# Chapter 1

# Steam Generation – An Overview

Steam generators, or boilers, use heat to convert water into steam for a variety of applications. Primary among these are electric power generation and industrial process heating. Steam is a key resource because of its wide availability, advantageous properties and nontoxic nature. Steam flow rates and operating conditions are the principal design considerations for any steam generator and can vary dramatically: from 1000 lb/h (0.1 kg/s) in one process use to more than 10 million lb/h (1260 kg/s) in large electric power plants; from about 14.7 psi (0.1013 MPa) and 212F (100C) in some heating applications to more than 4500 psi (31.03 MPa) and 1100F (593C) in advanced cycle power plants.

Fuel use and handling add to the complexity and variety of steam generating systems. The fuels used in most steam generators are coal, natural gas and oil. However, nuclear energy also plays a major role in at least the electric power generation area. Also, an increasing variety of biomass materials and process byproducts have become heat sources for steam generation. These include peat, wood and wood wastes, bagasse, straw, coffee grounds, corn husks, coal mine wastes (culm), and waste heat from steelmaking furnaces. Even renewable energy sources, e.g., solar, are being used to generate steam. The steam generating process has also been adapted to incorporate functions such as chemical recovery from paper pulping processes, volume reduction for municipal solid waste or trash, and hazardous waste destruction.

Steam generators designed to accomplish these tasks range from a small package boiler (Fig. 1) to large, high capacity utility boilers used to generate 1300 MW of electricity (Fig. 2). The former is a factory-assembled, fully-automated, gas-fired boiler, which can supply saturated steam for a large building, perhaps for a hospital. It arrives at the site with all controls and equipment assembled. The large field-erected utility boiler will produce more than 10 million lb/h (1260 kg/s) steam at 3860 psi (26.62 MPa) and 1010F (543C). Such a unit, or its companion nuclear option (Fig. 3), is part of some of the most complex and demanding engineering systems in operation today. Other examples, illustrating the range of combustion systems, are shown by the 750 t/d (680 tm/d) mass-fired refuse power boiler in Fig. 4 and the circulating fluidized-bed combustion boiler in Fig. 5.

The central job of the boiler designer in any of these applications is to combine fundamental science, technology, empirical data, and practical experience to produce a steam generating system that meets the steam supply requirements in the most economical package. Other factors in the design process include fuel characteristics, environmental protection, thermal efficiency, operations, maintenance and operating costs, regulatory requirements, and local geographic and weather conditions, among others. The design process involves balancing these complex and sometimes competing factors. For example, the reduction of pollutants such as nitrogen oxides ($NO_x$) may require a larger boiler volume, increasing capital costs and potentially increasing maintenance costs. Such a design activity is firmly based upon the physical and thermal sciences such as solid mechanics, thermodynamics, heat transfer, fluid mechanics and materials science. However, the real world is so complex and variable, and so interrelated, that it is only by applying the art of boiler design to combine science and practice that the most economical and dependable design can be achieved.

Steam generator design must also strive to address in advance the many changes occurring in the world to provide the best possible option. Fuel prices are expected to escalate while fuel supplies become less certain, thereby enforcing the need for continued efficiency improvement and fuel flexibility. Increased environmental protection will drive improvements in combustion to reduce $NO_x$ and in efficiency to reduce carbon dioxide ($CO_2$) emissions. Demand growth continues in many areas where steam generator load
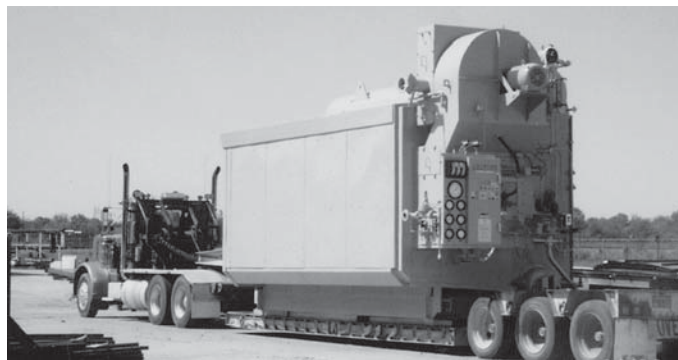
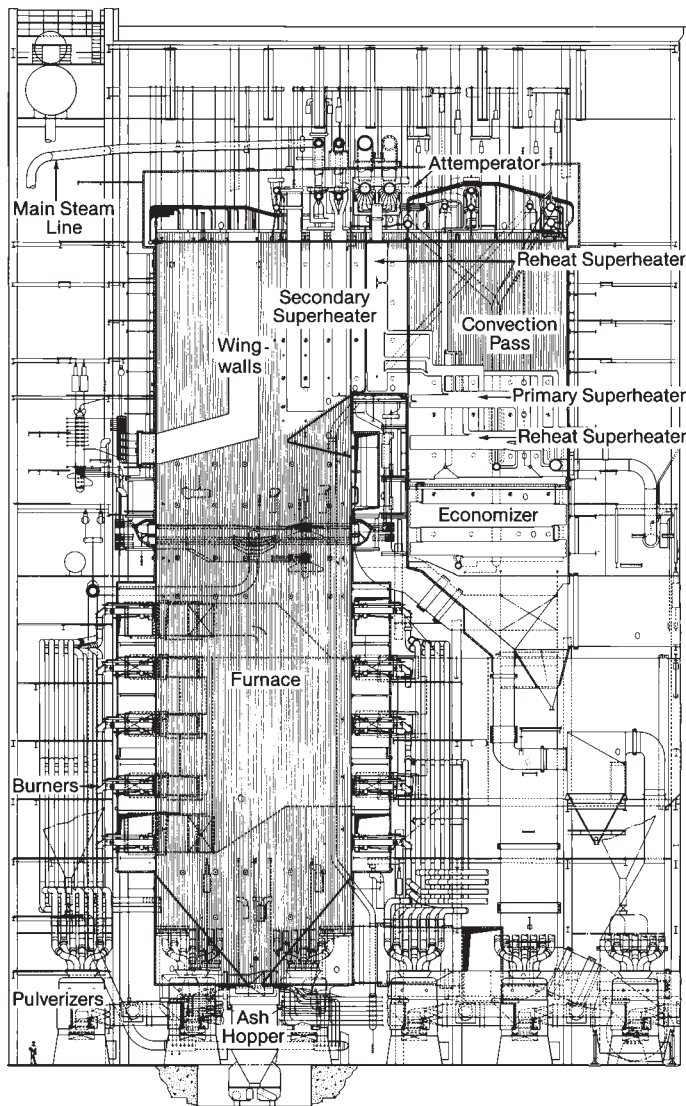

**Fig. 1** Small shop-assembled package boiler.

**Fig. 2** 1300 MW coal-fired utility steam generator.

may have to cycle up and down more frequently and at a faster rate.

There are technologies such as pressurized fluidized-bed combustion and integrated gasification combined cycle systems, plus others, which actually integrate the environmental control with the entire steam generation process to reduce emissions and increase



**Fig. 3** 900 MW nuclear power system.

power plant thermal efficiency. Also, modularization and further standardization will help reduce fabrication and erection schedules to meet more dynamic capacity addition needs.

## Steam generation fundamentals

### Boiling

The process of boiling water to make steam is a familiar phenomenon. Thermodynamically, instead of increasing the water temperature, the energy used results in a change of phase from a liquid to a gaseous state, i.e., water to steam. A steam generating system should provide a continuous process for this conversion.

The simplest case for such a device is a kettle boiler where a fixed quantity of water is heated (Fig. 6). The applied heat raises the water temperature. Eventually, for the given pressure, the boiling (*saturation*) temperature is reached and bubbles begin to form. As heat continues to be applied, the temperature remains constant, and steam escapes from the water surface. If the steam is continuously removed from the vessel, the temperature will remain constant until all of the water is evaporated. At this point, heat addition would increase the temperature of the kettle and of any steam remaining in the vessel. To provide a continuous process, all that is needed is a regulated supply of water to the vessel to equal the steam being generated and removed.

Technical and economic factors indicate that the most effective way to produce high pressure steam is to heat relatively small diameter tubes containing a continuous flow of water. Regardless of whether the energy source is nuclear or fossil fuel, two distinct boiling systems are
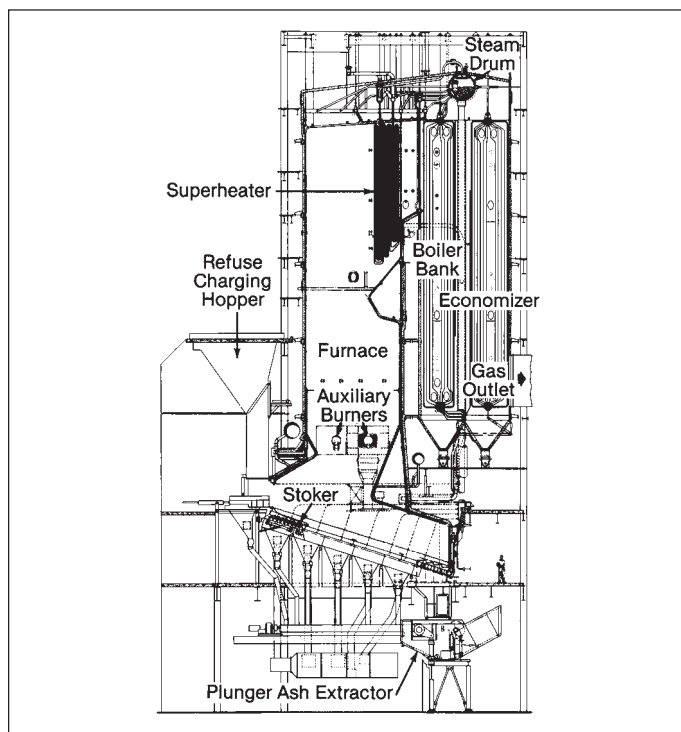


**Fig. 4** Babcock & Wilcox 750 ton per day mass-fired refuse power boiler.

used to accomplish this task: those that include a steam drum (see Fig. 7a), or fixed steam-water separation point, and those that do not (see Fig. 7b), termed once-through steam generators (OTSG).

The most common and simplest to control is the steam drum system. In this system, the drum serves as the point of separation of steam from water throughout its boiler's load range. Subcooled water (less than boiling temperature) enters the tube to which heat is applied. As the water flows through the tube, it is heated to the boiling point, bubbles are formed, and *wet* steam is generated. In most boilers, a steam-water mixture leaves the tube and enters the steam drum, where steam is separated from water. The remaining water is then mixed with the replacement water and returned to the heated tube.

Without a steam drum, i.e., for an OTSG system, subcooled water also enters the tube to which heat is applied, but the flowing water turns into steam some-where along the flow path (length of tube), dependent upon water flow rate (boiler load) and heat input rates. Shown in Fig. 7b, the flow rate and heat input are closely controlled and coordinated so that all of the water is evaporated and only steam leaves the tube. There is no need for the steam drum (fixed steam-water separation point).

## Circulation

For both types of boiling systems described above, water must continuously pass through, or circulate through, the tubes for the system to generate steam continuously. For an OTSG, water makes one pass through the boiler's tubes before becoming steam to be sent to the turbine-generator. However, for those boilers with a fixed steam-water separation point or steam drum, a molecule of water can make many passes through a circulation loop before it leaves as
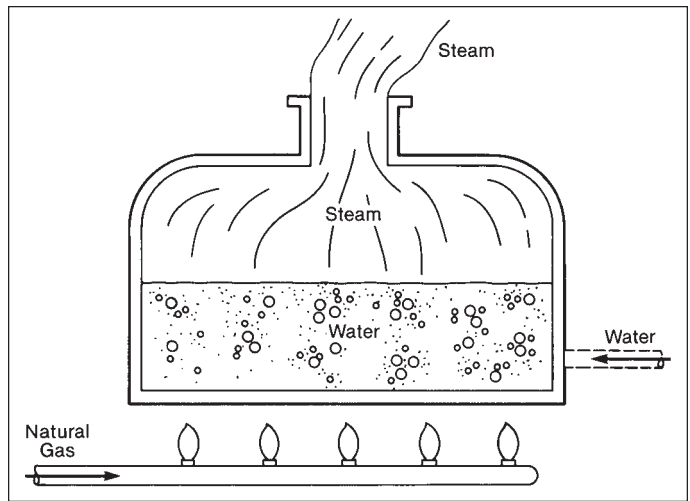


**Fig. 6** Simple kettle boiler.

steam to the turbine-generator. Options for this latter system are shown in Fig. 8.

