is moving in the opposite direction.

Therefore, for efficient operation with different loads, the amount of steam entering the cylinder should be regulated by changing the cutoff instead of closing the throttle. This changes the expansion ratio. Early cutoff saves fuel by letting less steam into the cylinder when the cylinder volume is small, so that it expands more times to fill the full cylinder at the end of stroke.

2.3.6 Paddles and Propellers

Mechanical power, from human muscles, had long been applied to vessels through the means of oars and paddles. Besides, there were water wheels in which the power of moving water, acting against paddles, was used to rotate a shaft. It was easy to then visualize a rotating wheel of paddles that would apply the power of a rotating shaft to the water below it. The first steamboats were, therefore, driven by paddle wheels.

Paddle wheels work very well when used in calm water, and with vessels that don't sink deep with a heavy cargo and float high with a light cargo. That is, when the depth of immersion of the wheel differs from its designed depth, as when the ship rolls in a seaway or floats lower with a heavy cargo. Besides, from the naval view, paddle wheels were both very vulnerable to battle damage and occupied valuable side space that could be devoted to guns.

Therefore, from early steam times there was a search for a different propelling system. This became the screw propeller system, which is unaffected by the rolling of the ship and by the amount of load carried (within normal limits), and which, with its machinery, can be below the water beyond the reach of gunfire. The screw propeller came into use about forty years after the first paddlers operated. The choice between paddle or screw propulsion greatly affected the shape of the steam engine employed, but it didn't directly affect the technology used in the engine. However, since the early steamboats were all paddlers, they had to use the early technology. Later on, some paddle steamers used the same latest technology of their times that was used on screw propelled ships. However, some other paddle steamers retained the technology of the middle period right up into modern times.

2.3.7 Superheating the Steam

To make a steam engine run, the steam supplied must have both higher temperature and higher pressure than the exhaust conditions. As long as steam is raised in the boiler, where both water and steam exist together, the temperature and pressure are linked. The higher the temperature, the higher the pressure that the steam creates. Such steam is called saturated steam, meaning that the moment it cools off a bit some of it condenses back into water and the pressure drops.

That is what happens as the steam goes through the engine. The engine subtracts some energy from the steam, cooling and expanding the steam to lower pressure. That causes some of the steam to condense, so that the engine is running on hot, high-pressure fog instead of dry steam. The water drops don't produce power. Since they take up less space than would the same weight of steam, the pressure drops more and the engine produces less power.

If the saturated steam is heated some more after it leaves the boiler, then, like any other gas, it will get hotter. Such steam is called superheated steam. With the greater amount of heat that is in superheated steam, more energy can be taken out of it before it starts to condense. That means that the engine runs on pure steam, with higher pressure, for more of the steam cycle than it would with saturated steam. That means more power from each pound of steam, which means less fuel for each unit of power.

Therefore, there were early attempts to superheat the steam. With low-pressure, low-temperature saturated steam, the steam temperature could be raised quite a bit with success. But as boiler pressures got higher, with the search for greater efficiency, as metals and designs improved, the superheated steam got too hot and the engines failed.

The problem was not that the metals of the boilers, superheaters, and engines could not stand the temperature. The problem was lubrication. As long as engines were lubricated with animal fat (tallow), temperatures were limited to what the tallow would stand. Get it too hot, and it turned to gritty clinker and scored the valve surfaces so they leaked.

Therefore, superheat was abandoned after initial success, because it was better to raise the pressure up to the maximum temperature the lubricant could stand instead of using lower pressure with superheat up to that temperature. Efficiency could not be improved through higher steam temperatures until better lubricants were devised. The history of technological progress is littered with such seemingly small and unanticipated problems that have to be overcome, even though science has told us which way to go.

2.3.8 The Single Cylinder Engine Crosses the Oceans

The single-cylinder engine, using low-pressure, low-temperature steam, could cross the ocean. The first trans-Atlantic steamers operated by Cunard, Collins, Vanderbilt, CGT, and others, were powered by single-cylinder engines, often driving paddle wheels. The typical paddle-wheel engine was of several hundred horsepower, but the largest, on the last trans-Atlantic paddlers, produced as much as 2,000 horsepower.

These vessels were much faster than sail, but they required so much coal for the passage that they could carry only a small weight of freight. Therefore, the freight had to be of high value: passengers, mail, gold and jewels, financial documents, and such. While these steamships established steam marine transportation, they were dependent upon sailing marine transport to deliver to their ports the coal that they used. They were uneconomic for carrying the large part of the world's goods that were heavy and of low value: coal, iron, wheat, cotton, and the like.

2.3.9 Two Cylinder Compound Engine

Raising the steam pressure and temperature meant that an engine could produce the same power with earlier cutoff, thus increasing the expansion ratio to the same pressure and temperature at release as before. The cylinder and piston had to be hotter at the beginning of the stroke, while they were just as cool at the end.

An early Watt engine might accept steam at 40psia and 267F and exhaust it at 8psia and 183F. Thus its cylinder worked over a temperature range of less than 100F. A century later, steam could be supplied at 180psia and 425F, and exhausted to the same conditions as the earlier engine. The later engine worked over a temperature range of 240F.

It was found that when any cylinder worked over too large a temperature range, much steam was wasted heating up the cylinder and piston, which had cooled to the exhaust temperature, back up to the temperature of the incoming steam. The obvious improvement was to pass the steam through two cylinders, first a high-pressure, high-temperature one, then a low-pressure, low-temperature one, so that each cylinder worked over a smaller temperature range.

2.3.10 The Compound Engine Makes Long Voyages

The engine with two stages of expansion was called the compound engine. Alfred Holt, about 1868, built and operated the first successful long-distance freighters using steel hulls, screw propeller, and compound engines. With the opening of the Suez Canal in 1869, these ships became successful in the Europe to Far East trade, over distances long thought impractical for steam.

2.3.11 The Triple Expansion Engine Conquers the Seas

The logical extension of the compound principle to three stages of expansion followed as higher steam pressures and temperatures were found practical. One important change was the development of petroleum lubricants that retained their lubricating qualities at much higher temperatures than did tallow. Another change was the development of reliable steel plates of uniform quality for building boilers that could withstand high steam pressures.

The first really successful triple expansion installation was in the steamship Aberdeen, of 1881, for the England to Australia trade, about as long a voyage as one could have. The triple expansion engine proved so economical of fuel and so durable that it took over almost all the world's freight business.

The triple expansion engine powered the world's freighters from 1881 until the last big production run of these engines to power the Liberty ships of World War 2. By then they were outdated, but engines were needed in a hurry, engines that could be built in any large machine shop, and, in any case, many were expected to be sunk in the war. They weren't expected to last long.

2.3.12 Quadruple Expansion Engine

Naturally, as techniques improved, it was seen that quadruple expansion engines would come next after the triple expansion engine. They did, but they were developed only for naval ships, passenger liners and the fastest freighters, where high power was required and only high efficiency engines could do that without burning too much fuel. The high-power reciprocating engine had developed about as far as it could. The enormous weights reciprocating at high speed imposed severe stresses on all parts and imposed great vibrations onto the ship's hull. Naval acceptance trials, where the engines were driven as hard as possible to demonstrate that the ship reached the required speeds, produced hair raising stories. Not only the noise and heat, but the air filled with water and oil vapor, the intense vibration, the water flung about because some bearings required cooling water hosed upon them, all contributed to a modern vision of Hell. The reciprocating engine was developed up to about 15,000 horsepower.

The development of the quadruple expansion marine reciprocating engine came to a halt when it was overtaken by a radically new type of steam engine.

2.4 Present Marine Engines

As long as steam pressures and temperatures were low, only the piston engine could extract power from steam. (The very first steam-driven device was a toy turbine, two thousand years ago, but all that it turned was itself, like a rotating lawn sprinkler.) As steam pressures and temperatures increased, so did the speed at which steam would escape through a hole, and, even better, through a specially-shaped nozzle. Such a nozzle converts the energy of the pressure and temperature of the steam into high-speed motion of the steam at low pressure. When there is sufficient weight of steam per second traveling at sufficient speed, there is a force that can be used to turn a shaft that is fitted with vanes to catch the steam.

