Maritime Steam; How Steam Revolutionized the World’s Shipping

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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: 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: 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: 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:

$$MaxEfficiency = \frac{HeatIn - HeatOut}{HeatIn} \qquad \text{Eq. 0.1}$$

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.

The marine version of the beam engine often drove the early paddle steamers. Such an engine drove the *Orizaba*, a model of which is shown in the main deck compartment of the *Berkeley*.

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.

In steam locomotives, where the tractive force varies greatly from starting the train, climbin a grade, running on the level, or descending a grade, almost all the control, once the engine has been started, is by controlling the cutoff point instead of throttling the steam. Controlling the cutoff point saves steam, while throttling the steam flow wastes steam. In ships, where the vessel spends most of its time at cruising speed, the Ahead setting of the valves is set at the most efficient cutoff point.

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 does not differ from its designed depth, as it does 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

2.4.1 Steam Turbine Engine

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 day 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.