Two different approaches to circulation are commonly used: natural or thermal circulation, and forced or pumped circulation. Natural circulation is illustrated in Fig. 8a. In the *downcomer*, unheated tube segment A-B, no steam is present. Heat addition generates a steam-water mixture in segment B-C. Because the steam and steam-water mixture in segment B-C are less dense than the water segment A-B, gravity will cause the water to flow downward in segment A-B and will
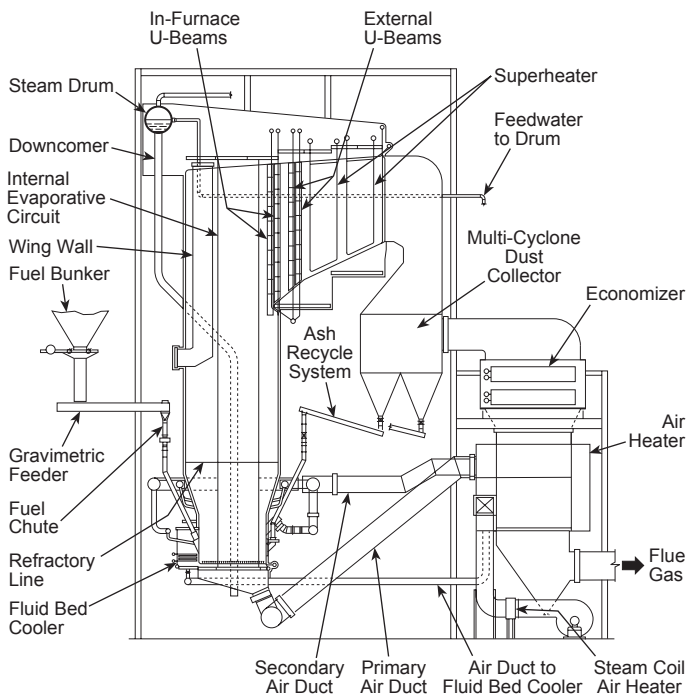


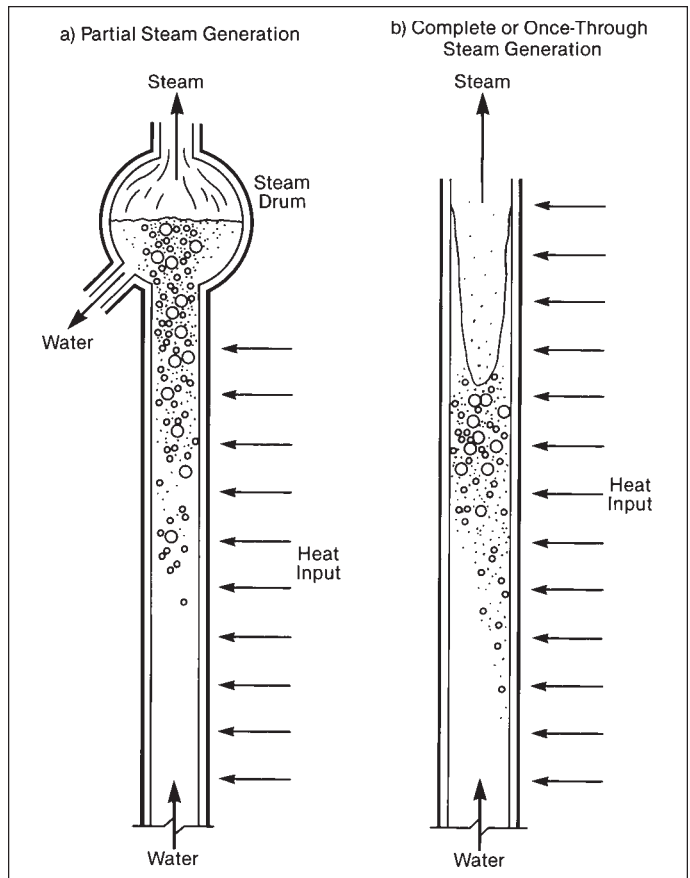**Fig. 5** Coal-fired circulating fluidized-bed combustion steam generator.



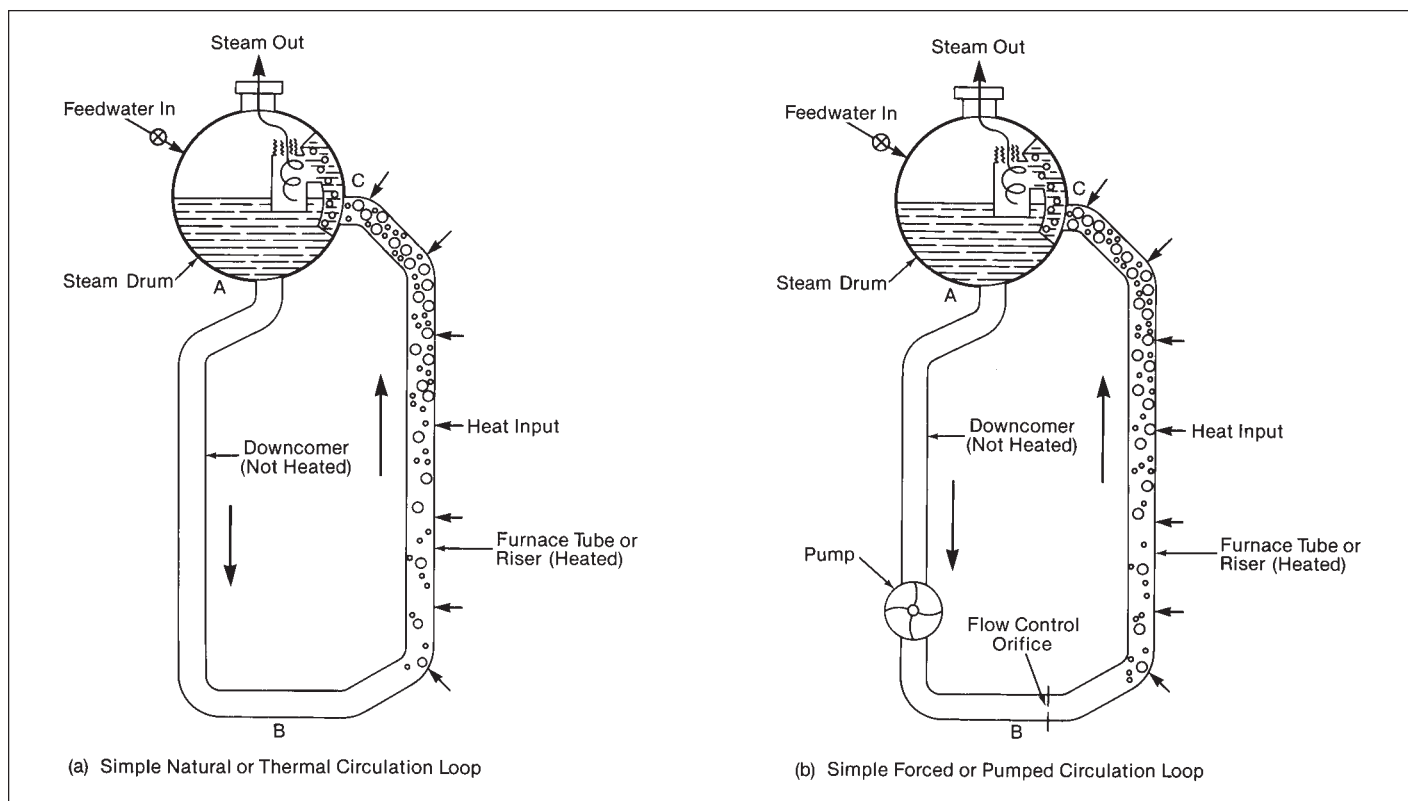**Fig. 7** Boiling process in tubular geometries.

**Fig. 8** Simple circulation systems.

cause the steam-water mixture (B-C) to move upward into the steam drum. The rate of water flow or circulation depends upon the difference in average density between the unheated water and the heated steam-water mixture.

The total circulation rate in a natural circulation system depends primarily upon four factors: 1) the height of the boiler, 2) the operating pressure, 3) the heat input rate, and 4) the free flow areas of the components. Taller boilers result in a larger total pressure difference between the heated and unheated legs and therefore can produce larger total flow rates. Higher operating pressures provide higher density steam and higher density steam-water mixtures. This reduces the total weight difference between the heated and unheated segments and tends to reduce flow rate. Higher heat input typically increases the amount of steam in the heated segments and reduces the average density of the steam-water mixture, increasing total flow rate. An increase in the cross-sectional (free flow) areas for the water or steam-water mixtures may increase the circulation rate. For each unit of steam produced, the amount of water entering the tube can vary from 3 to 25 units.

Forced or pumped circulation is illustrated in Fig. 8b. A mechanical pump is added to the simple flow loop and the pressure difference created by the pump controls the water flow rate.

The steam-water separation in the drum requires careful consideration. In small, low pressure boilers, steam-water separation can be easily accomplished with a large drum approximately half full of water. Natural gravity steam-water separation (similar to a kettle) can be sufficient. However, in today's high ca-

pacity, high pressure units, mechanical steam-water separators are needed to economically provide moisture-free steam from the drum. With such devices installed in the drum, the vessel diameter and cost can be significantly reduced.

At very high pressures, a point is reached where water no longer exhibits boiling behavior. Above this critical pressure [3200.11 psi (22.1 MPa)], the water temperature continuously increases with heat addition. Steam generators can be designed to operate at pressures above this critical pressure. Drums and steam-water separation are no longer required and the steam generator operates effectively on the once-through principle.

There are a large number of design methods used to evaluate the expected flow rate for a specific steam generator design and set of operating conditions. In addition, there are several criteria which establish the minimum required flow rate and maximum allowable steam content or quality in individual tubes, as well as the maximum allowable flow rates for the steam drum.

## System arrangement and key components

Most applications of steam generators involve the production of electricity or the supply of process steam. In some cases, a combination of the two applications, called *cogeneration*, is used. In each application, the steam generator is a major part of a larger system that has many subsystems and components. Fig. 9 shows a modern coal-fired power generating facility; Fig. 10 identifies the major subsystems. Key subsystems include fuel receiving and preparation, steam generator

and combustion, environmental protection, turbine-generator, and heat rejection including cooling tower.

First, follow the fuel and products of combustion (flue gas) through the system. The fuel handling system stores the fuel supply (coal in this example), prepares the fuel for combustion and transports it to the steam generator. The associated air system supplies air to the burners through a forced draft fan. The steam generator subsystem, which includes the air heater, burns the fuel-air mixture, recovers the heat, and generates the controlled high pressure and high temperature steam. The flue gas leaves the steam generator subsystem and selective catalytic reduction (SCR) system if supplied, then passes through particulate collection and sulfur dioxide ($SO_2$) scrubbing systems where pollutants are collected and the ash and solid scrubber residue are removed. The remaining flue gas is then sent to the stack through an induced draft fan.

Next, follow the steam-water path. The steam generator (boiler) evaporates water and supplies high temperature, high pressure steam, under carefully controlled conditions, to a turbine-generator set that produces the electricity. The steam may also be reheated in the steam generator, after passing through part of a multi-stage turbine system, by running the exhaust steam back to the boiler convection pass (reheater not shown). Ultimately, the steam is passed from the turbine to the condenser where the remaining waste heat is rejected. Before the water from the condenser is returned to the boiler, it passes through several pumps and heat exchangers (feedwater heaters) to increase its pressure and temperature. The heat absorbed by the condenser is eventually rejected to the atmosphere by one or more cooling towers. These cool-



**Fig. 9** Coal-fired utility power plant.

ing towers are perhaps the most visible component in the power system (Fig. 9). The natural draft cooling tower shown is basically a hollow cylindrical structure which circulates air and moisture to absorb the heat rejected by the condenser. Such cooling towers exist at most modern power plant sites, both nuclear- and fossil fuel-fired.

For an industrial power system, many of the same features are needed. However, the turbine-generator and heat rejection portions are replaced by the process application, such as radiant space heaters or heat exchangers.