The force exerted by a moving stream of water had been used in advanced waterwheels from about 1850. Most of these used high-volume streams moving rather slowly, but one type (Pelton wheel), used in mountainous areas where the water could be piped a great distance downhill, used much less water at much higher pressure. The water squirted from the nozzle against a wheel with cup-shaped vanes that reversed the water's direction. When the wheel rotated so that the vanes were going at half the speed of the water, the water ended up with no speed at all, and simply drained away from the cups, a very high efficiency.

The steam problem was that one had to use a smaller weight of steam travelling at much higher speed. That required the technology to build high-speed machines, and the insight that the speed of the steam could be caught efficiently only by doing so in many successive stages, each capturing only a portion of the steam's speed. Turbines, therefore, had to be rather large, and hence powerful, machines. These problems were worked out in the 1890s, and steam turbines were used to drive electrical generators in central generating stations.

Turbines first came to sea about 1900 for driving torpedo-boat destroyers, the fastest ships in the world. By 1907, the marine turbine was sufficiently developed, and so recognized, that it powered the British battleship Dreadnought and the two Cunard liners Mauretania and Lusitania. The Dreadnought revolutionized battleship design, and the Mauretania held the world's sustained speed records (one to three days) for the next twenty years.

The turbine had many advantages that outweighed its greater cost. For a given power, it was smaller and lighter, particularly when gears were applied so that the turbine could turn much faster than the propeller it drove. It didn't vibrate. It was totally enclosed. It rarely needed maintenance. And its bearings were outside the steam path. Doesn't sound like much, that? It enabled the steam temperature to be raised far beyond the capabilities of the lubricating oil. Steam pressures and temperatures were now governed by the alloy steels used for boilers and turbine vanes, and efficiency climbed as the knowledge of how to use such temperatures developed. (This author was once engaged in the manufacture of boiler feed pumps for a central generating station. Each pump developed 3,200 psi, and took 2,000 hp to drive it. Think of the power of the engine whose boilers required so much water at that pressure.) Marine turbine plants did not get that large, but steam turbines drove all the large ships of the next fifty years. The pressure and temperature of steam rose steadily as that both reduced the amount of fuel used and the weight and space required for the engine plant. From the 1930s through World War 2, the standard U.S. Navy installation used steam at 650psi and 800F. Later Soviet installations used 910psi and 932F, and the U.S. tried, but later discarded, installations at 1200psi and 950F. Commercial marine installations were considerably more conservative. Power increased up to about 30,000 hp per unit.

2.4.1.1 Nuclear-Heated Steam Turbine Engine

The nuclear powered ships and submarines (like the nuclear powered central electric generating stations) still use large steam turbines. The nuclear reaction produces heat, which is used to generate steam that is used in a conventional turbine. The nuclear reactor, in this sense, is really just a boiler. However, the limitations of the reactor materials prevent the use of such high temperatures, and hence of such high pressures, as were developed for oil-fired boilers. However, since the cost of the nuclear "fuel" is so low, the lowered steam efficiency is not that significant.

2.4.2 Diesel Engine

While the steam turbine took over the realm of high-power marine engines, the reciprocating engine lives on for smaller installations, but in an entirely new guise as the Diesel engine. The steam engine is an external combustion engine in which the combustion of fuel in air heats water, the working fluid, into steam, which then is sent to the working cylinder to perform work. The internal combustion engine uses the combustion air as the working fluid itself, by heating the air directly inside the cylinder as the fuel is burned therein.

In the steam engine, the steam, the working fluid, is compressed by being generated by heat from water in the boiler, under conditions of high pressure. It takes much less energy to pump the small volume of water into the boiler than can be obtained from the large volume of steam produced. The high-pressure steam is then expanded to extract its energy in the steam cylinder, or in the nozzle of the steam turbine.

In the internal combustion engine, the working fluid is air. The air is first compressed in the cylinder, then heated by combustion of the fuel inside the cylinder, and then expanded. Compression of the air requires energy, but more energy is available when expanding that air because the heat produced by combustion has raised the pressure of the air. The higher the initial compression, the more efficient is the cycle, just as high steam pressure makes a steam engine more efficient.

In the last period of reciprocating steam, some small high-speed engines were developed for special purposes, such as driving electrical generators. The mechanical solutions to high-speed operation, such as forced-feed lubrication and enclosed crankcases, later formed the genesis of the internal combustion engines.

There are two types of internal combustion reciprocating engine, spark ignition and compression ignition. In the spark ignition engine the fuel is mixed with the air before it is sucked into the engine, and the mixture is ignited at the appropriate time by an electrical spark inside the cylinder. The initial compression is limited by the temperature developed by compression to that below the ignition temperature of the fuel mix. The fuel has to vaporize easily into air and has to have a high ignition temperature. 100-octane gasoline is the best available for this purpose.

In the compression ignition engine, the fuel is not mixed with the air until after the air has been compressed. Indeed, the air is compressed so much that its own temperature is sufficient to ignite the fuel as it is sprayed into the cylinder. Such engines could use gasoline, but in practice they use the cheaper diesel oil (which also lubricates the fuel injector mechanism). Because the initial compression is so much higher, diesel engines are more efficient than gasoline engines. Therefore, for all serious marine uses, diesels are chosen over gasoline engines.

Because of the high cylinder pressures, diesel engines have to be very strongly built. Also, because the initial diesel engines did not turn particularly fast, they were large and heavy for their power. However, because they dispensed with the heavy boiler and its auxiliary machinery, the installation was lighter and smaller, as well as being more efficient. Two lines of diesels developed. The first were built just like the reciprocating steam engines, but with many mechanical refinements such as forced lubrication and enclosed crankcases. These first powered medium-sized merchant ships, and now are installed in sizes up to 20,000 hp in large bulk carriers.

The second line of diesels were the smaller high-speed diesels that, from the outside, look much more like very large truck engines and are rather similar to diesel locomotive engines. These power smaller vessels such as fishing boats, ferryboats, tugs, small craft of all kinds, special-purpose vessels, and the like. This type is also used in those submarines that are not nuclear powered.

2.4.3 Gas Turbine Engine

Just as the steam turbine developed to overcome the limitations of the reciprocating steam engine, so the gas turbine developed to overcome the limitations of the reciprocating internal combustion engine. The gas turbine uses the familiar sequence of compression of air, burning of fuel in that air, and expansion of that heated air to produce power. However, in the gas turbine this all occurs as one continuous flow through a machine that rotates at high speed. The entry end of the rotating shaft carries the compressor blades that suck in the air and compress it to several atmospheres pressure. As in many steam turbines, this is done in many stages of blades, but here each stage contributes a small pressure increase. Then this compressed air flows through burner chambers in which fuel is sprayed into it and burned. The heated air, at the same pressure but much greater volume because of the heating, flows out through nozzles against the turbine blades. The force of the flowing air against the turbine blades provides the power to both turn the compressor blades and to turn the power output shaft. Most of these turbines use two separate turbines in succession, the first to turn the compressor and the second to provide the output power.

As in all heat engines, the limiting efficiency is determined by the difference between the high temperature and the low. That is, between the highest temperature that the turbine blades can stand and the temperature of the incoming air. Because the turbine blades are continuously exposed to the hot gases, they run at that temperature. In a diesel engine, although the combustion temperatures are higher, the cylinder walls and the piston are exposed only intermittently to them and are cooled by the cooling system. Therefore, the gas turbine cannot be as efficient as the diesel. However, the gas turbine is light and powerful. Therefore, it is used only for special applications, such as in hovercraft, for giving sprint power to naval vessels that would cruise on diesel power, and lately, as efficiencies have been improved, as the sole power plant for naval vessels of destroyer size.

Marine Steam Engineering Basics
for
Touring the Steam Ships Berkeley and Medea
of the
San Diego Maritime Museum

John Forester, MS, PE

1 Steam Properties

1.1 Our Steam Engine Plants

Steam engines work by using the expansion of high-pressure steam to push against moving pistons in the cylinders of reciprocating engines, or against the moving vanes of steam turbines. When the Berkeley and the Medea were built, steam piston engines, after a century of development, were universal for marine use, and they continued up through the Liberty Ships of World War II that deliberately used an old design that was easy to build..

Change was coming. In the year that Berkeley was being designed, an experimental turbine-powered vessel sneaked into the British Navy's parade for Queen Victoria's Golden Jubilee, and outran Britain's fastest destroyers. Ten years later, the Diesel engine came into marine use, at first for small vessels, so that nowadays ships are powered either by turbines (steam or gas) or by diesels. The steam reciprocating engine, nowadays, is just a historical artifact, but it represented the very best that the technology of the time could produce.

