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SEMINAR WORK

Topic: Boiler Design.

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Boiler Design

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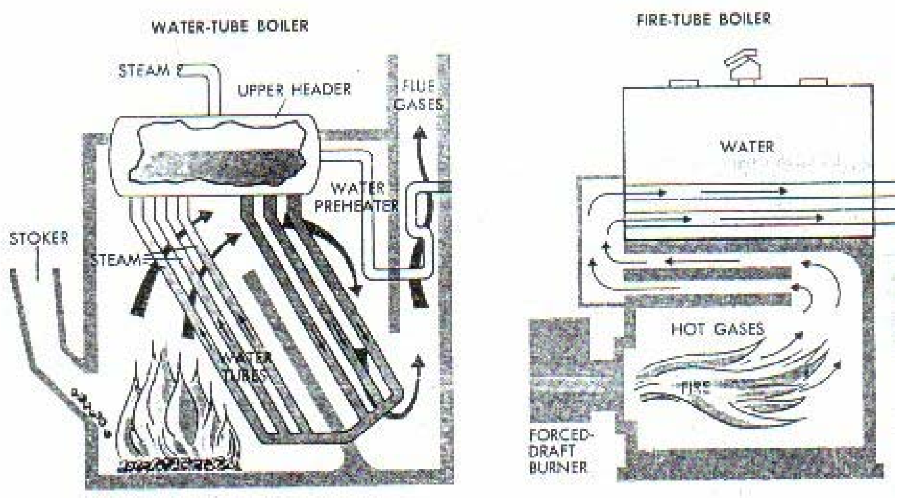
1. Abstract:

A boiler can be simply defined as a pressure vessel in which water is converted to steam by the application of heat. A modern boiler generally consists of a circuit of metal tubes supplied with water. The tubes are placed and arranged to present a maximum surface to a heat source, usually a combustion chamber where fuel is burned. The boiler tubes, combustion chamber, and associated fuel, air, water, and exhaust systems are designed and controlled as an integrated complex, which may be called a boiler, a steam plant, or a steam generator.

2. Introduction:

Boilers range in size and function from the compact units in domestic heating systems to 20-story complexes that drive giant steam turbines for electrical power production. A wide range of intermediate-size boilers are designed to match the demands of steam engines and steam turbines in stationary, marine, and locomotive applications. Boilers are also required to produce steam for industrial use as a process-energy source. Many space-heating systems utilize steam as a heat-circulation medium, but some systems, such as those serving several widespread buildings, are designed to use hot water as a medium. Such systems are equipped with special boilers that heat water to high temperatures but maintain sufficient pressure to keep it from vaporizing. The energy for most boilers is provided by the combustion of the fossil fuels-coal, oil, and gas. Coal is the major fuel, but most boilers are readily convertible from one fuel to another, Other fuels such as wood, waste gases from industrial processes, and solid wastes such as bagasse (from sugarcane), sawdust, and even trash and garbage serve as energy sources to a limited extent. An increasing number of large steam plants built since 1960 for generating electricity are designed to use nuclear fuel, which provides heat from radioactivity.

The most important part of any boiler is the heat-transfer surface, the area where water absorbs enough energy to become steam. Most modern boilers are water-tube boilers. In this type of boiler the water is passed through metal tubes, which are heated either by convection and conduction from the hot combustion gases that surround them or by direct radiation from the fire. In early designs, and in some small modern plants, the combustion gases are passed through tubes that are immersed in the water. Such boilers, called fire-tube boilers, consist -of a cylindrical shell with flat ends in which the water is contained and through which the tubes pass. Fire-tube boilers are limited to relatively low operating pressures because of the difficulty a of constructing a shell strong enough to with-S stand the high pressure required for efficient operation. As the pressure demands of steam engines and turbines increased, the fire-tube boiler was supplanted by the water-tube boiler in major installations. Small fire-tube units are's still manufactured, chiefly for domestic and small a industrial heating systems.



(a) (b)

Figure 1.

Figure (1.a) In water-tube boilers, water is circulated through tubes that are heated by hot combustion gases that pass around them, or by direct radiation from the fire.
Figure (1.b) In fire-tube boilers, hot combustion gases pass thrıugh a number of tubes from the fire box to the chimney. The gases heat the water flowing outside the tubes.

3 . History :

The development of the boiler is closely related to that of the steam engine, to which it is a necessary adjunct. Early versions of both more toys than serious inventions, are referred to in the writings of Hero (or Heron) of Alexandria, a Greek scientist of the 1st century A. D. However, it was not until the latter part of the 17th century that boilers in a real sense appeared on the scene. During this period, the greatest potential use for power seemed to be pumping water out of mines, and a number of engines were invented for this purpose.

These pumping engines, from those first successfully pioneered by Thomas Savery in 1699, to the engine patented in 1769 by James Watt, were not true steam engines, but atmospheric engines. Steam was used to fill a cylinder in which a piston was mounted. When the steam was suddenly condensed by a spray of water, a partial vacuum was created, and the piston was forced down by atmospheric pressure. The steam pressure that raised the piston, with the help of a counterweight, on each cycle of operation was only slightly above atmospheric pressure. the steam pressure was so low that without the counterweight, the piston would not have moved. Consequently, the boilers for these engines were of relatively simple design.

The boiler associated with Thomas Newcomen's engine, which came, into use in 1712, was known from its shape as a haystack boiler. It had a led dome and a copper bottom heated from below. The boiler was equipped with a safety valve, invented in 1680 by Denis Papin, that kept the steam pressure low. No boiler of this period operated at more than 10 pounds persquare inch (10 psi, or 0.70 kg/sq cm) of gauge pressure.

The wagon boiler, designed by James Watt, and in use from about 1774, had a horizontal design with a curved top and flat ends. It was heated at one end, and the combustion gases passed along the bottom of the boiler to the other end, where they were channeled back to heat the sides before entering the chimney at the hearth end.

4. System Descriptions:

4.1 Early High-Pressure Boilers. In true steam engines, where steam does mechanical work, it is advantageous to impart the highest pressure possible to the steam before it is released into the cylinder. Oliver Evans (1755-1819) of the United States and Richard Trevithick (1771-1833) of England saw the necessity of high-pressure engines for marine and locomotive applications, and were chiefly responsible for the adoption of higher steam pressures. Evans designed a boiler that developed steam pressures in the range of 100 psi (7.0 kg/sq cm). The chimney flue passed through the boiler shell, forming a single fire tube. Fire-tube boilers with several horizontal tubes were soon developed. In many of these boilers the fire was at one end of the horizontal boiler, and the tubes were arranged to circulate combustion gases through the shell twice, with the exhaust at the firing end.

4.2 Fire-Tube Locomotive and Marine Boilers. The fire-tube boiler designed in 1829 by George Stephenson for his locomotive Rocket possessed many of the features incorporated in 20th century steam locomotives. Although steam locomotives have been supplanted by diesel or electric locomotives in many areas, they are still widely used in the less industrialized nations of the world.

Such boilers produce about 55,000 Ib (25,000 kg) of steam per hour at a pressure of 240 psi (16.9 kg/sq cm). Coal is the primary fuel, and it is fired either by hand or by a mechanical stoker. However, oil is used where it is readily available. The steam outlet leading to the cylinders is placed in contact with the exhaust stack. This arrangement serves to heat the steam slightly beyond the vaporization temperature, thus imparting additional energy to it—a procedure called superheating.