In a nuclear power system (Fig. 11), the fossil fuel-fired steam generator is replaced by a nuclear reactor vessel and, typically, two or more steam generators. The coal handling system is replaced by a nuclear reactor fuel bundle handling and storage facility, and the large scale air pollution control equipment is not needed.
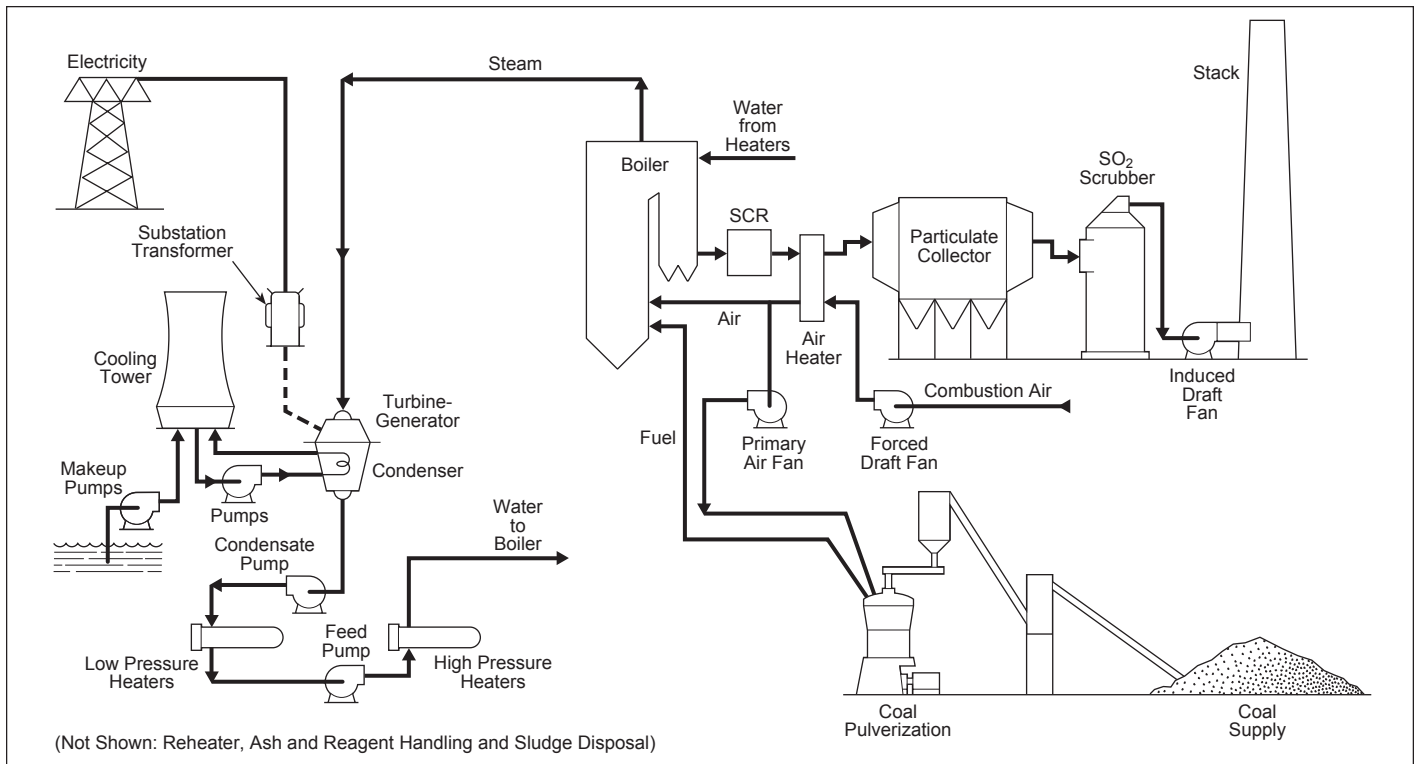


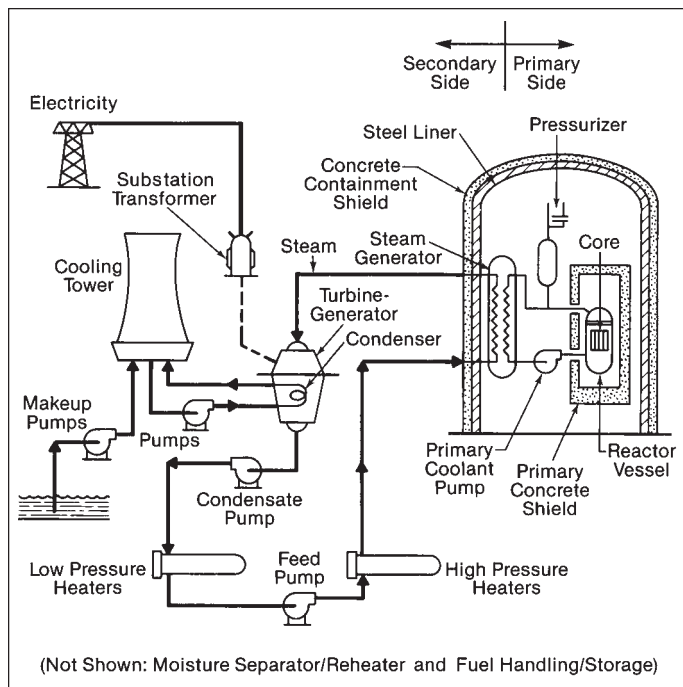**Fig. 10** Coal-fired utility power plant schematic.

**Fig. 11** Nuclear power plant schematic.

## Fossil steam generator classifications

Modern steam generating systems can be classified by various criteria. These include end use, firing method, operating pressure, fuel, and circulation method.

Utility steam generators are used primarily to generate electricity in large central power stations. They are designed to optimize overall thermodynamic efficiency at the highest possible availability. New units are typically characterized by large, main steam flow rates with superheated steam outlet pressures from 1800 to 3860 psi (12.41 to 26.62 MPa) with steam temperatures at or above 1050F (566C). A key characteristic of newer units is the use of a reheater section to increase overall cycle efficiency.

Industrial steam generators generally supply steam to processes or manufacturing activities and are designed with particular attention to: 1) process controlled (usually lower) pressures, 2) high reliability with minimum maintenance, 3) use of one or more locally inexpensive fuels, especially process byproducts or wastes, and 4) low initial capital and minimum operating costs. On a capacity basis, the larger users of such industrial units are the pulp and paper industry, municipal solid waste reduction industry, food processing industry, petroleum/petrochemical industry, independent power producers and cogenerators, and some large manufacturing operations. Operating pressures range from 150 to 1800 psi (1.04 to 12.41 MPa) with saturated or superheated steam conditions.

## Impact of energy source

The primary fuel selected has perhaps the most significant impact on the steam generator system configuration and design. In the case of nuclear energy, a truly unique system for containing the fuel and the nuclear reaction products has been developed with an

intense focus on safety and protecting the public from radiation exposure. Acceptable materials performance in the radiative environment and the long term thermal-hydraulic and mechanical performance are central to system design. When fossil, biomass, or byproduct fuels are burned, widely differing provisions must be made for fuel handling and preparation, fuel combustion, heat recovery, fouling of heat transfer surfaces, corrosion of materials, and emissions control. For example, in a natural gas-fired unit (Fig.12), there is minimal need for fuel storage and handling. Only a small furnace is needed for combustion, and closely spaced heat transfer surfaces may be used because of lack of ash deposits (fouling). The corrosion allowance is relatively small and the emissions control function is primarily for $NO_x$ formed during the combustion process. The result is a relatively small, compact and economical design.

If a solid fuel such as coal (which has a significant level of noncombustible ash) is used, the overall system is much more complex. This system could include extensive fuel handling and preparation facilities, a much larger furnace, and more widely spaced heat transfer surfaces. Additional components could be special cleaning equipment to reduce the impact of fouling and erosion, air preheating to dry the fuel and enhance combustion, more extensive environmental equipment, and equipment to collect and remove solid wastes.

The impact of fuel alone on a utility boiler design is clearly indicated in Fig. 12, where both steam generators produce the same steam flow rate. Further adding to the size and cost difference, but not shown, are the facts that the coal-fired boiler will be wider (dimension not shown) and will require more flue gas cleanup equipment to meet emissions requirements. The particular challenge when burning different solid fuels is indicated in Fig. 13, where provision is made for burning both pulverized (finely ground) coal using the burners and for wood chips and bark which are burned on the moving grate (stoker) at the bottom of the unit.

### Impact of steam conditions

The steam temperature and pressure for different boiler applications can have a significant impact on design. Fig. 14 identifies several typical boiler types, as well as the relative amount of heat input needed, for water heating, evaporation (boiling), superheating, and reheating, if required. The relative amount of energy needed for evaporation is dramatically reduced as operating pressure is increased. As a result, the relative amount of physical heat transfer surface (tubes) dedicated to each function can be dramatically different.

## Fossil fuel systems

### Fossil fuel steam generator components

Modern steam generators are a complex configuration of thermal-hydraulic (steam and water) sections which preheat and evaporate water, and superheat steam. These surfaces are arranged so that: 1) the fuel can be burned completely and efficiently while minimizing emissions, 2) the steam is generated at the required flow rate, pressure and temperature, and 3)
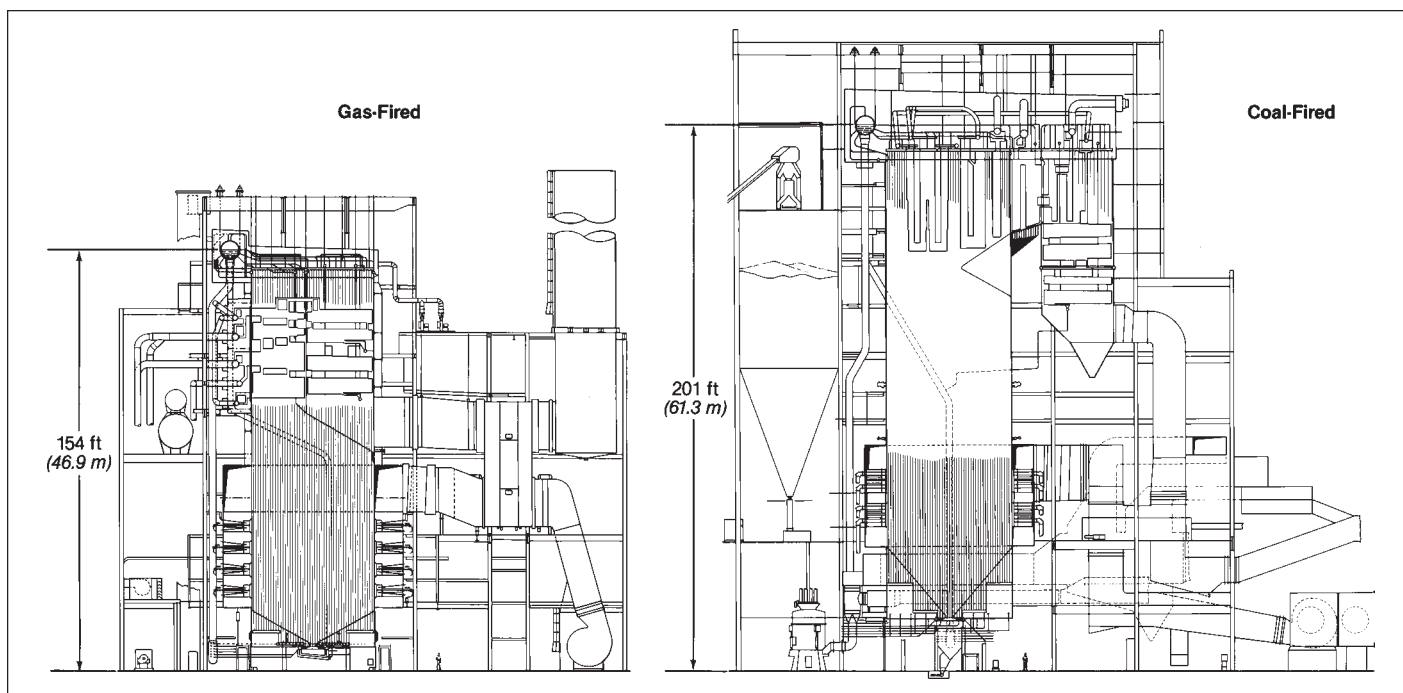
**Fig. 12** Comparison of gas- and coal-fired steam generators.

the maximum amount of energy is recovered. A relatively simple coal-fired utility boiler is illustrated in Fig. 15. The major components in the steam generating and heat recovery system include:

1. furnace and convection pass,
2. steam superheaters (primary and secondary),
3. steam reheater,
4. boiler or steam generating bank (industrial units only),
5. economizer,
6. steam drum,
7. attemperator and steam temperature control system, and
8. air heater.

These components are supported by a number of subsystems and pieces of equipment such as coal pulverizers, combustion system, flues, ducts, fans, gas-side cleaning equipment and ash removal equipment.

The *furnace* is a large enclosed open space for fuel combustion and for cooling of the flue gas before it enters the convection pass. Excessive gas temperatures leaving the furnace and entering the tube bundles could cause particle accumulation on the tubes or excessive tube metal temperatures. The specific geometry and dimensions of the furnace are highly influenced by the fuel and type of combustion equipment. In this case, finely ground or pulverized coal is blown into the furnace where it burns in suspension. The products of combustion then rise through the upper furnace. The superheater, reheater and economizer surfaces are typically located in the flue gas horizontal and vertical downflow sections of the boiler enclosure, called the *convection pass*.