The Berkeley's steam engine and boilers are typical of almost the highest development of the marine reciprocating piston engine, the three cylindered triple-expansion engine supplied with steam from the oil-fired straight watertube boilers. The Medea's steam engine and boiler, although built six years later, are typical of the previous generation of steam plants, the two-cylindered compound double-expansion engine supplied with steam from a firetube boiler, originally burning coal but since converted to oil.

The Berkeley was originally equipped with two firetube Scotch boilers, burning coal, similar in principle to the boiler of the Medea but different in design. After two years of service, the Berkeley was converted to oil, the same fuel used by the locomotives of her owner, the Southern Pacific Railroad. After twenty-six years of service, the two Scotch boilers were replaced by the present four watertube boilers.

1.2 The Steam Engine System

The steam engine plant consists of far more than the steam engine itself. The water and steam run through a continuous cycle of water boiled into steam, used in the engine, condensed back to water, and then pumped back into the boiler for reuse, a cycle first studied scientifically by the French engineer Sadi Carnot in 1824, about a century after the first steam engines had been built.

Therefore, the complete steam plant consists of a furnace in which to burn the fuel, the boiler in which the heat from the furnace is used to boil water into steam, the steam engine which turns the heat of the steam into mechanical power, the condenser which condenses the steam back into water, and the feed pump that pumps the water back into the boiler. We will look at each of these machines, but first you must learn a little about water and steam.

1.3 Water and Steam

1.3.1 The Temperature Cycle and Efficiency

Carnot showed that the possible efficiency of any heat engine depends on the temperature difference between the highest and the lowest temperatures of the working fluid, the water and the steam in our ships, divided by the highest temperature. The greater the temperature range, and the hotter the highest temperature, the more power produced for the fuel burned. The highest temperature is limited by the strength of the materials from which the boiler, steam pipes, and engine are made. In the highest development of the piston steam engine, the limit was set by the lubricating oil for the valve and piston; the steam was so hot that even special thick oil ran like water, but the Berkeley never approached those temperatures. Her maximum steam temperature was about 425 °F. The lowest usable temperature is that of the surroundings. There's no point in making a lower temperature, as in a refrigerator, because it costs much more energy to "make the cold" than you could get by using that "cold." (That's also explained by the Carnot cycle, for a refrigerator is a heat engine run in reverse.) However, since a ship floats in an infinite supply of cold water, the temperature of the seawater is the lowest temperature we can use. With the temperature range that the Berkeley used, the theoretical efficiency could be no higher than about 30%. Probably, only about 10% or 15% of the energy in the fuel could be actually used in driving the ship.

1.3.2 Boiling Temperature

Now that you have learned that the engine must work between the highest usable temperature and the lowest obtainable temperature, you need to know the properties of water and steam between those temperatures. You probably know that when water boils into steam it gets much larger, occupies much more space or volume. You probably also know that the air pressure around you at sea level is about 15 pounds per square inch. You probably all know that the boiling temperature of water into steam is 212 °F, and some of you know that if you go to higher altitudes, where the air pressure is lower, water boils at a lower temperature, making cooking slower, while if you confine the steam in a pressure cooker the temperature goes up to make cooking quicker.

There is an easy explanation for this. As water, the molecules are very close together, sticking together in fact, although they slip past each other, roll over each other, with little friction, making water a liquid. As steam, the same molecules rush about independently of each other, taking up much more space and making steam a gas, just like any other gas.

Temperature really refers to the speed with which the molecules of water are moving. At room pressure, very few of the molecules move fast enough to jump into the air against the pressure of the air and take up much more space as cold steam, or water vapor, or humidity, whatever you want to call it. That's room-temperature evaporation. As temperature increases, more and more of the molecules of water get fast enough to make the jump between the liquid and the gas against the pressure of the gas. At boiling temperature, enough of the molecules are going fast enough to push the air away and fill the space with steam. If the space is enclosed, as in a pressure cooker or a boiler, this increases the pressure. If the pressure is increased, then it is more difficult for the water molecules to jump into the gas, the steam, and take up more space, and some go slow enough to be captured again into the water.

Therefore, for every pressure there is a temperature at which water and steam can exist together. Contrariwise, for each temperature, there is a pressure at which water and steam can exist together.

The steam engine designer always works in absolute pressure, starting from zero pressure, as in the vacuum of outer space. This means that sea-level pressure is 15 psia, meaning pounds per square inch absolute. You must always remember that we exist at 15 psia. (The operating engineer considers ambient pressure to be zero. Thus his steam pressure gauges read pressure above ambient, or 15 psi less than the absolute pressure, and he measures pressure that is lower than ambient in inches of mercury of vacuum, which you will see on the gauges in the engineroom. 30 inches of vacuum is substantially equal to zero pressure.)

Here is a short table of steam pressures, temperatures, and volumes.

Steam Characteristics

Pressure, Pounds per Square Inch, Absolute	Boiling Temperature Degrees Fahrenheit	Volume, Cubic Feet per Pound
1	102	335
2	126	174
5	162	73
10	193	38
15	213	26
20	228	20

40	267	10.4
60	293	7.1
80	312	5.4
100	328	4.4
120	341	3.7
140	353	3.2
160	363	2.8
180	373	2.5
200	382	2.3

When considering the volume of a pound of steam, consider that a pound of water has a volume of only 0.016 cubic feet. Therefore, even at 200 psia, when water turns into steam, its volume increases by about 14 times.

You can see that if you can use the cold seawater as the lowest temperature, say 60 °F, the pressure would be less than 1 psia, and 1 pound of steam would require more than 340 cubic feet of space. The high-pressure cylinder of the Berkeley would hold about 2 pounds of steam, so that if that were expanded all the way to less than 1 psia pressure, it would occupy about 700 cubic feet, about the volume of a bathroom. That's just too large a cylinder to be practical. Therefore, the steam was not expanded to this volume, but to the volume allowed by the largest practical cylinder.

However, that doesn't say that the lowest cylinder pressure was about 5 psia. That was the pressure at which the steam was exhausted from the cylinder, but all during the stroke the back side of the piston was under the least pressure that it was possible to obtain, that of steam at the temperature of the cooling seawater, and hence less than 1 psia. If the condenser had any significant pressure in it, that is, it was showing less than 30 inches of vacuum, the engineer investigated to see what was wrong.

The very earliest engines didn't run on any significant steam pressure, only on the difference between steam at room pressure, 212 °F, and the vacuum of steam at room temperature, 60 °F. They were very inefficient, partly because of the small temperature range, which Carnot's cycle showed could not be efficient. However, they showed that it was important to have as good a vacuum as possible as the lowest pressure in the system.

1.4 Multiple Expansion Cylinders

You have learned the relationship between the temperature and the pressure of steam for containers in which both steam and water exist together. This is called wet steam, because if the temperature drops at all, some of the steam condenses into a fog of water droplets. For the moment, consider that the engine is running on wet steam direct from the boiler.

Suppose that the boiler steam is at 180 psia, which is approximately the pressure in the Berkeley's boilers, and 373 °F (assuming wet steam for this discussion). This steam could be allowed to fill a cylinder, pushing its piston all the way down, and doing a lot of work. However, when it was time for the piston to come back up the cylinder, the steam would have to be allowed to escape from 180 psia and 373 °F into either the atmosphere or into the condenser. That would waste much of the energy that the boiler had worked so hard to put into the steam.

Instead of wasting that energy, only a small amount of steam is allowed into the cylinder at the top of the piston stroke. Then the supply of steam is cut off, and the pressure of the steam gradually drops as the steam pushes the piston downward, until the steam has expanded to about 5 psia and 162 °F, while the pressure against the opposite side of the piston is maintained at effective zero. Then all the energy is got from the steam that it is practically possible to get.

There are several troubles with having all the expansion in one cylinder, but the big theoretical problem that it is impossible to overcome is that the cylinder must start at 373 °F at the start and will be cooled by the steam inside to 162 °F by the end of the stroke. Then, for the next stroke, the cylinder has to be heated up again with steam at 373 °F, thus wasting a lot of steam that condenses into water as it heats up the metal of the cylinder and piston. Furthermore, that cylinder and piston must be very large and very heavy, heavy because they must be strong enough to withstand the initial pressure, but large enough to contain the fully expanded steam. This means that it will take an enormous amount of steam to heat them up for the start of each stroke.