The Scotch marine boiler came into extensive use for marine service before World War I, and was also used in stationary installations with no change in name. These boilers are double-shelled, with the combustion chamber in the inner cylinder. Combustion gases pass to the rear of the boiler and return through fire tubes in the outer shell to the stack in front. This type of boiler cannot be built in large sizes and cannot operate at pressures much above 200 psi (14 kg/sq cm).

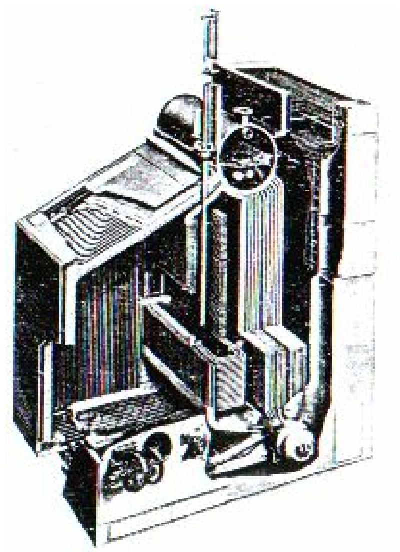


Figure 2. Marine Boiler used on an amphibious assault ship generates up to 120,000 pounds of steam an hour.

4.2.1 Firetube boilers

Early boilers consisted of closed vessels made from sheets of wrought iron which were lapped, riveted and formed into shapes varying from simple spheres to complex sections such as the "waggon" boiler of Watt (1788) illustrated by Fig. 3, so called because its shape resembled that of a covered waggon. These vessels were supported by brickwork over a fire which itself was supported on a grate. To make use of the surface not seen by the fire the products of combustion were circulated over much of the surface by means of flues formed in the brickwork, as illustrated. Such boilers were said to be "externally fired'. A serious disadvantage with this system of firing was that scale and sludge were precipitated from the water to the bottom of the boiler immediately over the fire and the hottest gases. This material insulated the metal from contact with the water which would otherwise have kept it at a safe temperature. In the absence of a deposit of this kind the metal in the bottom of the boiler would have been at about 200 °C for a working pressure of 0.7 bar (10 Ib in2) which was typical in those days. With 5 mm of scale and sludge the temperature of the metal would have been over 500 °C (sec Fig. 6.7). The metal would have then distorted and, even at this low pressure, ruptured disastrously.

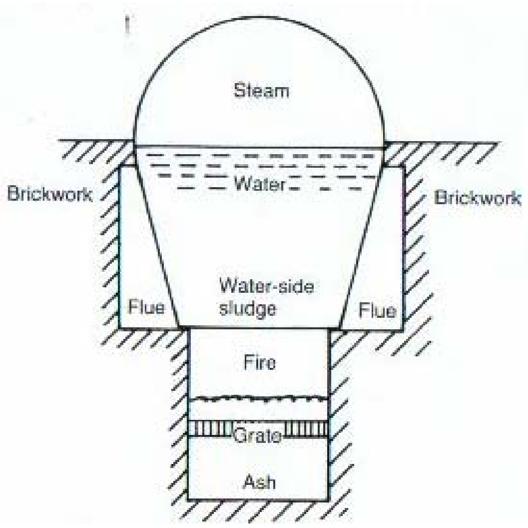


Figure 3. Watt's 'waggon' boiler.

The demand for more powerful engines created a need for boilers which would operate at higher pressures. This required new thinking to avoid the problem just discussed. Trevithick in Britain and Evans in the USA each conceived the idea of internal firing. This was done by making the pressure vessel cylindrical and providing an internal cylindrical furnace submerged beneath the water and large enough to accommodate a grate on which to burn the coal. The products of combustion passed from the fire along the flue, turned downwards to pass beneath the boiler to the front end, then the gases passed rearwards along the sides of the boiler through two brick flues, one either side, to a chimney. There were thus three 'gas passes' -the furnace, the bottom flue, and the side flues as illustrated by Fig. 4. Loose sludge would indeed still fall to the bottom of the boiler, but this was now relatively gently heated, not by live fire, but by products of combustion which had lost much of their heat content in the furnace. There was thus less risk to the bottom of the boiler, although scale could form on the furnace and endanger that. This was to remain a problem for many years and was not eradicated until the chemistry of water treatment was understood. In spite of this, Trevithick's 'Cornish' boiler could operate at pressures up to 7 bar, i.e. ten times greater than the earlier boilers. These internally fired boilers became known as 'shell' or 'firetube' boilers.

It was a short step from the single-furnace Cornish boiler to the larger, twin-furnace 'Lancashire' boiler patented by Fairbairn and Hetherington in 1844. This is illustrated by Fig. 5 and dominated the industrial steam-raising scene until the early 1950s. Possibly more than a thousand of these boilers are still working in the UK today although they are being replaced by the more efficient multitubular types known as 'Economies'.

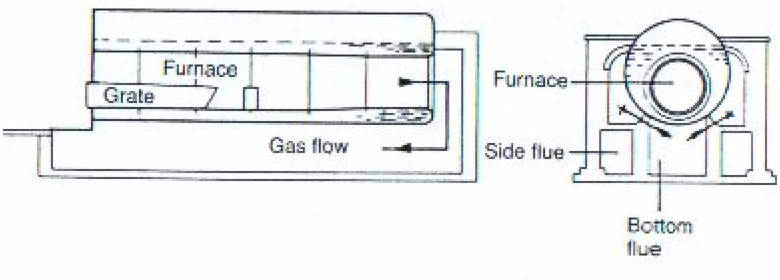


Figure 4. Cornish boiler 1810.

It will be appreciated that the greater the area of boiler surface exposed to heat transfer, the greater will be the amount of heat available from a given consumption of fuel, i.e. the efficiency of heat recovery will be greater. A large number of small-diameter tubes conveying hot gases through the body of water in the boiler provides such an increase in heated surface, and at the same time avoids the need for flues in the foundation and at the sides of the boiler. Such a boiler becomes 'self-contained'. The longer the tubes and the smaller their diameter the greater is the effectiveness of the heat transfer surface. These multi-tubular boilers are therefore much more compact for a given output than were their predecessors, and do not require to be set in brickwork. They found extensive application on ships and for locomotives where, in both cases, space is at a premium.

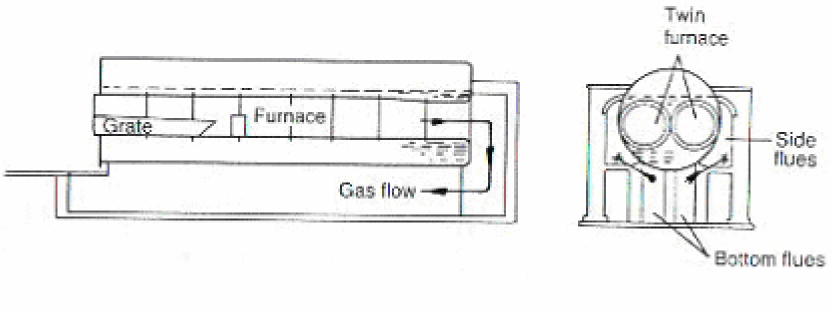


Figure 5. Lancashire Boiler 1844

Some early marine boilers were rectangular in section in order to make more effective use of the space available. Serious explosions occurred due to rupture at the corners. A vessel subject to internal pressure will tend towards a spherical shape, and other shapes will therefore be highly stressed in those areas which depart from the spherical. The nearest practical approach to the sphere, for boilers, is the cylinder, especially if the ends are domed. A design for a spherical boiler was actually patented in the early 1800s with the intention of being able to withstand pressures up to 200 bar. It was specified to be made from copper, 64 mm thick, but there is no record of it ever having been made. It was to have been externally fired, which in itself presents problems, but in the geometry of a sphere it would not seem to be feasible to use internal firing. Even with present-day alloy steels it is not permitted anywhere in the world in firetube boilers to expose metal more than 22 mm thick to fire or high-temperature gases. This is to avoid excessive thermal stress in the metal.