In modern steam generators, the furnace and convection pass walls are composed of steam- or water-cooled carbon steel or low alloy tubes to maintain wall metal temperatures within acceptable limits. These tubes are connected at the top and bottom by headers, or manifolds. These headers distribute or collect the water, steam or steam-water mixture. The furnace wall tubes in most modern units also serve as key steam generating components or surfaces. The tubes are welded together with steel bars to provide membrane wall panels which are gas-tight, continuous and rigid. The tubes are usually prefabricated into shippable membrane panels with openings for burners, observation doors, sootblowers (boiler gas-side surface cleaning equipment) and gas injection ports.

*Superheaters* and *reheaters* are specially designed in-line tube bundles that increase the temperature of saturated steam. In general terms, they are simple single-phase heat exchangers with steam flowing inside the tubes and the flue gas passing outside, generally in crossflow. These critical components are manufactured from steel alloy material because of their high operating temperature. They are typically configured to help control steam outlet temperatures, keep metal temperatures within acceptable limits, and control steam flow pressure loss.

The main difference between superheaters and reheaters is the steam pressure. In a typical drum boiler, the superheater outlet pressure might be 2700 psi (18.62 MPa) while the reheater outlet might be only 580 psi (4.0 MPa). The physical design and location of the surfaces depend upon the desired outlet temperatures, heat absorption, fuel ash characteristics and cleaning equipment. These surfaces can be either horizontal or vertical as shown. The superheater and sometimes reheater are often divided into multiple sections to help control steam temperature and optimize heat recovery.

The heat transfer surface in the furnace may not be sufficient to generate enough saturated steam for
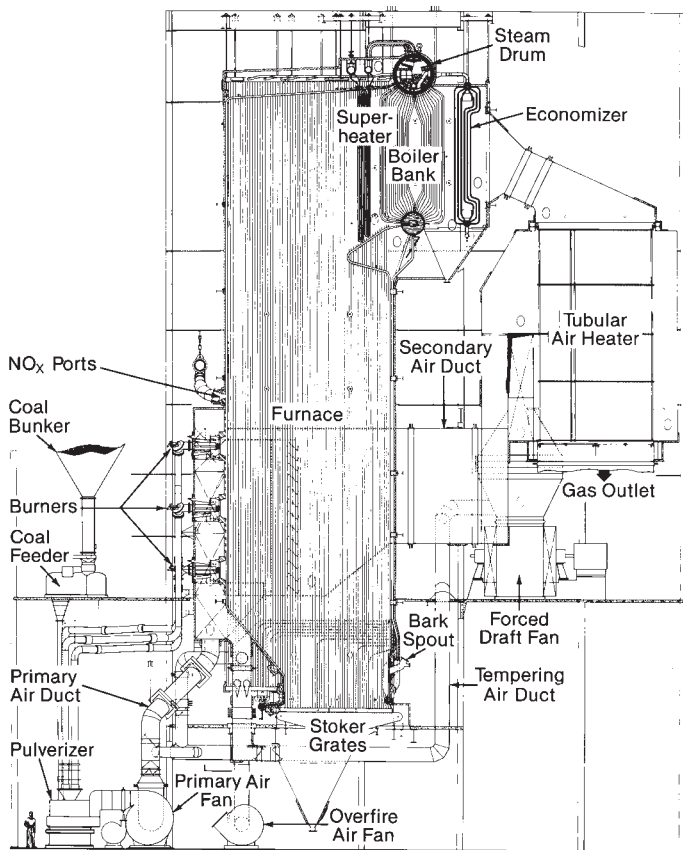
**Fig. 13** Large industrial boiler with multiple fuel capability.

the particular end use. If this is the case, an additional bank of heat exchanger tubes called the *boiler bank* or *steam generating bank* is added. (See Fig. 13.) This is needed on many smaller, low pressure industrial boilers, but is not often needed in high pressure utility boilers. This boiler bank is typically composed of the *steam drum* on top, a second drum on the bottom, and a series of bent connecting tubes. The steam drum internals and tube sizes are arranged so that subcooled water travels down the tubes (farthest from the furnace) into the lower drum. The water is then distributed to the other tubes where it is partially converted to steam and returned to the steam drum. The lower drum is often called the *mud drum* because this is where sediments found in the boiler water tend to settle out and collect.

The *economizer* is a counterflow heat exchanger for recovering energy from the flue gas beyond the superheater and, if used, the reheater. It increases the temperature of the water entering the steam drum. The tube bundle is typically an arrangement of parallel horizontal serpentine tubes with the water flowing inside but in the opposite direction (counterflow) to the flue gas. Tube spacing is as tight as possible to promote heat transfer while still permitting adequate tube surface cleaning and limiting flue gas-side pressure loss. By design, steam is usually not generated inside these tubes.

The *steam drum* is a large cylindrical vessel at the top of the boiler, in which saturated steam is separated from the steam-water mixture leaving the boiler tubes. Drums can be quite large with diameters of 3 to 6 ft

(0.9 to 1.8 m) and lengths approaching 100 ft (30.5 m). They are fabricated from thick steel plates rolled into cylinders with hemispherical heads. They house the steam-water separation equipment, purify the steam, mix the replacement or feedwater and chemicals, and provide limited water storage to accommodate small changes in unit load. Major connections to the steam drum are provided to receive the steam-water mixture from the boiler tubes, remove saturated steam, add replacement or makeup water, and return the near saturated water back to the inlet of the boiler tubes.

The *steam temperature control* system can be complex and include combinations of recirculating some of the flue gas to the bottom or top of the furnace, providing special gas flow passages at the back end of the steam generator, adjusting the combustion system, and adding water or low temperature steam to the high temperature steam flow (*attemperation*). The component most frequently used for the latter is called a *spray attemperator*. In large utility units, attemperators with direct injection of water or low temperature steam are used for dynamic control because of their rapid response. They are specially designed to resist thermal shock and are frequently located at the inlet of the superheater or between superheater sections to better control the superheater outlet metal temperatures. Positioning of individual superheater sections can also help maintain proper outlet steam temperatures.

The *air heater* is not a portion of the steam-water circuitry, but serves a key role in the steam generator system heat transfer and efficiency. In many cases, especially in high pressure boilers, the temperature of the flue gas leaving the economizer is still quite high. The air heater recovers much of this energy and adds it to the combustion air to reduce fuel use. Designs include tubular, flat plate, and regenerative heat exchangers, among others.

## Steam-water flow system

The steam-water components are arranged for the most economical system to provide a continuous supply of steam. The circulation system (excluding reheater) for a natural circulation, subcritical pressure, drum type steam generator is shown in Fig. 16. Feed-
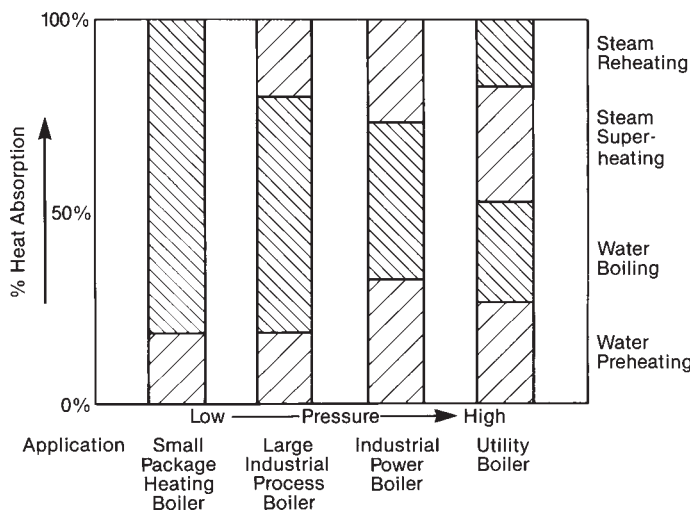


**Fig. 14** Steam generator energy absorption by function.

water enters the bottom header (A) of the economizer and passes upward in the opposite direction to the flue gas. It is collected in an outlet header (B), which may also be located in the flue gas stream. The water then flows through a number of pipes which connect the economizer outlet header to the steam drum. It is sometimes appropriate to run these tubes vertically (B-C) through the convection pass to economizer outlet headers located at the top of the boiler. These tubes can then serve as water-cooled supports for the horizontal superheater and reheater when these banks span too great a distance for end support. The feedwater is injected into the steam drum (D) where it mixes with the water discharged from the steam-water separators before entering connections to the *downcomer* pipes (D-E) which exit the steam drum.

The water travels around the furnace water wall circuits to generate steam. The water flows through the downcomer pipes (D-E) to the bottom of the furnace where *supply* tubes (E-F) route the circulating water to the individual lower furnace panel wall headers (F). The water rises through the furnace walls to individual outlet headers (G), absorbing energy to become a steam-water mixture. The mixture leaves the furnace wall outlet headers by means of *riser* tubes (G-D), to be discharged into the drum and steam-water separators. The separation equipment returns essentially steam-free water to the downcomer inlet connections. The residual moisture in the steam that leaves the primary steam separation devices is removed in secondary steam separators, and dry steam is discharged to the superheater through a number of drum outlet connections (H-I and H-J).

The steam circuitry serves dual functions: cooling the convection pass enclosure, and generating the required superheated steam conditions. Steam from the drum passes through multiple connections to a
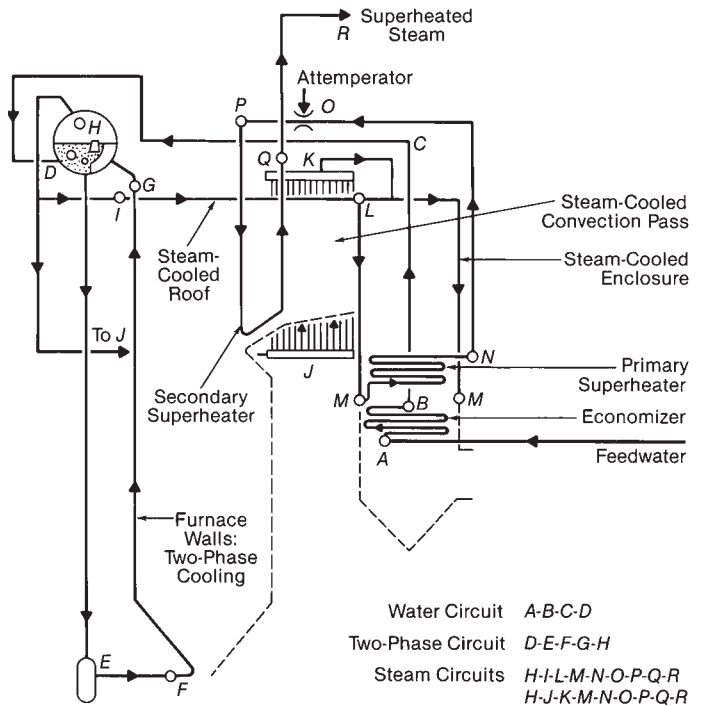


**Fig. 15** Coal-fired utility boiler.



**Fig. 16** Coal-fired boiler steam-water circulation system.

header (I) supplying the roof tubes and, separately, to headers (J) supplying the membrane panels in the pendant convection pass (so named because the superheater/reheater vertical tubes are hanging from supports above). The steam flows through these membrane panels to outlet headers (K). Steam from these headers and the roof tube outlet headers (L) then provides the cooling for the horizontal convection pass enclosure (L-M) (so named because the superheater/reheater/economizer tubes are horizontal in this flue gas downpass). Steam flows downward through these panels and is collected in outlet headers (M) just upstream of the economizer bank.

Steam flow then rises through the primary superheater and discharges through the outlet header (N) and connecting piping equipped with a spray attemperator (O). It then enters the secondary superheater inlet header (P), flowing through the superheater sections to an outlet header (Q). A discharge pipe (R) terminates outside of the boiler enclosure where the main steam lines route the steam flow to the control valves and turbine.