The answer to this problem is to have multiple cylinders, each of which operates over only part of the total range of temperatures and pressures. Thus each cylinder is heated and cooled only part of the total range for each of its strokes.

The highest pressure that was used for single cylinder marine engines, (in marine engines efficiency of fuel is the paramount consideration), was about 45 psia and 275 °F. The first development was an engine in which the expansion occurred in two cylinders, the high-pressure cylinder and the low-pressure cylinder, called the compound engine. This is the type of engine installed in the Medea.

As technology advanced to make higher boiler pressures and temperatures practical, the number of expansions was increased to three, with the high-pressure, intermediate-pressure, and low-pressure cylinders, as in the Berkeley and on into the Liberty ships of World War II.

1.5 Later Developments

Some ships went to even higher boiler pressures and temperatures and used quadruple-expansion engines, but this development was cut off by the introduction of the turbine in place of the reciprocating piston engine. Some of the triple-expansion engines actually had four cylinders, with two low-pressure cylinders of medium size, to keep the reciprocating weights down and to reduce vibration and bearing loads.

In the highest power applications of the reciprocating piston marine engine, as in warships, the engineroom at full power was full of vapors of oil and water. Some of the bearings had to be water-cooled with hoses spraying on the rotating crankshaft. The forces required to change the direction of the pistons at each stroke limited the speed at which the engine could be run. The vibration was terrific. While oil was pumped into the steam for lubricating the valves and pistons, lubrication was still a problem and the oil had then to be removed from the condensed water before it could be returned to the boilers. The engines needed frequent maintenance.

The turbine engine had many advantages. Because it had pure rotational motion, it didn't produce vibration. It could be made with an enormous number of steam expansions, like a piston engine with many expansion cylinders. Because its wearing parts, the shaft bearings, were outside the steam chambers, their lubrication did not limit the steam temperatures that it could use. Because its vanes moved at very high speed, it took much less space for a given horsepower than the reciprocating engine with its slow-moving pistons. It cost more because it was more difficult to manufacture, but it did a much better job.

2 The Berkeley's Steam Plant

2.1 Boilers

The four boilers are not the original boilers, which were two coal-burning Scotch fire-tube boilers, such as were installed in the Titanic fourteen years after the Berkeley was built. The present boilers are oil-burning Babcock and Wilcox cross-type straight-tube water-tube boilers, a typical installation for merchant ships and industrial plants of the time, probably 1926[1].

Fire-tube boilers have a large barrel containing the boiling water and steam, with tubes running from end to end through which the fire and combustion products flow to heat the water. Water-tube boilers are the opposite. Their tubes are full of water and steam and are heated by the fire on their outsides as they run through the firebox.

The Berkeley's boilers delivered steam at 165 pounds per square inch gauge pressure, or 180 psi absolute, which was superheated a further 50 degrees to 425 degrees F.[2]

2.1.1 Steam Drums

Across the top of each boiler is the horizontal steam drum, called that because it was about half full of water with the rest filled with steam, and from which the steam was taken. It was very important to keep the right amount of water in each boiler. Too much water, and you got water into the engine. Too little water, and the water tubes in the firebox would run dry, get overheated, and burst. You can see the glass tubes of the two water gauges for each boiler, and the three emergency water cocks for use if you can't see the glass gauges. If the water is at the correct level, you should get water out of the lower cock, steam out of the upper one, and mixed water and steam out of the middle one. You can also see the steam pressure gauges, which the fireman used as guides to regulate the amount of fuel being burned.

2.1.2 Firebox and Water Tubes

Looking into the firebox through its side opening, you see that the space above the fire is roofed by the sloping water tubes. The flames of the fire, and its hot gases, flow between and around the many layers of tubes that are above the fire. If you look into the side cleaning doors, you will see the many layers of tubes above the firebox. The tubes are sloped so that as the water boils into steam, the bubbles rise up the slope, making the water circulate throughout the boiler, from the drum, down the downcomers, up the sloping tubes as some of the water boils into steam, up the risers, and back to the steam drum, where the steam bubbles free out of the water and into the steam pipes and the water is returned for another circuit.

2.1.3 Downcomers and Risers

Riveted and forged into holes along the length of the steam drum are the many hollow forged steel downcomers, each with a zig-zag shape. The outer face of each downcomer has many square holes, each closed by a steel plate. Through some opened square holes you can see the ends of the water tubes, four per square hole, whose ends are expanded, steam-tight, into the inner sides of the downcomers. The water came down the hollow downcomers to enter the water tubes, which crossed the firebox.

On the other side of the firebox are risers, made just like the downcomers, from the top of which the mixture of water and steam returned, through large cross tubes, to the steam drum at the top of the boiler.

You can see the oil burners below the downcomers, giving off red light and a roaring sound, just as if oil were being burned today.

2.1.4 Superheater Tubes

At the start I told you that whenever steam and water are together in a container, for each temperature there is one pressure. Raise the temperature, and more steam is made and the pressure goes up. Lower the pressure, say by using some steam in an engine, and some of the water boils into steam until the temperature is reduced to that appropriate to the pressure. I also told you that heat engines get more efficient if the high temperature can be raised.

That's what a superheater does. When the steam leaves the steam drum, it is no longer in contact with water, but is just a plain gas, just like air. The steam from the steam drum goes through another set of tubes that run across the top of the firebox above the water tubes. They can't be right in the fire, or, with no water in them, they would get red hot, weaken and burst. However, above the water tubes the combustion gases are just hot enough to heat the steam to a temperature that is still safe but makes the engine more efficient. That superheated steam can be expanded further in the cylinders of the engine before it starts condensing into water.

2.2 Steam Pipe

The big asbestos-covered pipe carries the steam from the boilers to the engine room. Each boiler has its own stop valve, so that any boiler can be shut down without shutting down the others. Somewhere up there, too, are the safety valves that would let steam escape up the relief pipe next to the stack if either boiler got too hot with too much pressure. The steam pipe makes the U-bends that you see above so that when it expands from room temperature as the hot steam enters it, it can flex a bit instead of trying to push the ship apart and breaking in the process.

2.2.1 Throttle Valve

Now we are in the engine room. The first thing the steam reaches is the throttle valve that controls the amount of steam reaching the engine from the boilers. There it is, up at the top where the steam pipe reaches the engine. The throttle valve is operated by this long rod here, from the throttle-valve lever that is at the engineer's station.

2.3 Engine

The Berkeley's engine is a three-cylinder, triple-expansion, vertical, double-acting engine. Triple-expansion means that the steam passes through the high-pressure, intermediate-pressure, and low-pressure cylinders in turn, each one larger than the one before but using steam at lower pressure and lower temperature. Vertical means that the cylinders are above the crankshaft, typical for both steam and diesel marine propeller installations.[3] Double-acting means that the cylinders are closed at both top and bottom, so that the steam can push the piston both down and up, in contrast to the automobile engine in which the pistons can push only downward. These characteristics make the steam piston engine more complicated than a typical car engine.

2.3.1 Cylinders, Piston Rods, Connecting Rods, Crankshaft

Before you is the crankshaft with its three crank throws, one for each cylinder, equally spaced at 120 degrees of rotation. Each throw has its connecting rod going up to the crosshead guide. Because the cylinders are closed at both top and bottom, the connecting rod cannot go directly to the piston. The piston rod extends from the bottom of the cylinder, coming out through a steam-tight hole in the cylinder head, and is kept moving straight by the crosshead and its guide. The crosshead guide is that portion of the frame of the engine that is machined straight with the cylinder bore so the crosshead must move straight up and down in line with the cylinder. The connecting rod then connects this crosshead to the crankshaft.

2.3.2 Cylinders: High Pressure, Intermediate Pressure, and Low Pressure

The cylinders all have 36" stroke, but their diameters are different, as are their initial steam pressures: 22" dia @ 180 psia and 425°F; 34" dia @ 68 psia and 300°F; and 56" dia @ 27 psia and 244°F. The expansion ratio of the steam in each of the last two cylinders is easily calculated as the ratio of its volume to the volume of the one before. The expansion in the HP cylinder depends on the degree of cutoff of the high-pressure valve, which is probably about 40%, giving an expansion ratio of 2.5. The total expansion ratio of the whole engine is the product of each of the expansion ratios, or about 15 times. In going through the engine, the steam is expanded to about 15 times its initial volume, thus getting the maximum practical work out of it, according to the technology of the time.