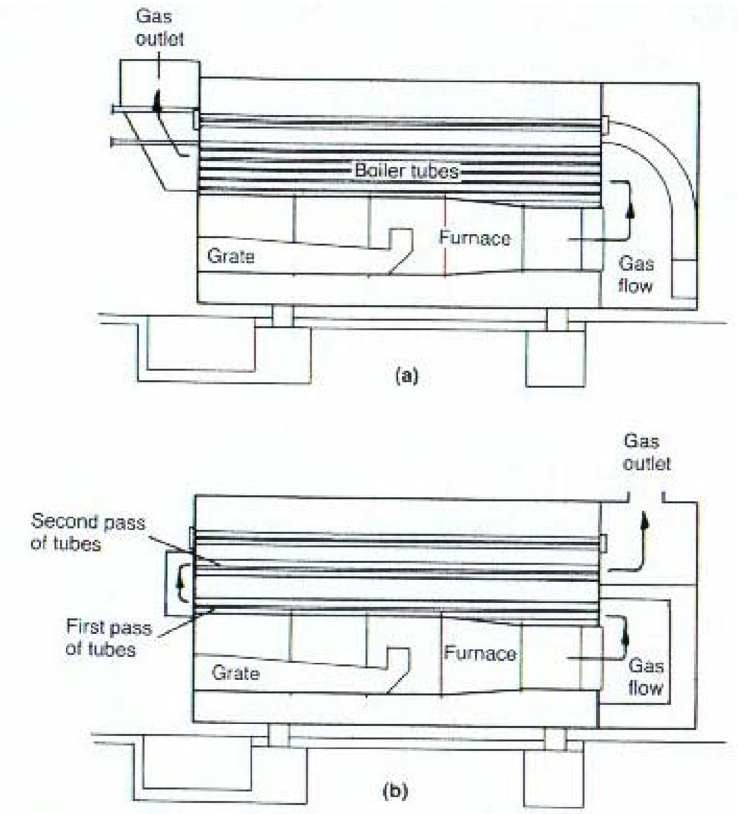


Figure 6. (a) Two pass and (b) Three pass dry-back Economic boilers.

Marine boilers were eventually all made cylindrical, but brickwork settings and external flues were quite unacceptable on board ship due to their size and weight. Multi-tubular boilers were therefore used and internal furnaces, up to four in number, were retained. The gases from the furnaces entered individual water-walled reversal chambers then, turning through 180°, entered a multiplicity of tubes each of about 75 mm bore. After passing through these, the gases entered the funnel. These were 'two-pass' boilers. Later, a three-pass version evolved in which the gases passed from the front to the back of the boiler through a further set of tubes. These boilers were known as 'Scotch Marine Boilers' and persisted from around 1850 until diesel power replaced steam.

The Scotch boiler was slowly adapted for land use, but as there was less restriction on space it was made longer. In the UK, the generic name is 'Economic' but in the USA it is still known as the 'Scotch' boiler. Being smaller, cheaper and inherently more efficient than the Lancashire type, it began to compete with the latter in the early 1930s. In the land-based boilers, the reversal chamber was refractory lined but in a later development the water-walled chamber was revived. Figures 6(a) and 6(b) illustrate, respectively, two-pass and three-pass Economic boilers with refractory reversal chambers, which are termed 'dry-back' boilers.

The three-pass Economic boiler suffered from a problem which arose from the use of a single end plate into which the tubes are connected (the tube plate) to accommodate both second- and third-pass tubes. The gases entered the second pass at about 1000 °C and left the third pass at about 250 °C. The tube plate was therefore subject to two different temperature conditions, which set up stresses and which led to leakage at the tube seats. In 1935 the Lincoln firm of Ruston and Hornsby patented a three-pass construction based on the three-pass Scotch marine boiler. This overcame the problem of a single tube plate being subjected to two different temperature regimes by providing separate tube plates for each condition (see Fig. 7). The water-walled reversal chamber was used, the front wall of which accommodated the furnace exit and the entries to the second-pass tubes. This water-walled, or 'wet-back', construction had the added advantage of replacing the heat-losing refractory linings of the earlier boilers with effective heat receiving surfaces. After passing to the front of the boiler, the gases reversed in the 'front smoke box' and returned to the rear of the boiler through tubes forming a third pass, these tubes being seated in an independent tube plate at the rear. The front tube plate of the boiler accommodated the outlets of the second-pass tubes and the inlets of the third pass, but there was no tube plate differential temperature problem since the gases left the second pass and entered the third pass at virtually the same temperature. This construction is now widely used throughout the world.

The next major development took place in the USA. During the Second World War a need arose for boilers to supply steam to field installations. It was essential that their installation and commissioning should take place in a minimum of time. To this end the boiler was supplied, not as hitherto as

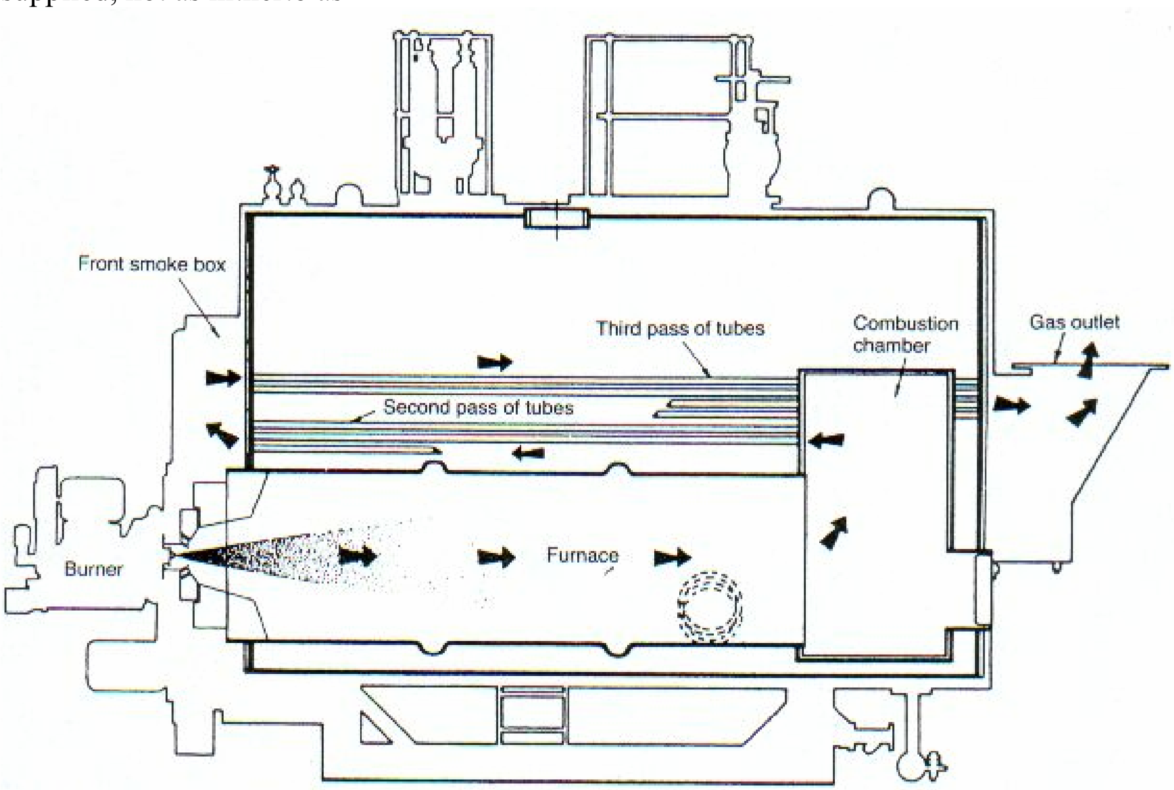


Figure 7. Wet-back three-pass Economic boiler.

a shell only to be fitted with firing equipment, pumps, valves and fans on site and from separate suppliers, but as a working entity complete with all auxiliaries. This was the so-called 'Package' boiler and consisted of a three-pass, dry-back, Scotch boiler mounted on a base frame. After the war this Package idea became very popular and all but the very large firetube boilers made today are of this concept. The boilers are delivered complete with all auxiliaries, as illustrated by Fig. 8; they are factory assembled, tested and ready for work, and are mainly of the three-pass wet-back type.