### Combustion system and auxiliaries

Most of the non-steam generating components and auxiliaries used in coal-fired steam generators are part of the fuel preparation and combustion systems. These include:

1.  fuel preparation: feeders and coal pulverizers,
2.  combustion system: burners, flame scanners, lighters, controls, windbox,
3.  air-gas handling: fans, flues and ducts, dampers, control and measurement systems, silencers, and
4.  other components and auxiliaries: sootblowers (heat transfer surface cleaning equipment), ash collection and handling equipment, control and monitoring equipment.
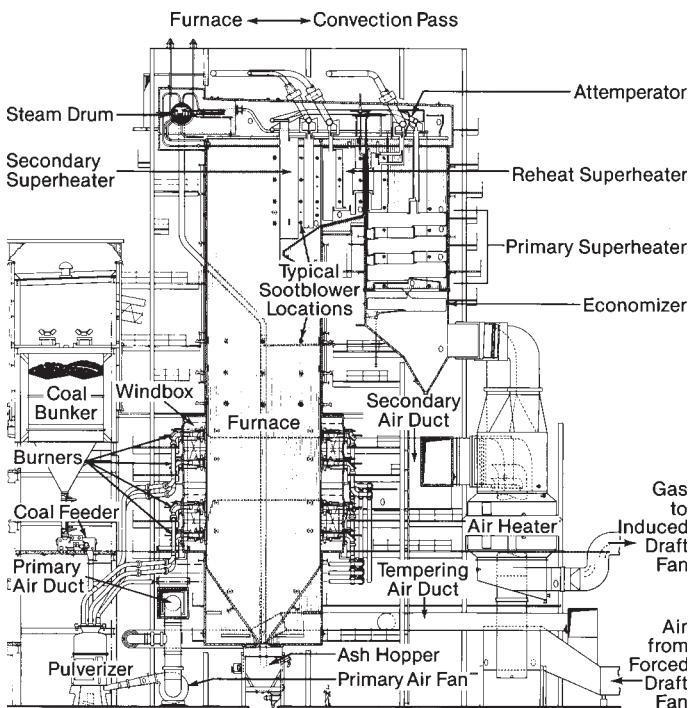
Because of their intimate relationship with the steam generation process, many of these components are supplied with the boiler. If not, careful specification and interaction with the steam generator manufacturer are critical.

The combustion system has a dramatic impact on overall furnace design. Wall mounted burners are shown in Figs. 15 and 17. These are typical for large coal-, oil-, or gas-fired units today. However, a variety of other systems are also used and are continuing to be developed to handle the variety of fuel characteristics and unit sizes. Other combustion systems include stokers (Figs. 4 and 13), Cyclone furnaces, and fluidized-bed combustion units (Fig. 5). All have their strengths and weaknesses for particular applications. Key elements of these systems involve the need to control the formation and emission of pollutants, provide complete efficient combustion, and handle inert material found in the fuel. The fuel characteristics play a central role in how these functions are met and how the equipment is sized and designed.

### Air-gas flow system

Many of these auxiliaries are identified in Fig. 17 along with the air-gas flow path in the large coal-fired utility boiler. Air is supplied by the *forced draft* fan (A) to the air heater (B) where it is heated to recover energy and enhance combustion. Most of the hot air (typically 70 to 80%), called secondary air, passes directly to the windboxes (C) where it is distributed to individual burners. The remaining 20 to 30%, called primary air, passes to the booster (or primary air) fan and then to the coal pulverizers (D) where the coal is dried and ground. The hot primary air then pneumatically conveys the pulverized coal to the burners (E) where it is mixed with the secondary air for combustion. The coal and air are rapidly mixed and burned in the furnace (F) and the flue gas then passes up through the furnace, being cooled primarily by radiation until it reaches the furnace exit (G). The gas then progressively passes through the secondary superheater, reheater, primary superheater and economizer before leaving the steam generator enclosure (H). The gas passes through the air heater (B) and then through any pollution control equipment and *induced draft* fan (I) before being exhausted to the atmosphere.

### Emissions control

A key element of fossil fuel-fired steam generator system design is environmental protection. A broad range of government regulations sets limits on primary gaseous, liquid and solid waste emissions from the steam generating process. For coal-, oil-, and gas-fired units, the primary air pollutant emissions include sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$) and airborne particulate or flyash. Water discharges include trace chemicals used to control corrosion and fouling as well as waste heat rejected from the condenser. Solid waste primarily involves the residual ash from the fuel and any spent sorbent from the pollution control systems.

The gaseous and solid waste from the fuel and combustion process can be minimized by fuel selection,
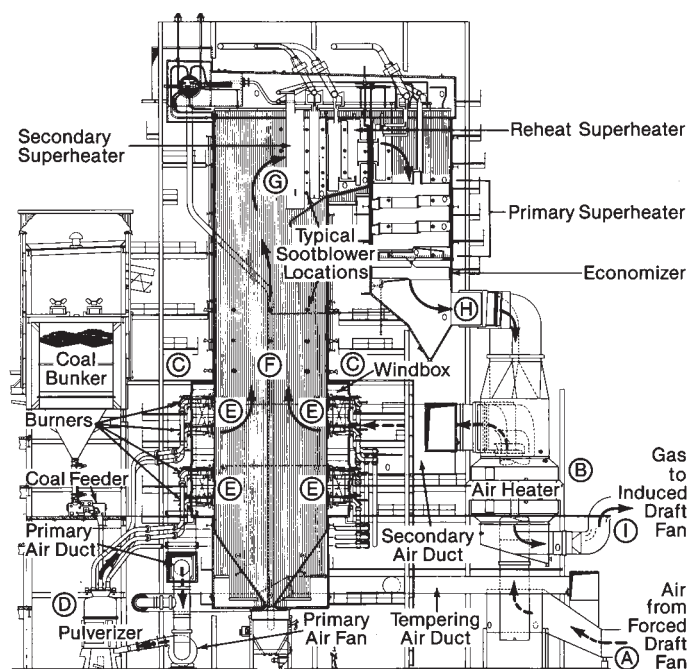


**Fig. 17**  Coal-fired boiler air/gas flow path.

control of the combustion process, and equipment located downstream of the steam generator. $SO_2$ emissions may be reduced by using fuels which contain low levels of sulfur, by fluidized-bed combustors, or by using a post-combustion scrubber system. Combustion $NO_x$ emissions are typically controlled by using equipment such as special low $NO_x$ burners or fluidized-bed combustors. Where it is required to significantly reduce $NO_x$ emissions (to levels lower than is practically achieved by combustion techniques alone), back-end or post-combustion techniques, such as selective catalytic reduction (SCR) or selective noncatalytic reduction (SNCR) technologies, are employed. Flyash or airborne particulate is collected by either a fabric filter (baghouse) or electrostatic precipitator (ESP) with removal efficiencies above 99%. The particulate collection equipment and $SO_2$ scrubbers produce solid byproduct streams which must be safely landfilled or used for some industrial applications.

The water discharges are minimized by installing recirculating cooling systems. An example of this is cooling towers that reject the waste heat from the power cycle to the air, instead of to a water source. These are used on virtually all new fossil and nuclear power plants. Chemical discharges are minimized by specially designed zero discharge systems. A set of emissions rates before and after control for a typical 500 MW power plant is shown in Table 1.

## Nuclear steam generating systems

### Overview

Nuclear steam generating systems include a series of highly specialized heat exchangers, pressure vessels, pumps and components which use the heat generated by nuclear fission reactions to efficiently and

**Table 1**
**Typical 500 MW Subcritical Coal-Fired Steam Generator Emissions and Byproducts***

Power System Characteristics
- 500 MW net
- 196 t/h (49.4 kg/s) bituminous coal
  - 2.5% sulfur
  - 16% ash
  - 12,360 Btu/lb (28,749 kJ/kg)
- 65% capacity factor

| Emission | Typical Control Equipment | Discharge Rate — t/h ($t_m$/h) Uncontrolled | | Controlled | |
|---|---|---|---|---|---|
| $SO_x$ as $SO_2$ | Wet limestone scrubber | 9.3 | (8.4) | 0.3 | (0.3) |
| $NO_x$ as $NO_2$ | Low $NO_x$ burners and SCR | 2.9 | (2.6) | 0.1 | (0.1) |
| $CO_2$ | Not applicable | 485 | (440) | — | — |
| Flyash to air** | Electrostatic precipitator or baghouse | 22.9 | (20.8) | 0.05 | (0.04) |
| Thermal discharge to water sources | Natural draft cooling tower | 2.8 x 10$^9$ Btu/h | (821 MW$_t$) | ~0 | (0) |
| Ash to landfill** | Controlled landfill | 9.1 | (8.3) | 32 | (29) |
| Scrubber sludge: gypsum plus water | Controlled landfill or wallboard quality gypsum | 0 | (0) | 27.7 | (25) |

\* See Chapter 32, Table 1, for a modern 615 MW supercritical coal-fired steam generator.
\*\* As flyash emissions to the air decline, ash to landfill increases.

safely generate steam. The system is based upon the energy released when atoms within certain materials, such as uranium, break apart or *fission*. Fission occurs when a fissionable atom nucleus captures a free subatomic particle – a neutron. This upsets the internal forces which hold the atom nucleus together. The nucleus splits apart producing new atoms as well as an average of two to three neutrons, gamma radiation and energy.

The nuclear steam supply system (NSSS) is designed to serve a number of functions: 1) house the nuclear fuel, 2) stimulate the controlled fission of the fuel, 3) control the nuclear reaction rate to produce the required amount of thermal energy, 4) collect the heat and generate steam, 5) safely contain the reaction products, and 6) provide backup systems to prevent release of radioactive material to the environment. Various systems have been developed to accomplish these functions. The main power producing system in commercial operation today is the pressurized water reactor (PWR).

A key difference between the nuclear and chemical energy driven systems is the quantity of fuel. The energy released per unit mass of nuclear fuel is many orders of magnitude greater than that for chemical based fuels. For example, 1 lb (0.454 kg) of 3% enriched uranium fuel produces about the same amount of thermal energy in a commercial nuclear system as 100,000 lb (45,360 kg) of coal in a fossil-fired steam system. While a 500 MW power plant must handle approximately one million tons of coal per year, the nuclear plant will handle only 10 tons of fuel. The fossil fuel plant must be designed for a continuous fuel supply process, while most nuclear plants use a batch fuel process, where about one third of the fuel is replaced during periodic outages. However, once the steam is generated, the balance of the power producing system (turbine, condenser, cooling system, etc.) is similar to that used in the fossil fuel plant.

## Nuclear steam system components

A typical nuclear steam system from The Babcock & Wilcox Company (B&W) is shown in Fig. 3 and a simplified schematic is shown in Fig. 18. This nuclear system consists of two coolant loops. The primary loop cools the reactor, transports heat to two or more steam generators (only one shown), and returns coolant to the reactor by four or more primary coolant pumps (only one shown). The coolant is high purity, subcooled, single-phase water flowing at very high rates [350,000 to 450,000 GPM (22,100 to 28,400 l/s)] at around 2200 psi (15.17 MPa) and an average temperature of approximately 580F (304C). The primary loop also contains a pressurizer to maintain the loop pressure at design operating levels.

The secondary loop includes the steam generation and interface with the balance of the power plant. High purity water from the last feedwater heater passes through the steam generator and is converted into steam. From the steam generator outlet, the saturated or superheated steam flows out of the containment building to the high pressure turbine. The operating pressure is typically around 1000 psi (6.9 MPa). The balance of the secondary loop resembles fossil fuel-fired systems. (See Figs. 10 and 11.)

The center of the NSSS is the reactor vessel and reactor core (Fig. 19). The fuel consists of compressed pellets [for example, 0.37 in. (9.4 mm) diameter by 0.7 in. (18 mm) long] of 2.5 to 5% enriched uranium oxide. These pellets are placed in zircaloy tubes which are sealed at both ends to protect the fuel and to contain the nuclear reaction products. The tubes are assembled into bundles with spacer and closure devices. These bundles are then assembled into the nuclear fuel core.

The reactor enclosure (Fig. 19) is a low alloy steel pressure vessel lined with stainless steel for corrosion protection. The rest of the reactor includes flow distribution devices, control rods, core support structures,
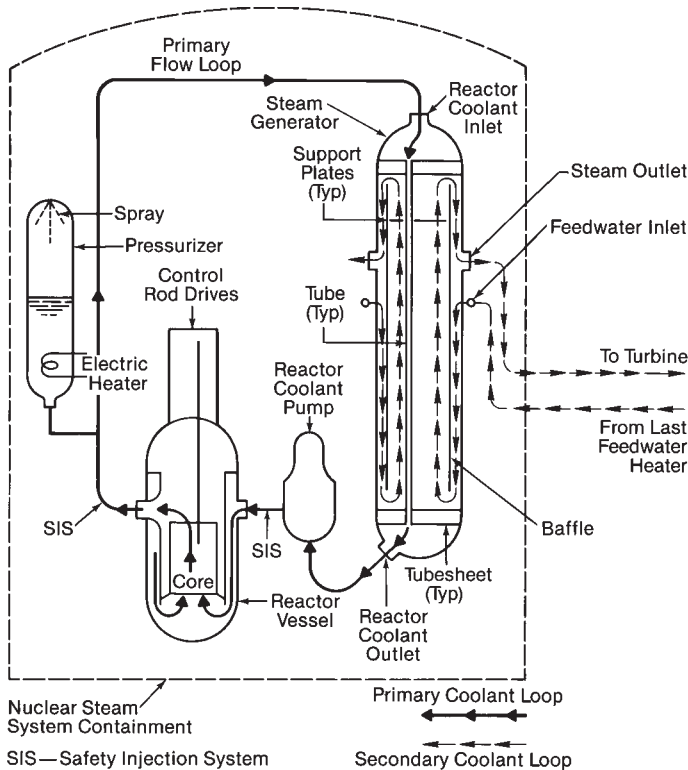
**Fig. 18** Nuclear steam system schematic.

thermal shielding and moderator. The moderator in this case is water which serves a dual purpose. It reduces the velocity of the neutrons thereby making the nuclear reactions more likely. It also serves as the coolant to maintain the core materials within acceptable temperature limits and transports thermal energy to the steam generators. The control rods contain neutron absorbing material and are moved into and out of the nuclear core to control the energy output.