Cylinder	Initial Pressure, psia	Initial Temp. °F	Diameter, inches	Capacity, cu. ft.	Expansion Ratio
HP	180	425	22	7.92	2.4
IP	68	300	34	18.9	2.4
LP	27	244	56	51.3	2.4
Exh	9	188	-	-	-

You probably think of steam as an airy nothing, not weighing much at all. Well, it isn't. Since the capacity of the high-pressure cylinder is 7.9 cu. ft. and the cutoff is at about 40% of the stroke, with steam at boiler pressure, this cylinder will admit about 1.25 pounds of steam per stroke. At 2 strokes per revolution and 125 rpm, that is 9.4 tons of steam per hour. Nine tons of steam per hour is what it took to push the Berkeley along at 14 knots, all boiled from 9 tons of water in the boilers, used in the engine, condensed back into water in the condenser, and finally pumped back into the boilers.

2.3.3 Engine Horsepower

The traditional way to measure the power of a reciprocating engine was to measure the pressure of the steam during each part of the stroke. For triple-expansion engines such as those on the Berkeley, this must be done for each cylinder and the results added. This measures the exact power of the steam provided in the engine, but does not account for the power that is absorbed by the engine in moving its own parts. The indicator produces a diagram that looks like a low boot or high shoe. The back of the shoe shows the increase in pressure when the steam is admitted. The level top of the diagram shows the continued pressure as the piston moves while the steam valve is still admitting steam. The curved sloping toe of the shoe shows the decrease in pressure as the steam expands after the steam upply is cut off. The tip of the toe shows the drop in pressure as the steam is exhausted, while the sole of the shoe shows the pressure during exhaust (condenser pressure or, in a multiple expansion engine, the pressure going to the next cylinder in the sequence). The area of the diagram indicates the power of each stroke of the piston.

The Berkeley's engine tested at 1,163 IHP (indicated horsepower) at 122.5 rpm. This gives 16 pounds of steam per indicated horsepower hour, which is about average for the time, design, and boiler pressure and temperature.

2.3.4 Valves: High Pressure, Intermediate Pressure, Low Pressure

Each cylinder has its own steam-control valve, which admits higher-pressure steam to one end of the cylinder while allowing the lower-pressure steam to escape from the other end of the cylinder. When you looked down on the top of the engine from the main deck, you saw the three circular cylinder heads with, also, a smaller circular cover and two larger rectangular covers. The small circular cover encloses the piston-like valve of the high-pressure cylinder, while the rectangular covers enclose the flat slide valves of the other two cylinders.

Each slide valve operates inside a steam chest, a rectangular cavity which is filled with steam at high pressure. Each slide valve is like a flat, rectangular box with its open side pressed against the machined flat face of the cylinder casting. The valve is pressed against the cylinder face by the difference in pressure between the steam that surrounds it and the exhaust steam that is inside it. The cylinder face has three long, horizontal, narrow ports cast into it. The upper and lower ports connect to the top and bottom of the cylinder. The center port leads to a passage that goes out the side of the cylinder casting as the exhaust. When the valve moves down, it uncovers the upper cylinder port to let steam in to the top of the cylinder to push the piston down, while it connects the lower cylinder port to the exhaust port, to let the steam in the bottom of the cylinder out to exhaust. The top and bottom lips of the valve are designed with particular widths, so that the steam is allowed in and out at the points in the piston stroke desired by the designer.

The higher the pressure of the steam, the harder the valve is pressed against the port face and the more power it takes to move it. Therefore, when steam pressures increased, the flat slide valve was replaced by the piston valve for at least the high-pressure cylinder, as in the Berkeley. The piston valve is a circular piston with an hour-glass shape, in which the steam pressures pressing inward from each end balance each other, as does the exhaust pressure from the center outward toward each end. (Some piston valves had steam at the ends, others had the steam in the center, but they were balanced either way.)

2.3.5 Valve Gear

Each valve is moved up and down by an eccentric and eccentric rod. You can see these eccentrics in pairs beside each crankshaft throw. Each eccentric is a circular disc mounted on the crankshaft, but mounted off-center (hence the name: eccentric). Therefore, as the crankshaft rotates, the eccentric appears to move up and down. Because each eccentric is circular, it can turn within the strap that surrounds it, thus pushing and pulling the eccentric rod up and down as the crankshaft turns. This up and down motion of the eccentric rod, which works like a connecting rod, is passed to the valve rod to drive the valve up and down. The eccentric is set a little more than 90 degrees ahead of the motion of the piston, so that the valve moves down to open the top end of the cylinder to steam when the piston is at the top of its stroke, ready to apply power in the new direction. At the same time, other part of the valve opens the other end of the cylinder to exhaust, letting the used steam leave the cylinder.

Now, remember what I said about using the steam expansively and how that made the engine more efficient? The valve is so made that it closes to steam when the piston has moved only partway through its stroke. Therefore, for the rest of the stroke, while the steam keeps pushing on the piston, its pressure and temperature fall. In fact, after the expansion in the high-pressure cylinder, the steam has cooled enough, because of the work that it has done on the high-pressure piston, that part of it has condensed into water in the form of fog.

2.3.6 Reversing Valve Gear

As I just said, and as you can see, each cylinder has a pair of eccentrics, not just one, to operate its valve. One eccentric is positioned on the crankshaft for ahead rotation, the other for astern rotation. The two eccentric rods are connected to the opposite ends of the curved link that you see above you, and the block that runs in the slot of the link is the lower end of the valve operating rod. When that link is moved to one side, only one eccentric rod moves the valve, say in the timing required for going ahead, while when the link is moved to the other side, the other eccentric rod moves the valve, for movement in the opposite direction.

This link, called the Stephenson link because it was first designed in his locomotive design office, has another advantage. As the link is moved a little way from one end of its travel, both eccentrics contribute to the motion of the valve. This changes the cutoff, the position of the piston at which the valve stops supplying steam to the cylinder. This changes the amount that the steam will expand in the cylinder for the rest of the stroke. Changing this isn't particularly important for ships, which usually run at full design speed for most of their voyages, but for locomotives, which require enormous pulling force to start a train or to pull it up a grade, but which require much less force to keep the train rolling on the level, the variable cutoff allowed the use of long cuttoff and much steam, although inefficiently, for starting the train, but short cutoff, using less steam but using it more efficiently, for just rolling along. If the same pressure drop were obtained by partially closing the throttle valve, most of the energy already put into the steam would be lost and the engine would operate very inefficiently.

The link is curved to a circle with the same radius as the length of the eccentric rods, so that moving the link does not, of itself, change the position of the valve.

2.3.7 Bypass valves

As I said, high-pressure steam from the boilers goes only to the valve of the high-pressure cylinder. That's fine when the engine is running; the steam has to wait in the steam pipe until the high-pressure valve opens to one end or the other of the cylinder. However, it is different when the engine is stopped and you want to start it. Remember what I said about using the steam expansively; the valve may be closed for both ends of the cylinder. Then you can't start the engine because no cylinder can receive steam. To start the engine, you may have to admit steam to the other cylinders, just until the engine starts moving. Well, one of the valves will be open to steam, if it could get steam. Up at the side of the cylinders are small steam pipes running from the throttle valve through small valves marked Bypass Valves to the valve chests of the intermediate- and low-pressure cylinders.

When the engineer needs to start the engine, and it won't start just by opening the throttle valve, he can open either of these bypass valves to let a little steam into the valve chests of the other cylinders just to get the engine moving. Once it is turning, he then closes the bypass valves to stop wasting high-pressure steam in the low-pressure cylinders.

2.3.8 Power Reverse Gear

The Stephenson links of the valve gears of all the cylinders are all shifted together, by the link rods, cranks, and wayshaft that connect them. For the Berkeley, this would have to be done for every crossing of San Francisco Bay. Working this by hand would be hard work, and slow.

Therefore, this shaft is rotated by the power reverse cylinder. The steam to this cylinder is controlled by a small valve worked by the engineer through the lever that has detent stops marked Ahead and Astern for the power reverse valve positions that make the power reverse piston go up or down.