For smaller boilers, the reverse-flame type of construction is often used, particularly for water heating. In this type the furnace has only one open end, the burner is positioned on the axis of the furnace firing towards the closed end, and the gases return concentrically round the outside of the flame as illustrated in Fig. 1.7. The single pass of boiler tubes is arranged concentrically around the furnace. Since there is only a single pass of tubes, turbulence promoters are fitted to increase the heat transfer and to reduce the exit gas temperature.

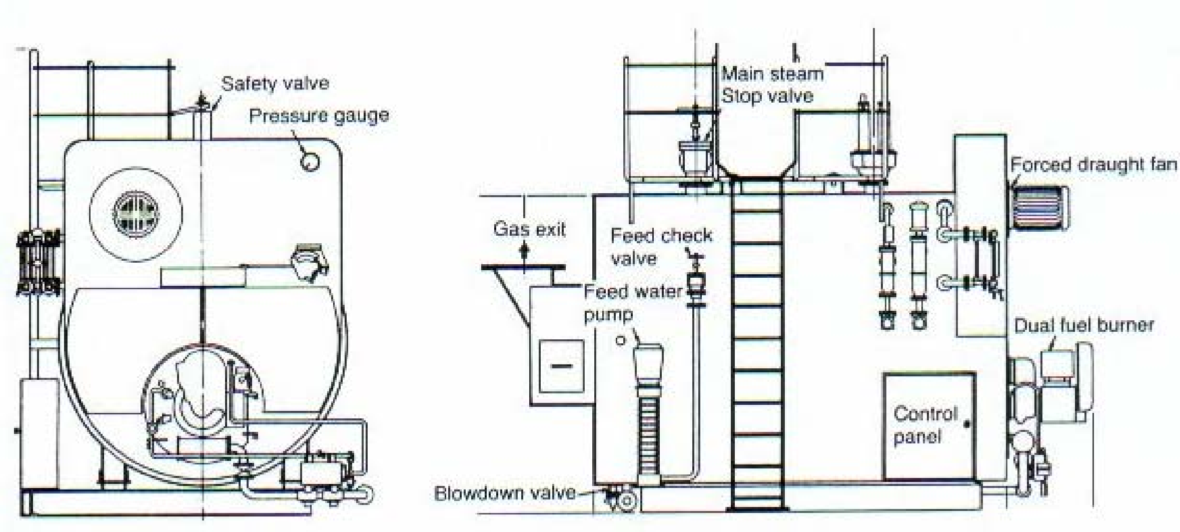


Figure 8. 'Packaged' firetube boiler.

The rear end of the furnace is inactive so far as gas flow is concerned since, due to the blank end, pressure builds up. It is important that the burner is designed to give a long, narrow, penetrating flame; a short, bushy flame will tend to be picked up by the outgoing gases and this will lead to burning gases entering the tubes, thus increasing the metal temperatures in this region.

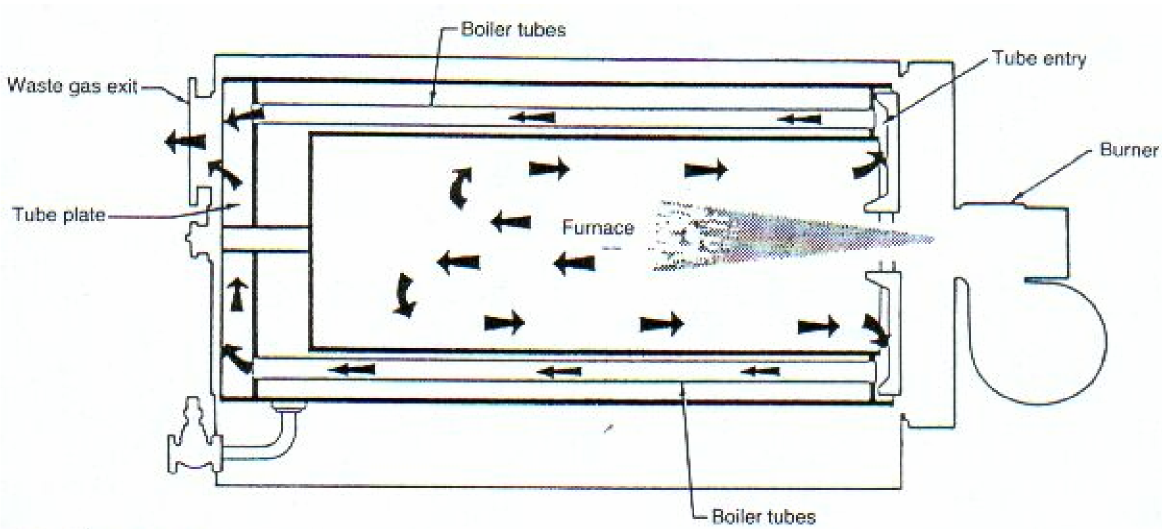


Figure 9. Reverse-flame boiler.

4.3 Water-Tube Boilers. Fire-tube boilers tend to be dangerous at high steam pressures. This 15 partly due to inherent structural problems and partly due to the relatively large quantity of water and steam contained in the boiler. In the event of a rupture in the boiler, the large amount of water and steam releases great destructive energy.

The increasing use of steam for power arc the desire for high pressures led to a large number of boiler explosions in the early 19th century This set off a search for a replacement for the fire-tube boiler. Water-tube boilers, which are especially suitable for high steam pressures-were the ultimate result, but the first half of the 19th century passed before effective water-tube boilers could be produced in quantity.

Many names are associated with the development of water-tube boilers. In 18O4, John Stevens of the United States developed a boiler with small tubes called a "porcupine" boiler. He used it in his Hudson River steamboat experiments. In 1824, Jacob Perkins built what is said to be the first flash-type water-tube boiler. In flash boilers, water is delivered to preheated tubes, and vaporizes almost immediately. (Small flash boilers were used on some steam automobiles and provided quick acceleration.)

Many features of the modem water-tube boiler were first used in a boiler invented is 1825 by Goldsworthy Gurney. His design incorporated a combustion chamber with waterwalls. that is, walls constructed of boiler tubes filled with water that are part of the circulation system. Gumey's boiler met with little success, and the waterwall concept lapsed for almost a century.
In the boiler patented by Stephen Wilcox in 1856 the water tubes were placed in an inclined bank above the fire. In 1867, Wilcox and George H. Babcock jointly produced the first Babcock and Wilcox boiler. It used cast-iron steam-generating tubes placed in vertical rows over a grate. Tubes of steel or wrought iron connected these with headers leading to the separating drum, where water was separated from the steam and recirculated. This boiler, called a sectional header boiler, was one of the basic designs widely used until the 1930's. Another basic design, developed in about 1890 by the Stirling Company, had three upper steam drums and one lower drum connected together by water tubes. Both these designs were very effective and in late versions could be operated at pressures as high as 500 psi (35 kg/sq cm).