The steam generators can be of two types, once-through (Fig. 20) and recirculating (Fig. 21). In both types, the pressure vessel is a large heat exchanger designed to generate steam for the secondary loop from heat contained in the primary coolant. The primary coolant enters a plenum and passes through several thousand small diameter [approximately 0.625 in. (15.9 mm)] Inconel® tubes. The steam generator is a large, carbon steel pressure vessel. Specially designed tubesheets, support plates, shrouds, and baffles provide effective heat transfer, avoid thermal expansion problems, and avoid flow-induced vibration.

In the once-through steam generator (OTSG), Fig. 20, the secondary loop water flows from the bottom to the top of the shell side of the tube bundle and is continuously converted from water to superheated steam. The superheated steam then passes to the high pressure turbine.

In the recirculating steam generator (RSG), Fig. 21, water moves from the bottom to the top of the shell side of the tube bundle being converted partially into steam. The steam-water mixture passes into the upper shell where steam-water separators supply saturated dry steam to the steam generator outlet. The steam is sent to the high pressure turbine. The water leaving the

steam generator upper shell is mixed with feedwater and is returned to the bottom of the tube bundle.

The pressurizer is a simple cylindrical pressure vessel which contains both water and steam at equilibrium. Electrical heaters and spray systems maintain the pressure in the pressurizer vessel and the primary loop within set limits. The primary loop circulating pumps maintain high flow rates to the reactor core to control its temperature and transfer heat to the steam generators.

A number of support systems are also provided. These include reactor coolant charging systems, makeup water addition, spent fuel storage cooling, and decay heat removal systems for when the reactor is shut down. Other specialized systems protect the reactor system in the case of a loss of coolant event. The key function of these systems is to keep the fuel bundle temperature within safe limits if the primary coolant flow is interrupted.

## Nuclear steam system classifications

A variety of reactor systems have been developed to recover thermal energy from nuclear fuel and to generate steam for power generation. These are usually identified by their coolant and moderator types. The principal systems for power generation include:

1. *Pressurized water reactor (PWR)* This is the system discussed above, using water as both reactor coolant and moderator, and enriched uranium oxide as the fuel.
2. *Boiling water reactor (BWR)* The steam generator is eliminated and steam is generated directly in the reactor core. A steam-water mixture cools and moderates the reactor core. Enriched uranium oxide fuel is used.
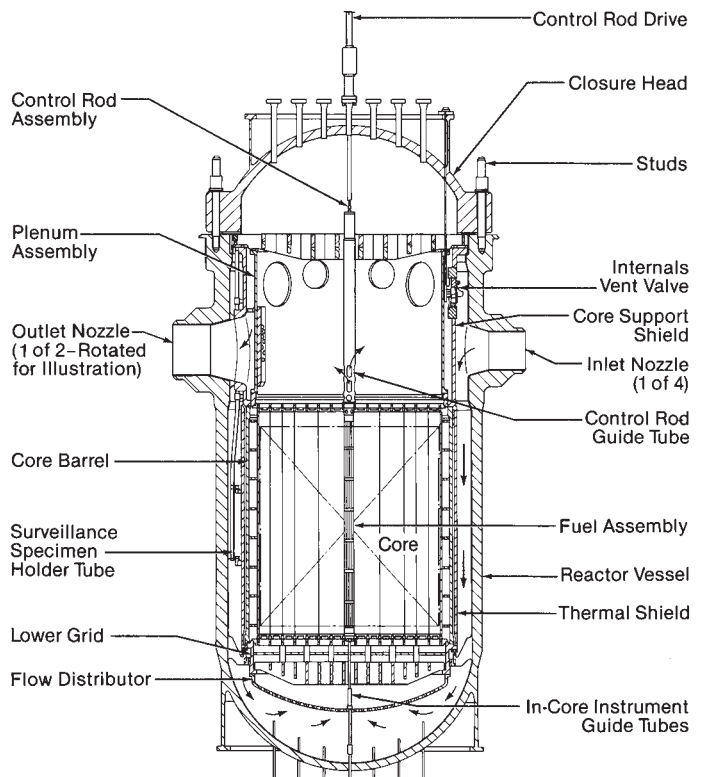


**Fig. 19** Reactor vessel and internals.

3. *CANDU (PHWR)* Heavy water (deuterium) is used as the moderator and primary loop coolant. The reactor configuration is unique but the steam generator is similar to the recirculating steam generator for the PWR. Natural (not enriched) uranium oxide is used as the fuel.

4. *Gas-cooled reactors* These are a variety of gas-cooled reactors which are typically moderated by graphite and cooled by helium or carbon dioxide.

5. *Breeder reactors* These are advanced reactor systems using sodium as the reactor coolant with no moderator. These systems are specially designed to produce more fissionable nuclear fuel than they use.

## Engineered safety systems

Safety is a major concern in the design, construction and operation of nuclear power generating facilities. The focus of these efforts is to minimize the likelihood of a release of radioactive materials to the environment. Three approaches are used to accomplish this goal. First, the nuclear power industry has developed one of the most extensive and rigorous quality control programs for the design, construction and maintenance of nuclear facilities. Second, reactor systems are designed with multiple barriers to prevent radioactive material release. These include high temperature ceramic fuel pellets, sealed fuel rods, reactor vessel and primary coolant system, and the contain-
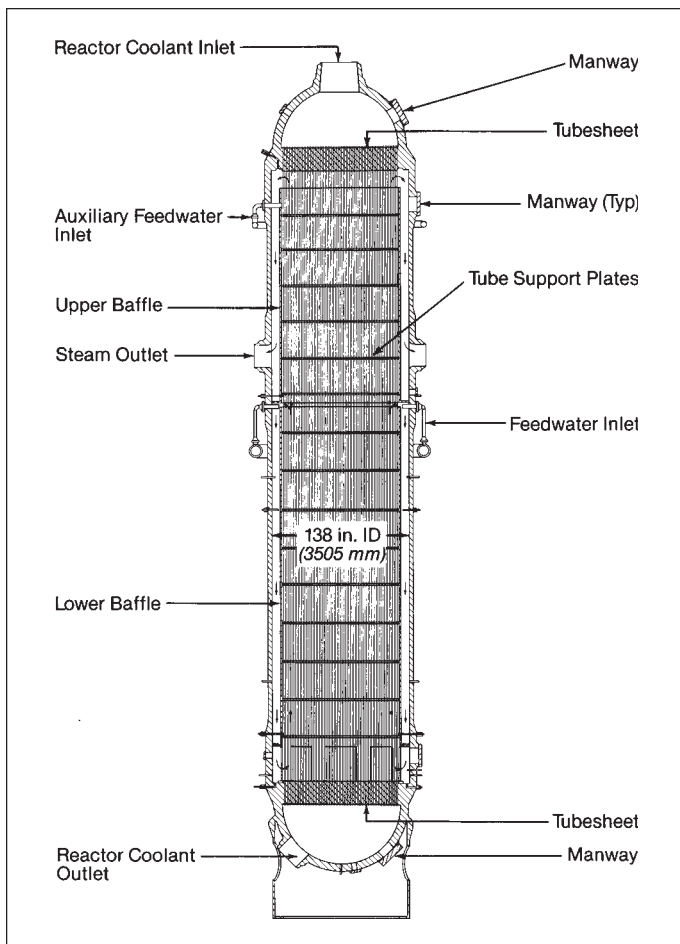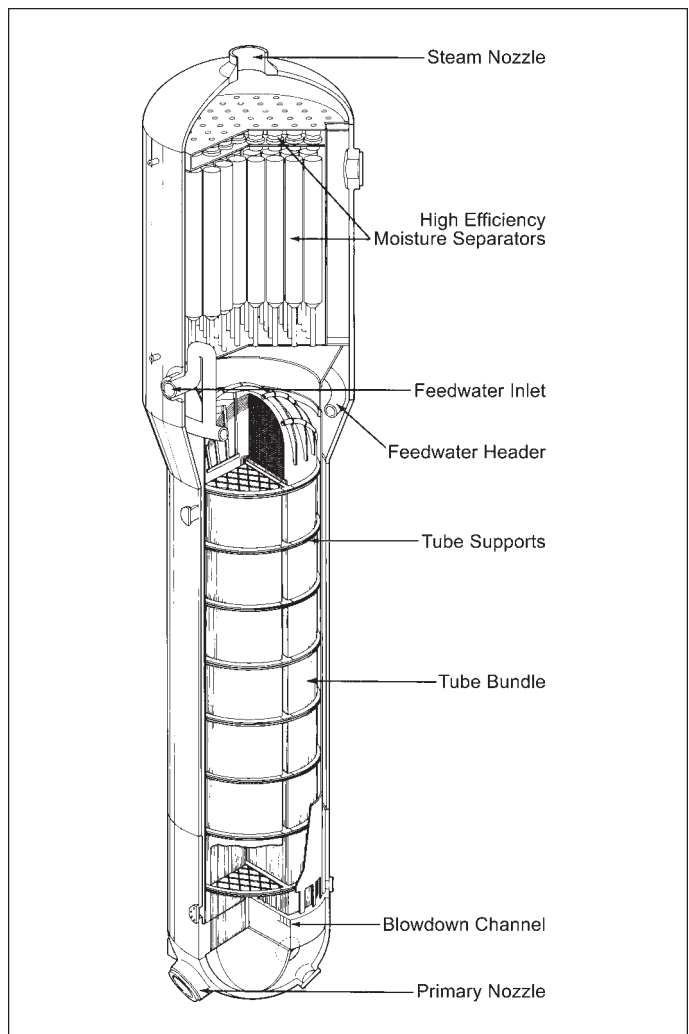


**Fig. 21** Recirculating steam generator.

ment building including both the carbon steel reactor containment vessel and the reinforced concrete shield building. The third approach includes a series of engineered safety systems to address loss of coolant conditions and maintain the integrity of the multiple barriers. These systems include:

1. emergency reactor trip systems including rapid insertion of control rods and the addition of soluble neutron poisons in the primary coolant to shut down the nuclear reaction,
2. high and low pressure emergency core cooling systems to keep the reactor core temperature within acceptable limits and remove heat from the fuel in the event of a major loss of primary coolant or a small pipe break,
3. a heat removal system for the cooling water and containment building, and
4. spray and filtering systems to collect and remove radioactivity from the containment building.

Because of the high power densities and decay heat generation, the reactor integrity depends upon the continuous cooling of the nuclear fuel rods. Multiple independent components and backup power supplies are provided for all critical systems.



**Fig. 20** Once-through steam generator.

## Steam system design

### Steam generator interfaces

The steam generator system's primary function is to convert chemical or nuclear energy bound in the fuel to heat and produce high temperature, high pressure steam. The variety of fuel sources, the high temperature nature of these processes, and the large number of subsystem interfaces contribute to the challenging nature of the design process. The initial steps in evaluating the steam generating system include establishing key interfaces with other plant systems and with the power cycle. These are typically set by the end user or consulting engineer after an in-depth evaluation indicates: 1) the need for the expanded power supply or steam source, 2) the most economical fuel selection and type of steam producing system, 3) the plant location, and 4) the desired power cycle or process steam conditions. The key requirements fall into six major areas:

1. Steam minimum, nominal, and maximum flow rates; pressure and temperature; need for one or more steam reheat stages; auxiliary equipment steam usage; and future requirements.
2. Source of the steam flow makeup or replacement water supply, water chemistry and inlet temperature.
3. The type and range of fuels considered, including worst case conditions, and the chemical analyses (proximate and ultimate analyses) for each fuel or mixture of fuels.
4. Elevation above sea level, overall climate history and forecast, earthquake potential and space limitations.
5. Emissions control requirements and applicable government regulations and standards.
6. The types of auxiliary equipment; overall plant and boiler efficiency; access needs; evaluation penalties, e.g., power usage; planned operating modes including expected load cycling requirements, e.g., peaking, intermediate or base load; and likely future plant use.

When these interfaces are established, boiler design and evaluation may begin.