2.3.9 Cylinder Drains

Also up alongside the cylinders you will see the other small valves marked Cylinder Drains, which are worked by long shafts from the engineer's position. Consider starting the engine from cold. When steam enters the cold engine, much more of the steam will condense until the valve chests, valves, cylinders and pistons heat up to the temperature of the steam. That will make a lot of water in the cylinders. If, when the piston approached the end of its stroke, the space remaining was filled with water instead of steam, the piston would hit the water just as hard if it had hit the cylinder head directly. That would cause great damage to the engine. Therefore, each cylinder is fitted with these drain cocks at each end, to let the water out as it forms, until the engine gets up to working temperature.

When you see movies of steam locomotives starting out, you often see bursts of steam blowing sideways from the cylinders. It looks spectacular, and sometimes is done just for show, but its real purpose is to blow the condensed water out of the cylinders until they get to operating temperature, just like the cylinder drains on the Berkeley's engine.

2.4 Condenser

The low-pressure steam escapes from the low-pressure cylinder through the condenser trunk into the condenser, which is a large chamber that is cast as part of the frame of the engine. You can see the large rectangular condenser trunk extending downward from near the low-pressure cylinder. Compare this with the small steam pipe (much smaller than the insulation that encloses it), and you will have an idea of how much the steam expands when going through the engine. It expands about 13 times.

The condenser is the reverse of the boiler. Remember that the boiler takes water and passes it through tubes that are heated by the fire until it turns into steam. The condenser is a similar chamber through which a nest of tubes pass. However, these tubes convey the cooling water, while the exhaust steam fills the chamber. The condenser consists of three chambers, the center of which, and much the largest, is the vacuum chamber into which the exhaust steam flows. At each end of the condenser is a separate water chamber, closed by the cover that you see. These two water chambers are connected by many tubes that go straight through the main condenser chamber. Cold seawater is sucked in from overside by a circulating pump, passed into one water chamber, through the tubes, where the water picks up heat by condensing the steam that surrounds the tubes, is collected in the other water chamber, and then returns overside through the cooling water outlet.

2.4.1 Condensate (Air) Pump

Remember the discussion about steam at the beginning? Steam can exist at room temperature if the pressure is low enough, in a partial vacuum. If the engine is able to use very low-pressure, low-temperature steam, it will be more efficient. The condenser exposes the used steam to tubes cooled by cold seawater. Therefore, the pressure can be very low and the engine most efficient. However, the condenser will eventually fill up with water that is condensed from the steam (and with the small amount of air that was originally disolved in the boiler feed water). Therefore, the condenser is emptied by the Condensate Pump. This is also called the Air Pump, because it removes both the condensed water and the air that accumulates wth it. Because the water has a much smaller volume than the steam from the boiler, the condensate pump can be much smaller than the engine itself.

The condensate pump is a vertical pump with a single steam cylinder and two water cylinders. One water cylinder is driven directly by the steam cylinder, the other is driven by a rocking beam pivoted so that as one water piston descends, the other ascends. The steam valve is actuated by the motion of the rocking beam, so that when the piston moves down the valve is also moved down, ready to admit steam to the bottom of the cylinder to drive the piston up again.

You can guess how much water comes from the condenser by the sizes of the pipes that connect the condenser, the condensate pump, and the hot well.

2.4.2 Circulating Pump

The condenser must be continually cooled by a flow of cold seawater through its tubes. This water is pumped throught the condenser and back overside by this centrifugal circulating pump. This circulates a lot of water, as you can guess by the sizes of the pipes that connect it to the condenser and overside. To cool 9 tons of steam per hour requires about 90 tons of seawater per hour. A centrifugal pump works something like a propeller, in which a rotating, bladed wheel spins the water in a circle, and hence increases its pressure so that it moves through the pipes. Centrifugal pumps are best at moving much water at low pressure, as used here for the condenser, and work at relatively high speed. This one is driven by a single-cylinder steam engine whose valve is operated by a single eccentric (because it is never reversed). There is also a second circulating pump of the cross-compound type.

2.4.3 Cross-compound Pumps

A cross-compound pump consists of two pumps in one frame. Each pump has a steam cylinder that directly drives its pump cylinder. The reason that there are two pumps built into one frame is that pump #1 drives the valve for pump #2, and vice versa. You can see the valve linkage above the piston rods. Therefore, when pump #1 makes a stroke to end A, it shifts the valve that causes the steam to drive pump #2 to end B. As pump #2 reaches end B, it shifts the valve for pump #1, making it return to end B. The valve linkages are set up so that pump #1 always causes pump #2 to go to the same end as pump #1 is, while pump #2 always causes pump #1 to go to the opposite end as pump #2 is.

You will see many pumps of this design in the Berkeley's engine room. Cross-compound pumps are not particularly efficient, because they admit steam to the cylinder for the full length of the stroke, instead of using the steam expansively, but they are convenient when small amounts of fluid must be pumped.

Cross-compound pumps are used for bilge water removal, fresh water service, lubricating oil, fuel oil (in the boiler room), and the fire pump (in the engine room casing on the main deck).

2.5 Hot Well

The condensed water from the condenser goes from the condensate pump into these rectangular tanks, named the hot well. That is, they act as the well that supplies the boiler with water, and the water is warm, not quite cold. When in use, the tanks of the hot well were filled with loofas, a kind of vegetable sponge that is the skeleton of a particularly fibrous vegetable squash. Remember, to lubricate the engine's valves and pistons, oil was pumped into the steam just as it entered the engine. That oil comes out with the condensed water, but it should not be pumped back into the boilers. The loofa sponges absorbed the oil and were wrung out and replaced as they filled with oil.

2.6 Feed Pumps

The boiler water is used over and over again, for two reasons. At sea, there is no natural source of fresh water, and salt water ruins boilers.[4] Even where fresh water was available on shore, as for steam locomotives, the railroad system engineer had to be careful to site his water tanks where "boiler quality" water, free of sediment and disolved minerals, was available. Once used, the water is of boiler quality, being distilled water. So even though the Berkeley had sources of fresh water on each side of the Bay, she used the water from the hot well over and over again, with only enough new water to replace that which was lost by leakage to the atmosphere.

That condensed water has to be pumped back into the boiler against the pressure of the steam in the boiler. There are two boiler pumps, because the boiler fires must be put out and the ship must stop if no boiler pump is working. The main boiler-feed pump is a single-cylinder, direct drive pump with the steam cylinder above the water cylinder, with the water valve chambers prominently in view. The valves inside are just flappers that fall over a grating. As the pump piston drives, the water is pumped out through the grating, lifting the flapper. When the pump piston goes in the opposite direction, the flapper falls suddenly onto the grating, preventing the water from returning. This sudden closing causes strong pressure pulses, water hammering, in the discharge pipe. On the discharge side there is a tall copper bell, that is kept full of air to act as a spring that smooths out the bumps in the water pressure as the water valves open and close.

The auxiliar boiler-feed pump is of the cross-compoud design.

2.7 Thrust Blocks

Connected to each end of the main engine's crankshaft are the propeller shafts to the propellers at each end of the ship. Each propeller will be pushing or pulling the ship along. That means that there must be a connection between each propeller and the hull of the ship, to transmit the force that moves the ship. Since the shaft must be rotating for the propellers to develop thrust, this connection must be a thrust bearing of some type. Since the engine's crankshaft should not be designed to take end thrust, at each end of the engineroom, where the shaft leaves that compartment, there is a thrust block to take the thrust, in whichever direction, of the propeller to which it is connected. Each thrust block consists of three collars rigidly mounted on the shaft, and on each side of each collar are two thrust rings that are fixed to the hull. These are all enclosed and run in a bath of oil, with oil pipes to supply fresh oil. As the shaft turns and pushes in one direction, its collars push up against the rings, which absorb the thrust while allowing the shaft to turn.

Each thrust block has three collars because only a single collar would scrape against its ring under the full thrust of the propeller. This is because, although the collars are continually supplied with oil, the oil is not forced between the collars and the rings. There is sufficient frictional loss that the thrust bearings must be cooled by water, delivered and returned through the pipes connected to each bearing. This was the original type of thrust block, and as ships increased in size and power, they became increasingly unreliable, liable to run hot and scrape metal to metal. This difficulty was corrected just about the time of Berkeley's design by the Kingsbury thrust bearing.