As industry developed during the last century, so the use of boilers for raising steam became widespread and, for various reasons, disastrous explosions sometimes occurred. Boilers of that period consisted of heated pressure vessels of large diameter and subject to internal pressure which set up tensile stresses in the walls of the enclosure. The value of this stress, known as 'hoop stress' is given by

$$f = (P \times D) / 2T$$

Where:

- f is the hoop stress;
- P is the internal working pressure;
- D is the vessel diameter; and
- T is the thickness of the metal.
- (All in self-consistent units).

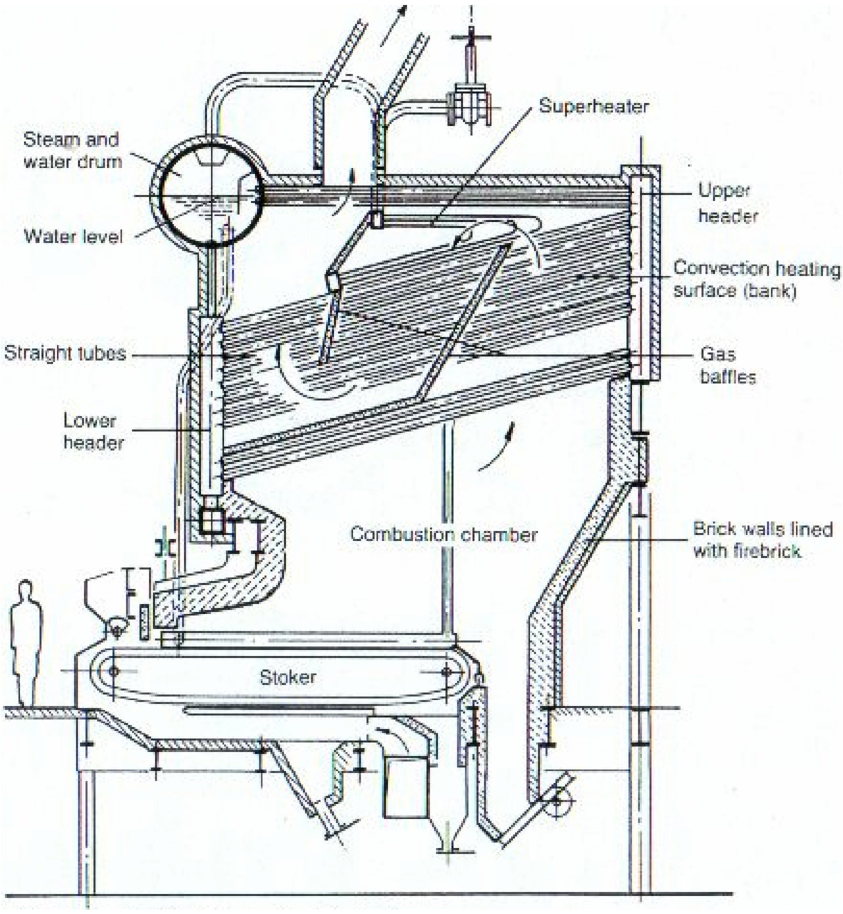


Figure 10. Early straight-tube water-tube boiler.

It will be seen that, for a given stress f, as D increases with increasing output of the boiler, T must also increase. If the working pressure P increases, then either D must be decreased or T be increased to keep f within acceptable limits. If T is increased then the mass of the boiler and its cost of manufacture both increase. The attractive alternative is to decrease D. This approach formed the basis for the water-tube boiler in which the water is contained within tubes and the gases pass across the outside of them.

There were a number of early designs of water-tube boiler developed throughout the late eighteenth and the nineteenth centuries. As is frequently the case with development today, the rate of progress seemed to have been restricted by the availability of tubes and suitable materials to withstand the higher operating pressures that were being aimed at.

The forerunners of today's designs appear to have been a compromise between a firetube and a water-tube boiler as developed by Stephen Wilcox in 1856, a straight-tube boiler patented in 1867 by George Babcock and Stephen Wilcox, and subsequently in 1877 by a design of the type illustrated by Fig. 1.9. With the latter design of boiler the water-filled tubes were inclined and the ends belled or 'expanded' into headers at each end, which were in turn connected to a cylindrical vessel called the steam drum. This drum contained water having a space above, into which the steam generated in the tubes was released before being discharged to the steam consumer.

The boiler-heated surfaces consisted of a group or 'bank' of tubes of about 75 mm bore, some of which were exposed to the fire, the others to the flow of hot gases produced by the combustion process. Baffles were provided in the bank of tubes to create a number of gas paths and thus to increase the effectiveness of the heated surface, as illustrated by Fig. 10. In this way the heat was transferred to the water in the boiler through tubes of relatively thin section when compared with the thickness of a firetube boiler shell. This being so, the working pressure could be raised considerably above that possible in a firetube boiler. Moreover, should atube rupture occur, the consequences would be less serious than if the furnace or shell of a firetube boiler ruptured.

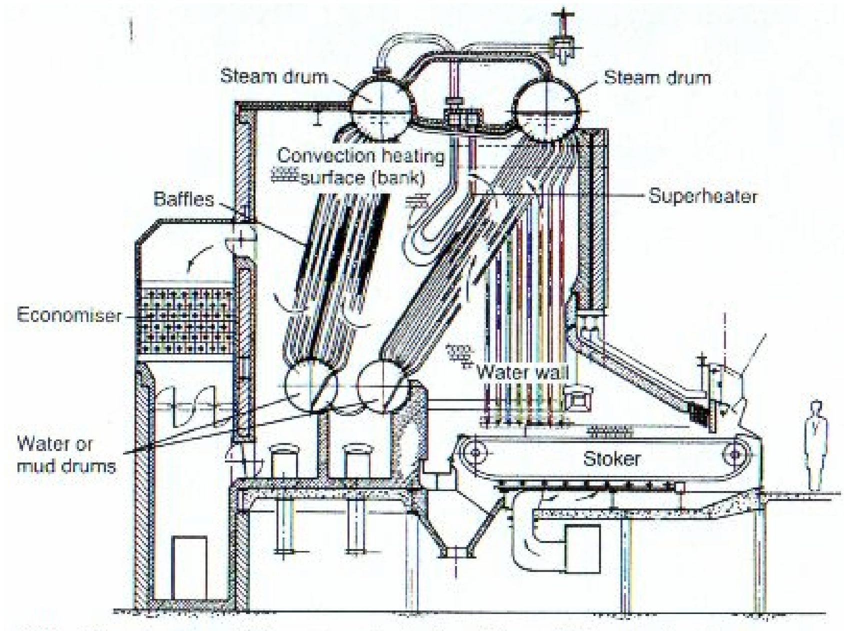


Figure 11. Four-drum bent-tube water-tube boiler with partially cooled walls.

While this construction persisted for many years, it had pressure limitations, and eventually multidrum boilers with bent tubes were developed, one such design being illustrated by Fig. 1.10. The lower drums into which boiler water impurities settled became known as 'mud drums'.