### Systematic approach

There are a variety of evaluation approaches that can be used to meet the specific steam generator performance requirements. These include the multiple iterations commonly found in thermal design where real world complexities and nonlinear, noncontinuous interactions prevent a straightforward solution. The process begins by understanding the particular application and system to define conditions such as steam flow requirements, fuel source, operating dynamics, and emissions limits, among others. From these, the designer proceeds to assess the steam generator options, interfaces, and equipment needs to achieve performance. Using a coal-fired boiler as an example, a systematic approach would include the following:

1. Specify the steam supply requirements to define the overall inputs of fuel, air and water, and the steam output conditions.

2. Evaluate the heat balances and heat absorption by type of steam generator surface.
3. Perform combustion calculations to define heat input and gas flow requirements.
4. Configure the combustion system to complete the combustion process while minimizing emissions (fuel preparation, combustion and air handling).
5. Configure the furnace and other heat transfer surfaces to satisfy temperature, material, and performance tradeoffs while meeting the system control needs.
6. Size other water-side and steam-side components.
7. Specify the back-end tradeoffs on the final heat recovery devices such as water heaters (economizers) and air heaters.
8. Check the steam generating system performance to ensure that the design criteria are met.
9. Verify overall unit performance.
10. Repeat steps 2 through 9 until the desired steam mass flow and temperature are achieved over the specified range of load conditions.
11. Use American Society of Mechanical Engineers (ASME) Code rules to design pressure parts to meet the anticipated operating conditions and complete detailed mechanical design.
12. Design and integrate environmental protection equipment to achieve prescribed emissions levels.
13. Incorporate auxiliaries as needed, such as tube surface cleaning equipment, fans, instrumentation and controls, to complete the design and assure safe and continuous operation.

The life cycle and daily operation of the steam generator (and the plant in which it will operate) are important elements to be considered from the beginning of the design and throughout the design process. Today, some steam generators will be required to operate efficiently and reliably for up to 60 years or more. During this time, many components will wear out because of the aggressive environment, so routine inspection of pressure parts is needed to assure continued reliability. Unit operating procedures, such as the permitted severity and magnitude of transients, may be monitored to prevent reduced unit life. Operating practices including water treatment, cycling operation procedures, and preventive maintenance programs, among others, can significantly affect steam generator availability and reliability. Key unit components may be upgraded to improve performance. In each case, decisions made during the design phase and subsequent operation can substantially enhance the life and performance of the unit.

### System design example

Now that the basic fossil fuel and nuclear steam generating systems have been described, it is appropriate to explore the general design and engineering process. While each of the many systems requires specialized evaluations, they share many common elements. To illustrate how the design process works, a small industrial B&W PFI gas-fired boiler has been selected for discussion. (See Figs. 22 and 23.)

Basically, the customer has one overriding need: when the valve is turned on, steam is expected to be

supplied at the desired pressure, temperature and flow rate. In this example, the customer specifies 400,000 lb/h (50.4 kg/s) of superheated steam at 600 psi (4.14 MPa) and 850F (454C). The customer has agreed to supply high purity feedwater at 280F (138C) and to supply natural gas as a fuel source. As with all steam generating systems, there are a number of additional constraints and requirements as discussed in *Steam generator interfaces*, but the major job of the steam generator or boiler is to supply steam.

Combustion of the natural gas produces a stream of combustion products or flue gas at perhaps 3600F (1982C). To maximize the steam generator thermal efficiency, it is important to cool these gases as much as possible while generating the steam. The minimum flue gas outlet temperature is established based upon technical and economic factors (discussed below). For now, a 310F (154C) outlet temperature to the exhaust stack is selected. The approximate steam and flue gas temperature curves are shown in Fig. 24 and define the heat transfer process. The heat transfer surface for the furnace, boiler bank, superheater and air heater is approximately 69,000 ft$^2$ (6410 m$^2$).

From a design perspective, the PFI boiler can be viewed as either a steam heater or gas cooler. The latter approach is most often selected for design. The design fuel heat input is calculated by dividing the steam heat output by the target steam generator thermal efficiency. Based upon the resulting fuel flow, combustion calculations define the air flow requirements and combustion products gas weight. The heat transfer surface is then configured in the most economical way to cool the flue gas to the temperature necessary for the target steam generator efficiency. Before proceeding to follow the gas through the cooling process, the amount of heat recovery for each of the different boiler surfaces (superheater and boiler) must be established.

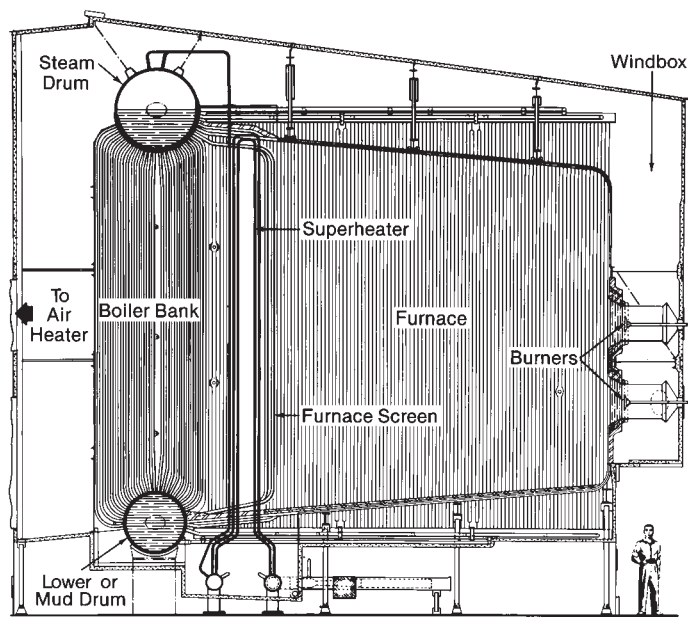Fig. 25 illustrates the water heating process from an inlet temperature of 280F (138C) to the superheater



Fig. 23 Small industrial boiler – sectional view.

steam outlet temperature of 850F (454C). This curve indicates that about 20% of the heat absorbed is used to raise the water from its inlet temperature to the saturation temperature of 490F (254C). 60% of the energy is then used to evaporate the water to produce saturated steam. The remaining 20% of the heat input is used to superheat or raise the steam temperature to the desired outlet temperature of 850F (454C).

The fuel and the combustion process selected set the geometry of the furnace. In this case, simple circular burners are used. The objective of the burners is to mix the fuel and air rapidly to produce a stable flame and complete combustion while minimizing the formation of NO$_x$ emissions. Burners are available in several standardized sizes. The specific size and number are selected from past experience to provide the desired heat input rate while permitting the necessary level of load range control. The windbox, which distributes the air to individual burners, is designed to provide a uniform air flow at low enough velocities to permit the burners to function properly.

The furnace volume is then set to allow complete fuel combustion. The distances between burners and between the burners and the floor, roof, and side walls are determined from the known characteristics of the particular burner flame. Adequate clearances are specified to prevent flame impingement on the furnace surfaces, which could overheat the tubes and cause tube failures.

Once the furnace dimensions are set, this volume is enclosed in a water-cooled membrane panel surface. This construction provides a gas-tight, all steel enclosure which minimizes energy loss, generates some steam and minimizes furnace maintenance. As shown in Fig. 23, the roof and floor tubes are inclined slightly to enhance water flow and prevent steam from collecting on the tube surface. Trapped steam could result in overheating of the tubes. Heat transfer from the flame to the furnace enclosure surfaces occurs primarily by thermal radiation. As a result, the heat input rates per
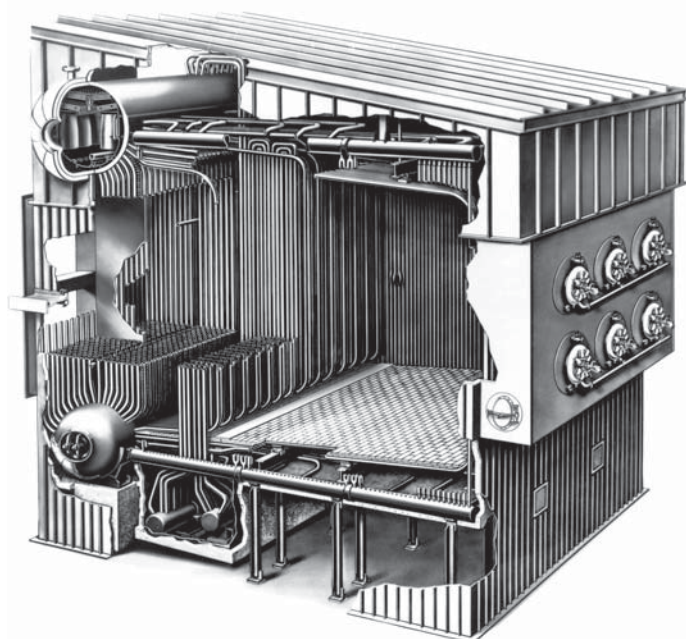

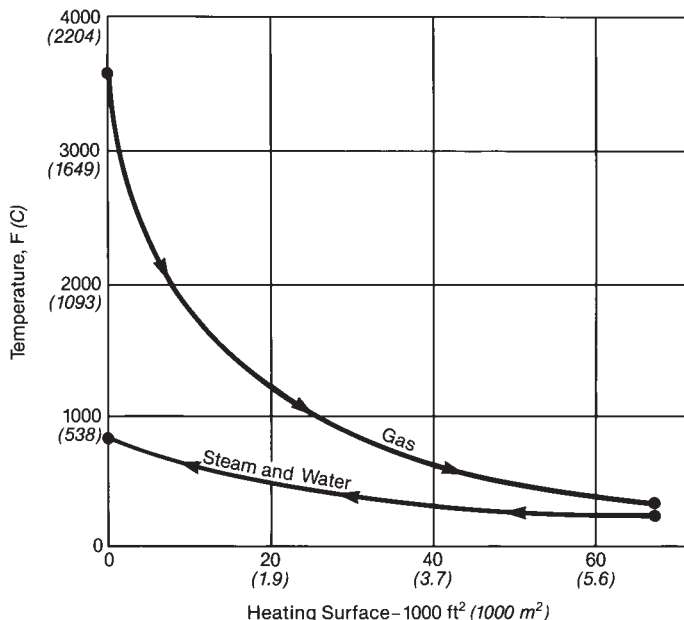
Fig. 22 Small PFI industrial boiler.

**Fig. 24** Industrial boiler – temperature versus heat transfer surface.

unit area of surface are very high and relatively independent of the tubewall temperatures. Boiling water provides an effective means to cool the tubes and keep the tube metal temperatures within acceptable limits as long as the boiling conditions are maintained.

Fig. 26 shows the effect of the furnace on gas temperature. The gas temperature is reduced from 3600 at point A to 2400F at point B (1982 to 1316C), while boiling takes place in the water walls (points 1 to 2). A large amount of heat transfer takes place on a small amount of surface. From the furnace, the gases pass through the furnace screen tubes shown in Fig. 23. The temperature drops a small amount [50F (28C)] from points B to C in Fig. 26, but more importantly, the superheater surface is partially shielded from the furnace thermal radiation. The furnace screen tubes are connected to the drum and contain boiling water. Next, the gas passes through the superheater where the gas temperature drops from 2350 at point C to 1750F at point D (1288 to 954C). Saturated steam from the drum is passed through the superheater tubing to raise its temperature from 490F (254C) saturation temperature to the 850F (454C) desired outlet temperature (points 5 to 4).

The location of the superheater and its configuration are critical in order to keep the steam outlet temperature constant under all load conditions. This involves radiation heat transfer from the furnace with convection heat transfer from the gas passing across the surface. In addition, where dirty gases such as combustion products from coal are used, the spacing of the superheater tubes is also adjusted to accommodate the accumulation of fouling ash deposits and the use of cleaning equipment.

After the superheater, almost half of the energy in the gas stream has been recovered with only a small amount of heat transfer surface [approximately 6400 ft² (595 m²)]. This is possible because of the large temperature difference between the gas and the boiling

water or steam. The gas temperature has now been dramatically reduced, requiring much larger heat transfer surfaces to recover incremental amounts of energy.