The Kingsbury bearing used only one collar. However, the ring was divided into six or eight segments, called slippers, which were mounted on a fixed ring. Each slipper presented a flat face against the shaft's collar, and a slightly curved face against the fixed ring, so it could rock a little in the direction that allowed the leading edge to lift away from the shaft's collar just a small amount. As the shaft turned, it picked up oil from the bath below. That oil was squeezed between the collar and the slipper, lifting the edge of the slipper so that the slipper was gliding on a wedge of oil under pressure. Of course, the oil was squeezed out at the inner and outer edges of the slipper, but with oil of the proper consistency, and enough rotational speed of the shaft, that movement was so slow that the slipper still floated for its entire length on the wedge of oil. There was no metal-to-metal contact, just metal to oil to metal again. Isn't that a wonderful idea? As it happens, that mechanism, squeezing the oil into a wedge inside the bearing, is the same mechanism that allows the cylindrical bearings of your car's engine to run for thousands of miles with little wear. Kingsbury was inventive enough to work out how to apply the same principle to a flat thrust bearing.

2.8 Auxiliary Machinery

2.8.1 Lubricating Pumps and System

The engine is served by a lubricating pump that supplies oil through pipes to the engine's steam supply and to its major bearings. The pump is a horizontal cross-compound pump, and you can see the oil piping on many parts of the engine.

2.8.2 Fire and Bilge Pumps

The fire and bilge pumps are also cross-compound pumps, with rather large water cylinders to supply large quantities of water at little pressure without using excessive steam.

2.8.3 Cabin Heating Fan

The cabin is supplied with warm air driven by this large fan, rather a new idea at the time. Because this fan would be run most of the time on cold San Francisco Bay, its engine was designed to be efficient. It is a compound, or double-expansion, engine, with two cylinders controlled by a single valve driven by one eccentric.

2.8.4 Generators

The Berkeley was supplied with electricity from two steam-powered generators. The original installation didn't work very well, and was replaced after a few years. That is probably why the main generator, in the engine room, is driven by a steam turbine instead of a steam reciprocating engine as is all the other auxiliary equipment. The steam turbine gives a smooth, vibration-free rotation with very little to go wrong with it, and packs much power into small space and weight. This one on the Berkeley is the first sign of times to come, when nearly all the horsepower produced by steam engines comes from turbines instead of reciprocating engines.

General Electric was taking no chances with the future when it put the nameplate on the generator's turbine in 1907. The nameplate says that the turbine is licensed for all uses except as a prime mover for marine or aviation uses. If you wanted to power your plane with a steam turbine like that one, you would have to pay a higher license fee. Well, GE didn't start making aircraft turbines until more than 35 years later, and then they were gas turbines, not steam ones.

The auxiliary generator is inside the engine-room casing on the main deck, driven by a single-cylinder steam engine.

3 Significant Steam Advances

Now that you understand how the triple-expansion engine works, you can understand the significant advances that it embodies

3.1 Newcomen's Early Engine

The first useful steam engine, built by Newcomen in 1712, pumped water from coal mines. It used so much coal for its power that it was used only at coal mines. Its boiler was separate, but all other functions occurred inside the single cylinder. This was a vertical, open-topped cylinder whose piston was pushed downward by atmospheric pressure when the steam inside it was condensed by a water jet. The piston pulled down a chain attached to one end of a pivoted beam, whose other end lifted the pump pistons. The system was balanced so that the pump pistons fell of their own weight, pulling the piston to full stroke. The lower end of the cylinder had three cocks: for steam from the boiler, for water from an overhead tank, and to the drain.

Here's the operating sequence. Open the steam cock to let steam into the cylinder, so that the weight of the pump could pull the piston to full stroke. Open the drain so the steam could blow out the water from the previous stroke. Close the drain and steam cocks. Open the water cock to let water into the cylinder (remember, this steam is at ambient pressure; the water tank was on the engine-house roof). The water spray condensed the steam, making a vacuum, so that the atmospheric pressure above the piston pushed it down, thus lifting the pump pistons and pumping out the water. Then close the water cock and open the steam cock again so the piston could be pulled upward again by the weight of the pump pistons. In the early engines, the valve operation was by hand, but very soon the valves were operated automatically by rods from the main beam.

The Newcomen engine wasted steam for two reasons.

1. 1: For every stroke, the cylinder had to be reheated from water temperature to steam temperature.
2. 2: The steam filled the cylinder at boiler pressure, instead of being expanded inside the cylinder.

3.2 James Watt's Perfected Engine

Fifty years after Newcomen's invention, James Watt perfected it. Watt was an instrument mechanic associated with Glasgow University, where Joseph Black had discovered latent heat, the additional heat required to be added to water to make steam, or to be taken from steam to condense it into water. Watt was asked to repair a model of a Newcomen engine. In doing so, in 1765, he realized that much steam would be saved if the cylinder was always kept hot and the steam was condensed in a separate condenser that was always kept cold. The separate condenser made the steam engine economical for many other purposes than pumping coal mines. In 1782, Watt put a head on the open cylinder, so that steam pressure could push the piston down as well as push it up, in what is called the double-acting cylinder. Watt's engines allowed the use of higher pressure steam whose valve was closed before the piston reached the end of the stroke, thus using the steam expansively for the remainder of the stroke, but Watt was very conservative, fearing explosions, and never progressed to high-pressure steam, relying on low-pressure steam and the vacuum produced by the condenser.

3.3 Multiple Expansion Engines

Oliver Evans, Richard Trevithick, George Stephenson, and others, developed the high-pressure steam engine that did not use a condenser, but discharged the steam at, or above, atmospheric pressure. If the boiler pressure was more than several times that of the atmosphere, the engine was smaller and lighter than a condensing engine, and not much less economical. This is the engine that powers steam locomotives.

High-pressure steam required better materials and construction. Once these became available, it was possible to supply high-pressure steam to condensing engines, thus saving steam by closing the steam valve with the piston near the start of its stroke and using the expansive power of the steam for the rest of the stroke. The higher the initial pressure and temperature, the earlier in the stroke the steam valve could be closed. A large, single-cylinder marine engine is shown in the first picture.

With steam of higher pressure and temperature at the beginning of the stroke, but of the same low pressure and temperature as early engines at the end of the stroke, the cylinder and piston had to be reheated at the start of each stroke, wasting steam heat as the Newcomen engine had done.

John Elder, in 1854, divided the steam expansion into two cylinders, so that each cycled through a smaller range of temperatures and pressures. This was called the compound engine, as used in the Medea, and was suitable for steam pressures of about 100 psia. The compound engine was sufficiently economical to enable steamships to sail almost anywhere in the world.

Improvements in materials and designs, even in lubrication, allowed still higher pressures and temperatures, and this allowed a further division of the steam cycle into three cylinders, the triple-expansion engine. The British Navy used the first triple-expansion engine, in a cruiser in 1887, and that type of engine was used in the American cruiser Olympia, built six years before the Berkeley, also at the Union Iron Works in San Francisco. Compared to the Berkeley's single engine of 1163 horsepower, the Olympia had two engines of almost 9,000 horsepower each (6,750 designed). The triple-expansion engine worked best at pressures of 155-185 psia, so that the Berkeley was at the upper range of desirable steam pressures for the triple-expansion design.

The next logical step was to divide the steam cycle among four cylinders, the quadruple-expansion engine. This design used steam pressures of 240 psia or higher, and was the final development of marine reciprocating steam engines. Such an engine is that in the picture, for the steamship Inchmona, using steam at 270 psia

The next step was the turbine engine, which could use much higher steam pressures and temperatures. The standard USN steam plant of WW II used steam at 600 psia and 850 °F.