In the early boilers, the tubes were situated in an enclosure made of brickwork lined on the inside with firebrick, as illustrated by Fig. 10. Eventually, the brick walls were partially covered on the fire side by water-tubes, called water-walls, connected to the steam drum direct or by headers and pipes as illustrated by Fig. 11. These absorbed heat from the combustion process, thereby reducing the temperature of the gases flowing to the tube bank gave some protection to the brick walls and eventually, as the percentage of the wall area covered by tubes increased, gave scope for reducing the heat loss from the walls to atmosphere.

Designs progressed until, at present, the walls are usually completely covered with water-cooled surface (Fig. 12). These walls arc formed either by tubes touching each other, called 'tangent tubes', or by tubes connected together by strips of steel welded axially between them called 'welded walls'.

With increasing working pressures and the use of economisers and airheaters it has become more economical to reduce the number of boiler drums, the two-drum type of boiler now being the most popular design among industrial water-tube

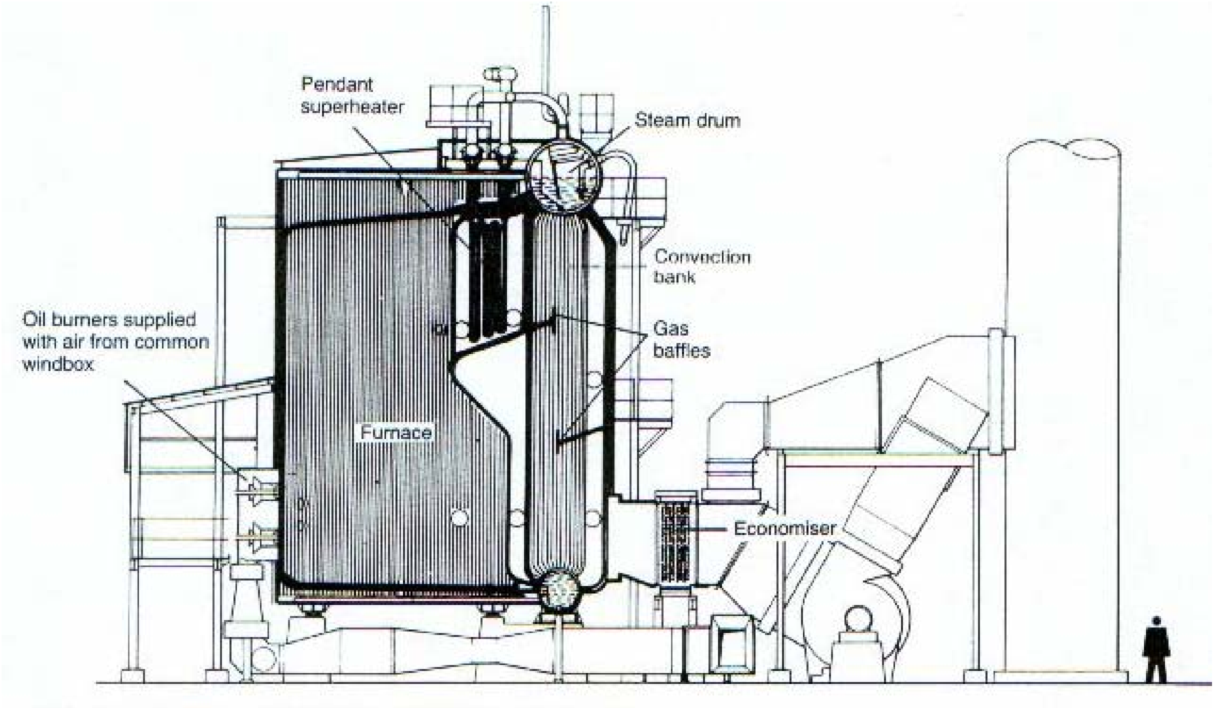


Figure 12. Two-drum oil or gas-fired boiler with fully cooled walls.

boilers operating at pressures up to 100 bar, although a number of single-drum types are available.

Recently, the 'Composite' boiler has been developed in which the water-tube and firetube principles are combined (Fig. 13). With this design, the steam drum and convection bank of a conventional water-tube boiler are replaced by a shell containing a large number of small-bore tubes only, i.e. a firetube boiler with no furnaces. The water-walls of the furnace are connected by pipes to the firetube boiler which acts also as the steam drum. The design combines the advantages of the low-cost firetube boiler with its large steam/water drum and consequent low steam disengagement velocity, with the ability to arrange the water-tube furnace with its flexible combustion space so as to incorporate the type of firing equipment most suitable for a particular fuel and application.

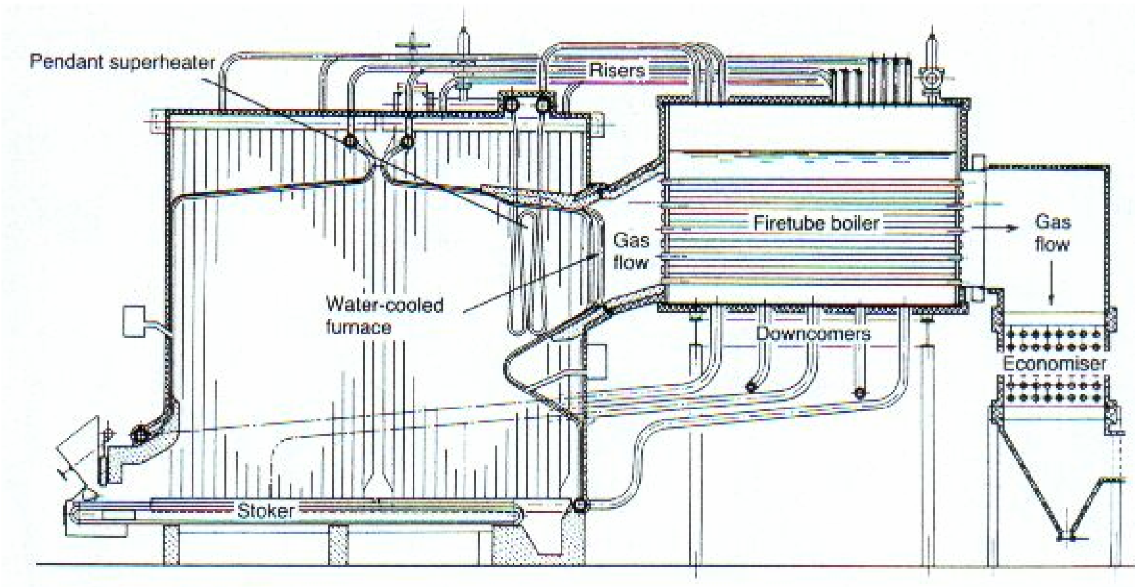


Figure 13. Composite boiler.

5. Applications

The purchaser of boiler plant has the option of choosing the firetube. the water-tube, or the composite types. Each of these has quite distinct characteristics, and although firetube boilers are inherently cheaper than water-tube boilers for the same output and pressure, it is the purpose for which the energy output is required that will determine which type is used.

It has been estimated that in 1979, there were over 73 000 steam boilers (excluding utility boilers) operating in the UK, of which 61% were horizontal firetube boilers, 5% water-tube, the remainder being 'vertical' and 'brick flue' (the last becoming rapidly obsolescent). To these must be added a considerable but unstated number of hot-water boilers operating at medium- and high-water temperatures. These are used mainly for space heating, but also for some process applications. They are likely to be mainly of the firetube type, although water-tube boilers of the 'La Mont' forced-circulation type are used. It looks as though there could be about 100 000 industrial boilers in operation in the UK, 60 000 firetube and 5000 water-tube, the rest being obsolescent.