The balance of the steam is generated by passing the gas through the boiler bank. (See Figs. 22 and 23.) This bank is composed of a large number of water-containing tubes that connect the steam drum to a lower (mud) drum. The temperature of the boiling water is effectively constant (points 5 to 6 in Fig. 26), while the gas temperature drops by almost 1000F (556C) to an outlet temperature of 760F (404C), between points D and E. The tubes are spaced as closely as possible to increase the gas flow heat transfer rate. If a particulate-laden gas stream were present, the spacing would be set to limit erosion of the tubes, reduce the heat transfer degradation due to ash deposits, and permit removal of the ash. Spacing is also controlled by the allowable pressure drop across the bank. In addition, a baffle can be used in the boiler bank bundle to force the gas to travel at higher velocity through the bundle, increase the heat transfer rate, and thereby reduce the bundle size and cost. To recover this additional percentage of the supplied energy, the boiler bank contains more than 32,000 ft² (3000 m²) of surface, or approximately nine times more surface per unit of energy than in the high temperature furnace and superheater. At this point in the process, the temperature difference between the saturated water and gas is only 270F (150C), between points 6 and E in Fig. 26.

Economics and technical limits dictate the type and arrangement of additional heat transfer surfaces. An economizer or water-cooled heat exchanger could be used to heat the makeup or feedwater and cool the gas. The lowest gas exit temperature possible is the inlet temperature of the feedwater [280F (138C)]. However, the economizer would have to be infinitely large to accomplish this goal. Even if the exit gas temperature is 310F (154C), the temperature difference at this point in the heat exchanger would only be 30F (17C), still making the heat exchanger relatively large. Instead of incorporating an economizer, an air preheater could be used to recover the remaining gas energy and preheat the combustion air. This would reduce the
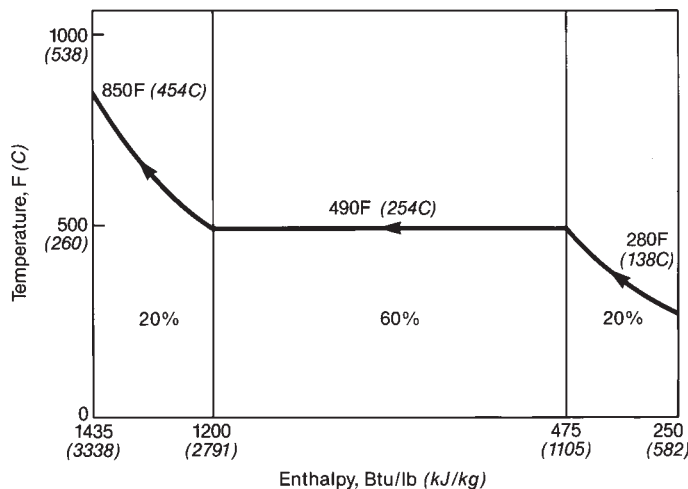


**Fig. 25** Steam-water temperature profile.

natural gas needed to heat the steam generator. Air heaters can be very compact. Also, air preheating can enhance the combustion of many difficult to burn fuels such as coal. All of the parameters are reviewed to select the most economical solution that meets the technical requirements.

In this case, the decision has been made to use an air heater and not an economizer. The air heater is designed to take 80F (27C) ambient air (point 9) and increase the temperature to 570F (299C), at point 8. This hot air is then fed to the burners. At the same time, the gas temperature is dropped from 760F (404C) to the desired 310F (154C) outlet temperature (points E to F). If a much lower gas outlet temperature than 310F (154C) is used, the heat exchanger surfaces may become uneconomically large, although this is a case by case decision. In addition, for fuels such as oil or coal which can produce acid constituents in the gas stream (such as sulfur oxides), lower exit gas temperatures may result in condensation of these constituents onto the heat transfer surfaces, and excessive corrosion damage. The gas is then exhausted through the stack to the atmosphere.

Finally, the feedwater temperature increases from 280F (138C) to saturation temperature of 490F (254C). In the absence of an economizer, the feedwater is supplied directly to the drum where it is mixed with the water flowing through the boiler bank tubes and furnace. The flow rate of this circulating water in industrial units is approximately 25 times higher than the feedwater flow rate. Therefore, when the feedwater is mixed in the drum, it quickly approaches the saturation temperature without appreciably lowering the temperature of the recirculating water in the boiler tubes.

Reviewing the water portion of the system, the feedwater is supplied to the drum where it mixes with the recirculating water after the steam is extracted and sent to the superheater. The drum internals are spe-

cially designed so that the now slightly subcooled water flows down through a portion of the boiler bank tubes to the lower or mud drum. This water is then distributed to the remainder of the boiler bank tubes (also called risers) and the furnace enclosure tubes where it is partially converted to steam (approximately 4% steam by weight). The steam-water mixture is then returned to the steam drum. Here, the steam-water mixture is passed through *separators* where the steam is separated from the water. The steam is then sent to the superheater, and from there to its end use. The remaining water is mixed with the feedwater and is again distributed to the downcomer tubes.

## Other steam producing systems

A variety of additional systems also produce steam for power and process applications. These systems usually take advantage of low cost or free fuels, a combination of power cycles and processes, and recovery of waste heat in order to reduce overall costs. Examples of these include:

1. *Gas turbine combined cycle (CC)* Advanced gas turbines with heat recovery steam generators as part of a bottoming cycle to use waste heat recovery and increase thermal efficiency.
2. *Integrated gasification combined cycle (IGCC)* Adds a coal gasifier to the CC to reduce fuel costs and minimize airborne emissions.
3. *Pressurized fluidized-bed combustion (PFBC)* Includes higher pressure combustion with gas cleaning and expansion of the combustion products through a gas turbine.
4. *Blast furnace hood heat recovery* Generates steam using the waste heat from a blast furnace.
5. *Solar steam generator* Uses concentrators to collect and concentrate solar radiation and generate steam.

## Common technical elements

The design of steam generating systems involves the combination of scientific and technical fundamentals, empirical data, practical experience and designer insight. While technology has advanced significantly, it is still not possible to base the design of modern systems on fundamentals alone. Instead, the fundamentals provide the basis for combining field data and empirical methods.

Even given the wide variety of shapes, sizes and applications (see Fig. 27), steam generator design involves the application of a common set of technologies. The functional performance of the steam generator is established by combining thermodynamics, heat transfer, fluid mechanics, chemistry, and combustion science or nuclear science with practical knowledge of the fouling of heat transfer surfaces and empirical knowledge of the behavior of boiling water. The design and supply of the hardware are aided by structural design and advanced materials properties research combined with expertise in manufacturing technologies and erection skills to produce a quality, reliable product to meet the highly demanding system requirements.
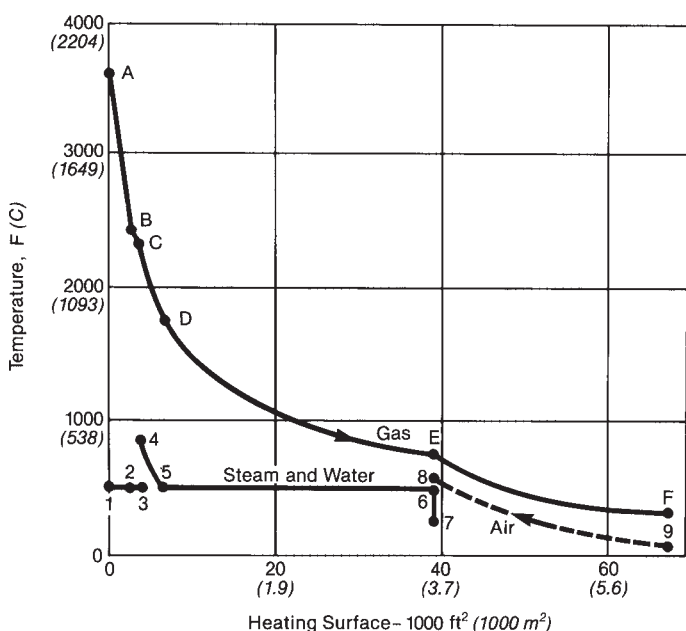


**Fig. 26** Gas and steam temperature schematic.

**Fig. 27** This energy complex in the northern U.S. includes four coal-fired steam systems, ranging from 80 to 330 MW, installed over a 25-year period.

The ASME Boiler and Pressure Vessel Code is the firm basis from which steam generator pressure parts can be safely designed. Once built, the operation and maintenance of the steam generator are critical to ensure a long life and reliable service. Water chemistry and chemical cleaning are increasingly recognized as central elements in any ongoing operating program. The impact of fuel and any residual flyash is important in evaluating the corrosion and fouling of heat transfer surfaces. The use of modern techniques to periodically inspect the integrity of the steam generator tubes leads to the ability to extend steam generator life and improve overall performance. These are accomplished by the application of engineered component modification to better meet the changing needs of the steam generating system. Finally, the control systems which monitor and operate many subsystems to optimize unit performance are important to maintain system reliability and efficiency.

All of these functions – functional performance, mechanical design, manufacture, construction, operation, maintenance, and life extension – must be fully combined to provide the best steam generating system. Long term success depends upon a complete life cycle approach to the steam generating system. Steam generator system operators routinely require their equipment to operate continuously and reliably for more than 60 years in increasingly demanding conditions. Therefore, it is important to consider later boiler life, including component replacement, in the initial phases of boiler specification. Changes in design to reduce initial capital cost must be weighed against their possible impact on future operation.

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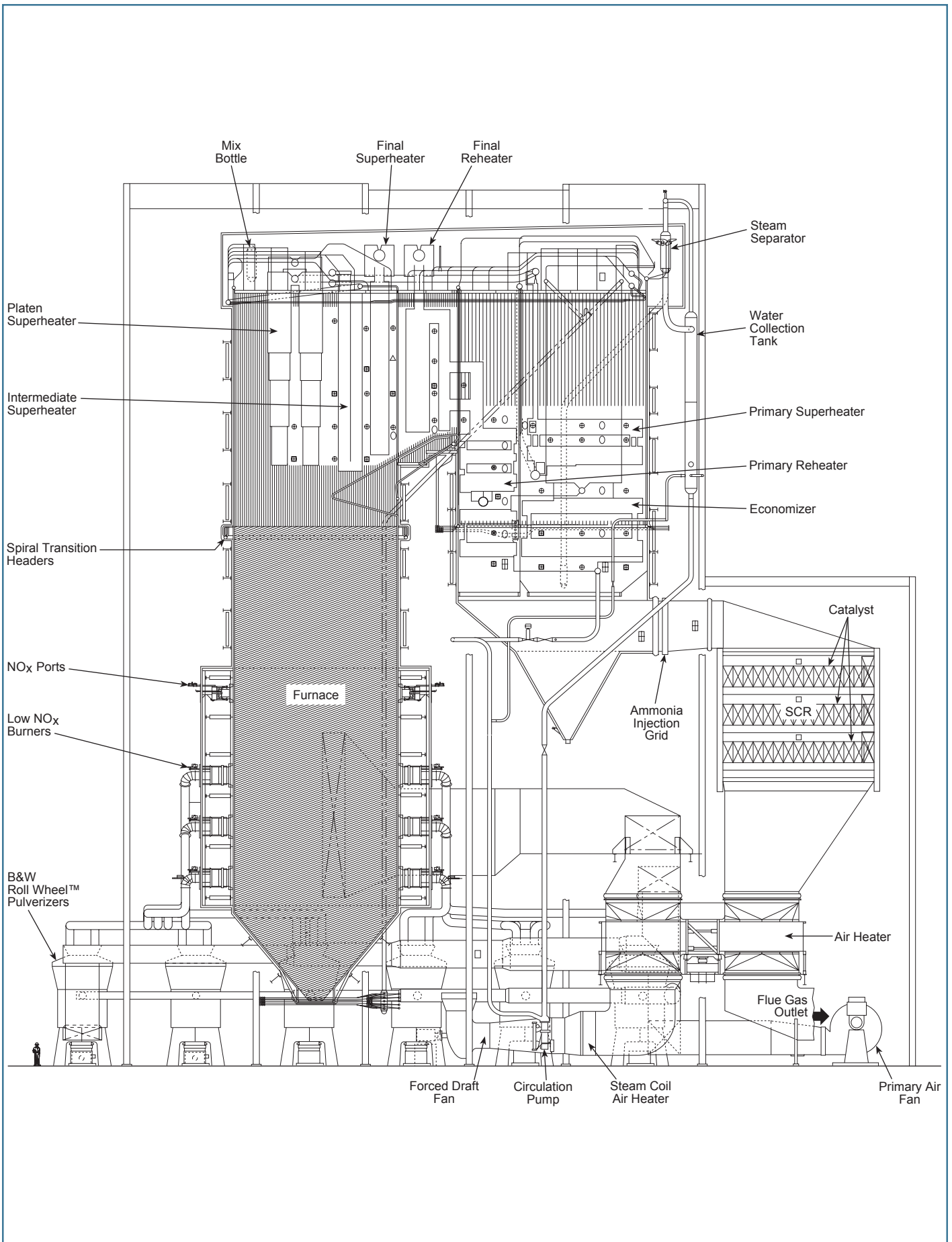
750 MW once-through spiral wound universal pressure (SWUP™) coal-fired utility boiler.