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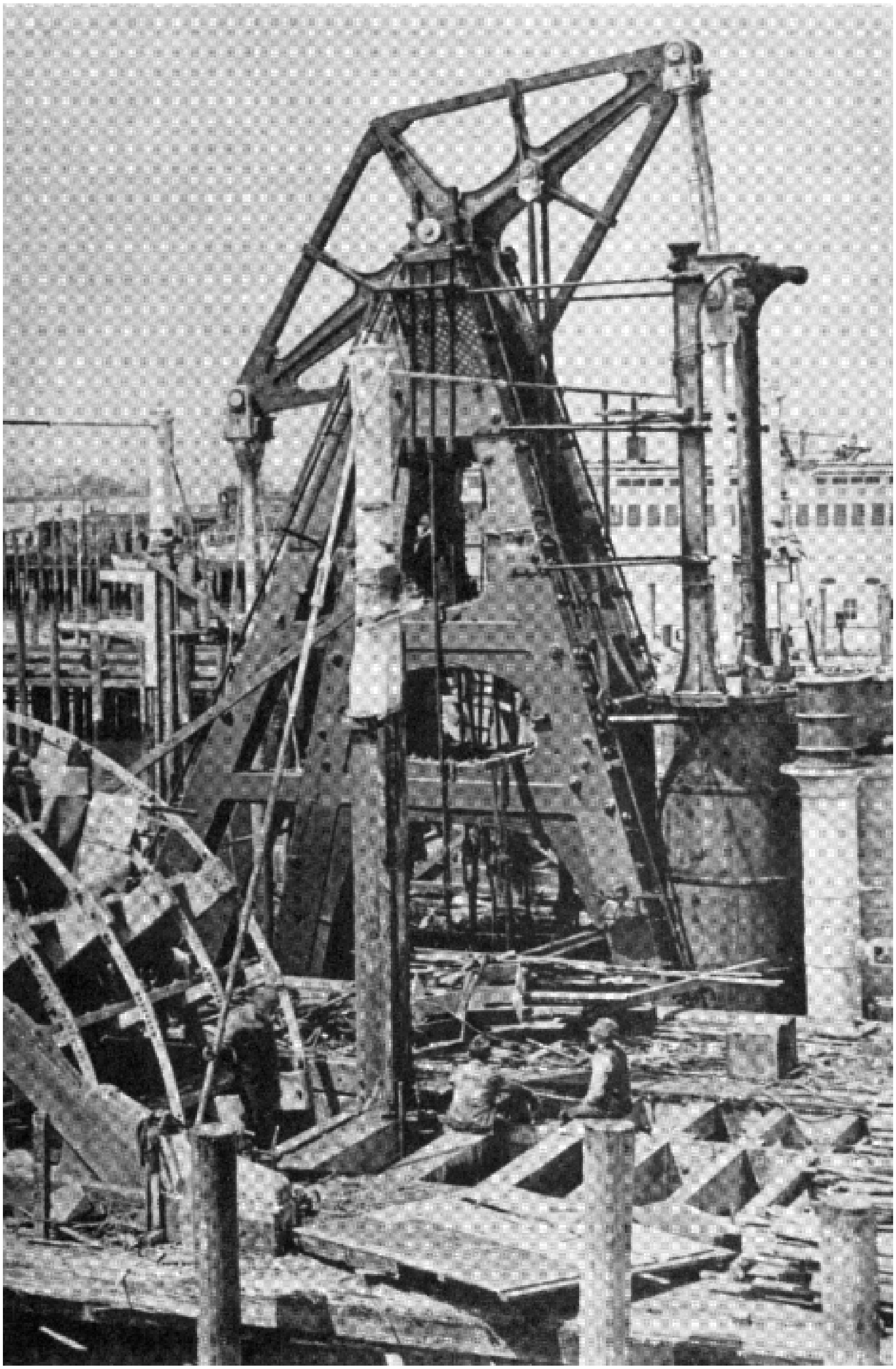
1. Some say the boilers were replaced in 1924.

2. Some say that the new boilers were run at the 200 psig for which they were rated.

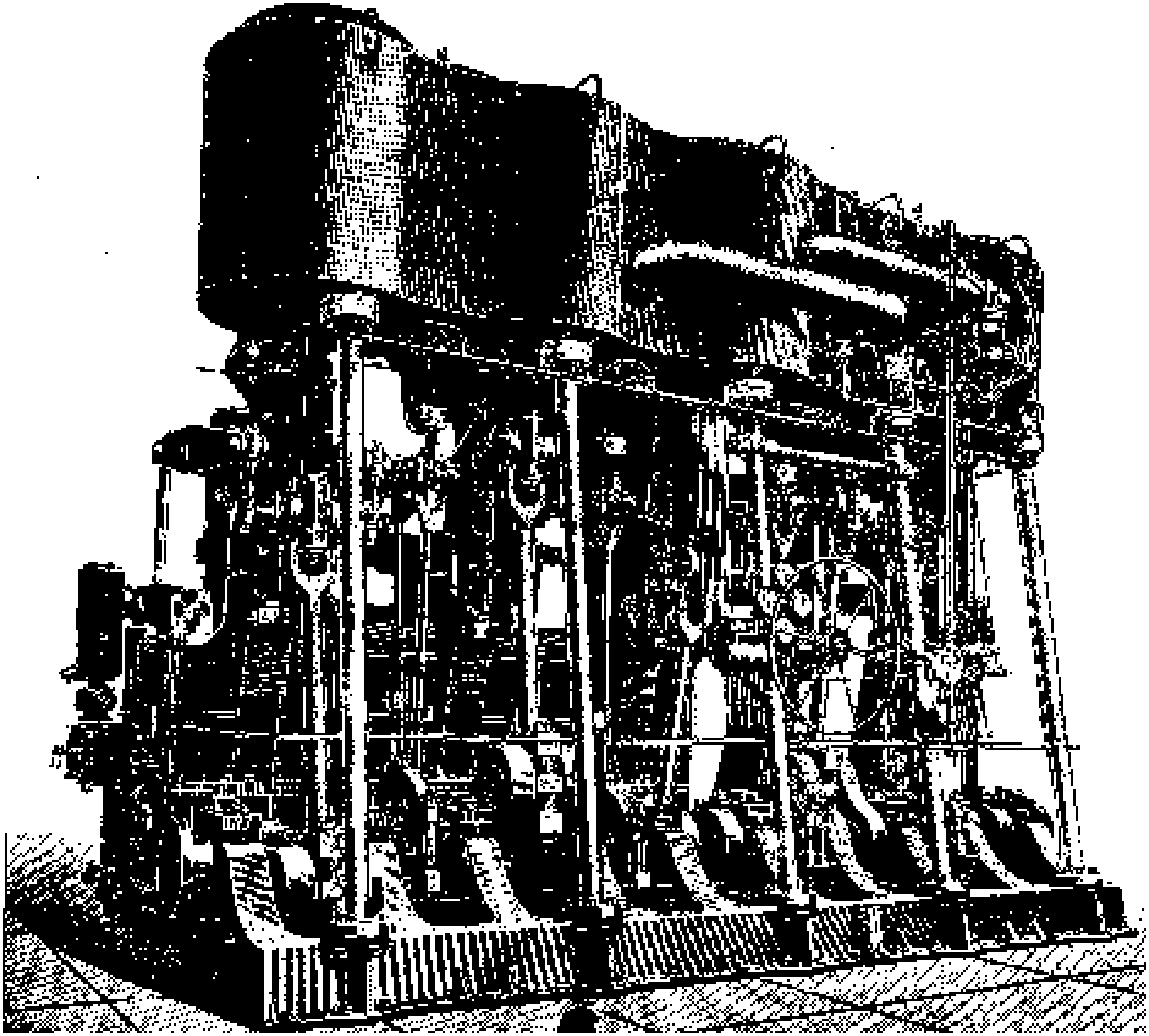
3. Paddlewheel engines were often two-cylinder horizontal, for sternwheelers and for Mississippi sidewheelers with separate engines for each independent sidewheel, or inclined, for sidewheelers with a single paddleshaft, or single-cylinder with the cylinder at the bottom, for sidewheelers with walking beam engines.

4. In the early days of steam at sea, they did use seawater in the boilers, but the salt built up inside as the water boiled off. This required both

frequent blowing down of the boiler to remove the over-salted water, and frequent shutdown for boiler cleaning. It also limited steam pressures and temperatures to inefficient levels. In those days, the condenser did not keep the steam separated from the cooling water, but just injected the cooling seawater into the condenser chamber.



This picture of a "walking beam" single-cylinder paddlewheel engine was taken while the Southern Pacific ferry Ukia was being rebuilt into the Southern Pacific ferry Eureka, which is now at the San Francisco Maritime Museum. Note the large size of the cylinder compared to that of the workmen.



This is the quadruple-expansion five-cylinder engine of the express cargo vessel Inchmona, built about 1904. You can estimate the size of the engine from the handwheel by which the engineer changed the gear from ahead to astern.