The most common type by number is obviously the firetube boiler, but by capacity water-tube boilers account for 29% of the total, which suggests much larger unit outputs for this category. Indeed, it is known that most water-tube boilers are concentrated in those large industrial complexes operating continuously throughout the year where demands for power and heat are in good balance, e.g. chemical works, oil refineries andthe steel industry. For power production, high pressure and temperature are needed, often beyond the scope of firetube boilers. Where heat only is needed, e.g. space heating, in breweries, in laundries and in the food industries, indeed in most of the general run of industries, the firetube boilers suffice - this accounts for their preponderance by number.

6.Modern Boilers

In large modern boilers the circulation patterns are box or ring shaped, with large parts placed in a waterwall arrangement. At first the tubes in waterwalls were shielded by blocks of refractory material, but in modern boilers they are bare to the fire. Refractory material is employed as a casing to insulate the combustion chamber from heat loss to the exterior. In general, the steam-generating tubes are concentrated in the waterwalls, and the remainder of the boiler-tube circuit is devoted to accessory equipment such as superheaters, reheaters, and heat conservation devices.

6.1 Superheaters. When the first steam turbines were applied to electrical power production in the late 19th century, it became necessary to add superheaters to boiler design because turbines work most effectively with high-pressure steam and require superheated steam for optimum efficiency. Superheated steam is steam heated away from the presence of water so that its temperature rises above the boiling point of water for the pressure at which the boiler operates.

Superheaters are part of the equipment of all marine, locomotive, and large stationary boilers. They consist of a nest of boiler tubes supplied with steam from the steam drum. Radiant superheaters are those placed in sight of the fire, and convection superheaters are in the path of combustion gases exiting from the
furnace.

In early designs, steam was superheated only by some 50°F (10°C) above the temperature of the steam in the drum; but superheats as high as 500°F (260°C), which yield total steam temperatures of 1200°F (649°C), have become common in boilers linked to turbines.

6.2 Reheaters. When superheated steam expands in a turbine it drops in pressure, loses its superheat, and becomes wet. The water in the steam can damage turbine blades and lower the effectiveness or the turbine. Consequently, this steam is led out of the turbine after it has passed through the early high-pressure stages. It is then piped back to a reheater, a device similar in design and placement to a superheater, where it is reheated to approximately the original superheat temperature. From the reheater, the steam enters the turbine at a succeeding stage and passes through the remainder of the turbine. It exhausts at low pressure and is condensed into water for recirculation to the boiler.

6.3 Heat-Conservation Devices. The combustion gases in a boiler are at a temperature of 2500° F (1370° C) or higher. Even after delivering energy to the heat-absorption surfaces of the boiler, superheater, and reheater, they retain temperatures of 800-1100 F (430-593°C). Plant operators cannot afford to waste this energy, so it is usual to install conservation devices.

One such device is the economizer, a series of tubes placed in the path of the combustion gases as they leave the superheaters and reheaters. The boiler feedwater passes through the 1 economizer, where it is preheated before enter- 1 ing the boiler itself.

To conserve more of the residual heat in the waste gases, which are still at 400-600°F (200-320°C), an air preheater is placed in the exhaust stream. The function of the air preheater is to transfer heat from the exhaust to the incoming 1 air that is being led to the combustion chamber. 1 One type of air preheater is an arrangement of I tubes or plates that enclose alternate streams 1 of incoming air and exhaust gases. Another type, 1 the Ljungstrom preheater, is a large, continuously rotating drum of heavy metal vanes placed .1 so that the vanes move across the path of the i hot exhaust gases and then across the path of the 1 cool incoming air. As they rotate, the metal vanes 1 absorb heat from the exhaust gases and transfer 1 it to the incoming air.

After passing the air preheaters, the combustion gases have been cooled to about 250°F (121° C) and are allowed to pass into the chimney for delivery to the outside atmosphere.

6.4 Air Circulation. In many boilers the necessary movement of air into the furnace and of combustion gases up into the stack is induced by the] draft created by the stack design. However, in larger plants it is necessary to augment this now with fans.

A forced-draft fan placed in the intake passages pushes the air into the furnace and drives I the combustion gases past such resistances as the superheater and other equipment. It may be supplemented by an induced-draft fan located in the stack base, which augments the natural draw of the stack.

In pressurized furnaces, usually associated with marine boilers, the combustion gases are moved entirely by the forced-draft created by a powerful fan, and the stack serves only to disperse waste gases.

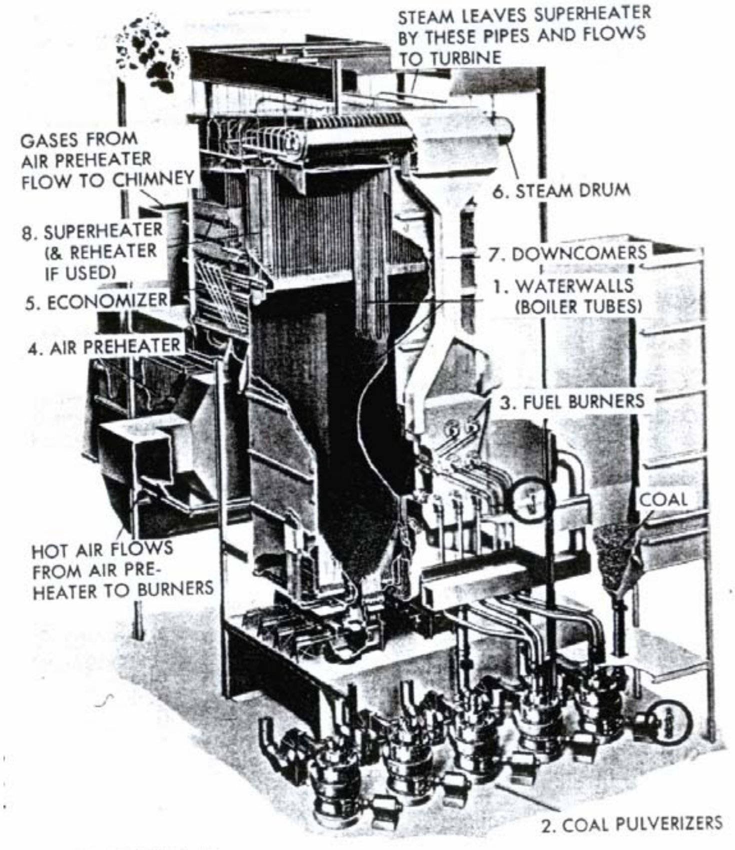


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Figure 14. Typical radiant boiler for a central service station (for size comparison note circled men). Units of this type have design pressures as high as 2,800 psi and have been built for steam capacities of 2,400,000 pounds per hour. This unit has overhead supports. Most of the steam j, generated in the waterwalls (1). Coal is ground to talcum-powder fineness in pulverizers (2) and blown through burners (3) into the furnace where it is mixed with hot air flowing from the air preheater (4). Water enters the unit through the economizer (5)* where it is preheated, and then flows to the steam drum (6). It flows down through downcomers (7) to distributing headers at the bottom of the unit, and then rises through the steam

generating tubes (1). It discharges into the steam drum, where steam and water are separated. The steam flows to the superheater (8), where its temperature is increased to the required level. Finally it flows to the turbine.

6.5 Water Supply and Circulation. In most boiler systems a large portion of the steam produced is recondensed into water after use and returned to the boiler as feedwater. Makeup water to replenish operating losses must be treated to remove or neutralize impurities, which might cause corrosion or deposits on the boiler tubes. The feedwater for domestic boilers is generally untreated, but these boilers are operated seasonally and are not subject to the same conditions as boilers in continuous operation. Periodic maintenance and inspection are required for all boilers, but the least difficulty exists with the large steam generators, which are supplied with distilled feedwater both for continuous feed and makeup.

In boilers operating at pressures below about 1500 psi (106 kg/sq cm), the circulation of water and steam through the boiler occurs naturally. As water passes through the boiler tubes, it absorbs heat from the furnace, steam bubbles are formed, and the lighter water-steam mixture rises in the boiler tubes to the steam drum, where water and steam are separated. The steam flows to the superheaters where its temperature is raised to the required level. The water returns through pipes called downcomers to the water header at the foot of the waterwalls to reenter the boiler tubes. The motive force for the circulation is provided by the difference in density between the relatively light water-steam mixture in the water tubes and the relatively heavy cooler water in the downcomers.

Above 1500 psi (106 kg/sq cm), approaching the critical pressure of 3206 psi (225.4 kg/sq cm), the point where water and steam have the same density, natural circulation is insufficient. High-pressure boilers require forced-circulation, and pumps are installed in the downcomers to circulate the water. The \vater and steam are separated in the steam drum. In boilers operating at pressures above 2800 psi (197 kg/sq cm), both below and above critical pressure, water is not recovered at the steam drum at all. In these "once-through" boilers, a constant flow of water is pumped through the downcomers and remains in the liquid phase.

6.6 Fuel. The most common energy sources for boilers are the hydrocarbon fuels—coal, oil, and gas-and nuclear power. Of the hydrocarbon fuels, oil is preferred for marine boilers because it is easily pumped and stored. Oil and gas are both used in domestic boilers because of the simplicity of firing these fuels. Where they are plentiful and cheap, these fuels are also used in industrial applications. Coal is used most widely in power plants because of its low cost, even though special machinery is required for its handling and firing.

6.7 Coal. Coal is used in solid form for small and intermediate boilers, and crushed or pulverized in the large boilers. Solid coal is fired by mechanical stokers, of which there are three major types: (1) The chain-grate stoker is a continuous, moving belt made of Links. A thin layer of coal is fed onto it at the front of the boiler and travels rearward, undergoing combustion as air is blown up through the grate. Solid ash is dropped off the grate at its rear end. (2) In an underfeed stoker the fuel bed is re-plenished from beneath by coal-loading rams. Air is blown through the mass of coal, which burns at the top surface. (3) A spreader stoker flings coal in small pieces over a bed of burning fuel.

The physical size of stokers is definitely limited, and maintenance is a problem in the large-size ones. Stokers are used mainly in boilers of less than 100,000 Ib (45,000 kg) per hour steaming capacity.

There is no limit to the size of boilers using pulverized coal, and a large percentage of power plant boilers are fired with this fuel. In most plants the coal is pulverized as needed and released directly into the primary airstream for delivery to the burners. The powdered coal in suspension is easily ignited, and the addition of secondary- air from the air preheaters creates turbulence and completes combustion. Under these conditions, the coal-air mixture burns in the same way as an atomized liquid fuel.

However, pulverized coal leaves a residue of fly ash, a solid waste light enough to exit through the stack and contaminate the air. A portion of this ash drops to the furnace floor as a powder, a solid clinker, or liquid slag. Filters and electrostatic precipitators are placed in the exhaust system to trap the remainder, but enough may escape to be a source of air pollution.

An alternative fuel combustion system for large boilers is the cyclone furnace. This is a large water-cooled external combustion chamber, in which crushed coal is burned as it is swirled around. The cyclone furnace replaces the combustion chamber inside the boiler. A cyclone furnace minimizes fly ash problems and also obviates the need for pulverizing machinery.

But a serious problem is associated with all coal firing, regardless of combustion system. The sulfur that is present in all coals produces sulfur dioxide (SO_3) during combustion. Sulfur dioxide is an objectionable gas that is difficult to remove from stack gases. This pollutant has caused restrictions to be placed on the use of coal and some residual oils in certain areas.

6.8 Nuclear Power. Nuclear steam generators are becoming increasingly common in large power plant designs for several reasons. The cost of nuclear fuels of the uranium family has been dropping and apparently will continue to do so. Fears of an accidental nuclear explosion have abated, owing to the years of successful operation of the early plants. And, in contrast to coal-powered plants, nuclear power plants do not pollute the air.

Nuclear boilers employ a reactor containing nuclear fuel elements in bolder canisters. The water or other heat transfer medium in which these elements are immersed absorbs the heat generated by nuclear activity. The steam produced is utilized in normal steam turbines.

Nuclear reactors are equipped with moderator control rods that can be inserted into the reactor core to slow down the nuclear activity by absorbing neutrons. Under emergency conditions the moderator elements drop into place automatically, eliminating the danger of explosion. It is estimated that by the mid-1970's more than half the electric power produced in the United States will be from plants powered by nuclear fuel.

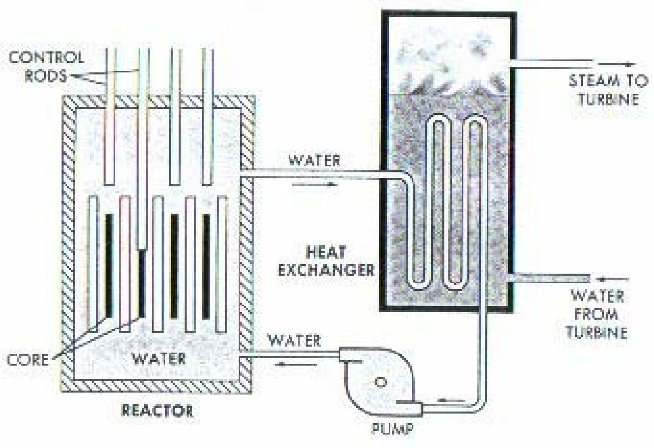

Figure 15. Nuclear Steam Generator.
The nuclear fuel (uranium) control rods, and heat transfer medium (water) are contained in a pressure vessel. The water, heated to high temperatures by the fissioning or splitting of uranium atoms flows through a heat exchanger where it turns water into steam. The steam is then piped to a turbine. The control rods can be lowered to slow down the nuclear activity.

6.9 Boiler Operation. Most modern boilers are under complete automatic control, with the rate of fuel combustion adjusted almost instantly to meet the steam requirements of the associated
turbine, engine, or heating system. All boilers must be provided with equipment such as safety valves, water level controls, indicating gauges and provision for rapid cutoff of fuel combustion and accessory equipment. Large power-plant boilers have monitoring devices that include television cameras to observe the stack, the furnace, and distant gauges.

The efficiency of modern boilers is extreme high, approaching 90% for large boilers with heat conservation devices, particularly air preheaters, In small-capacity boilers, where the heat-absorption surface is often inadequate, efficiency is lower, wasted heat escaping in exhaust gases still at high temperatures. Domestic boilers employing solid fuels in many cases have efficiencies little greater than 50%. In modern domestic boilers fired by gas or oil, efficiencies are about 75%.

6.10 Special Boiler Types. Some power plants use liquid mercury instead of water as the energy medium. The advantage of mercury is that at the low pressure of 100 psi (7.0 kg/sq cm),it boils at 907 ^{o}F (486 ^{o}C), so that efficient, high temperature operation can be achieved at relatively low pressure. However, there appears little evidence that mercury-vapor boilers will ever find extensive use, since the vapor is highly toxic, and liquid mercury in large amounts represents a very sizable capital investment.

Another specialized boiler, one that is heated by electric heat, is feasible only where hydro-electric power is so cheap as to make electric heating more economical than fuel combustion Electrically heated boilers are used chiefly for generating steam that is to be used in industrial plants.

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