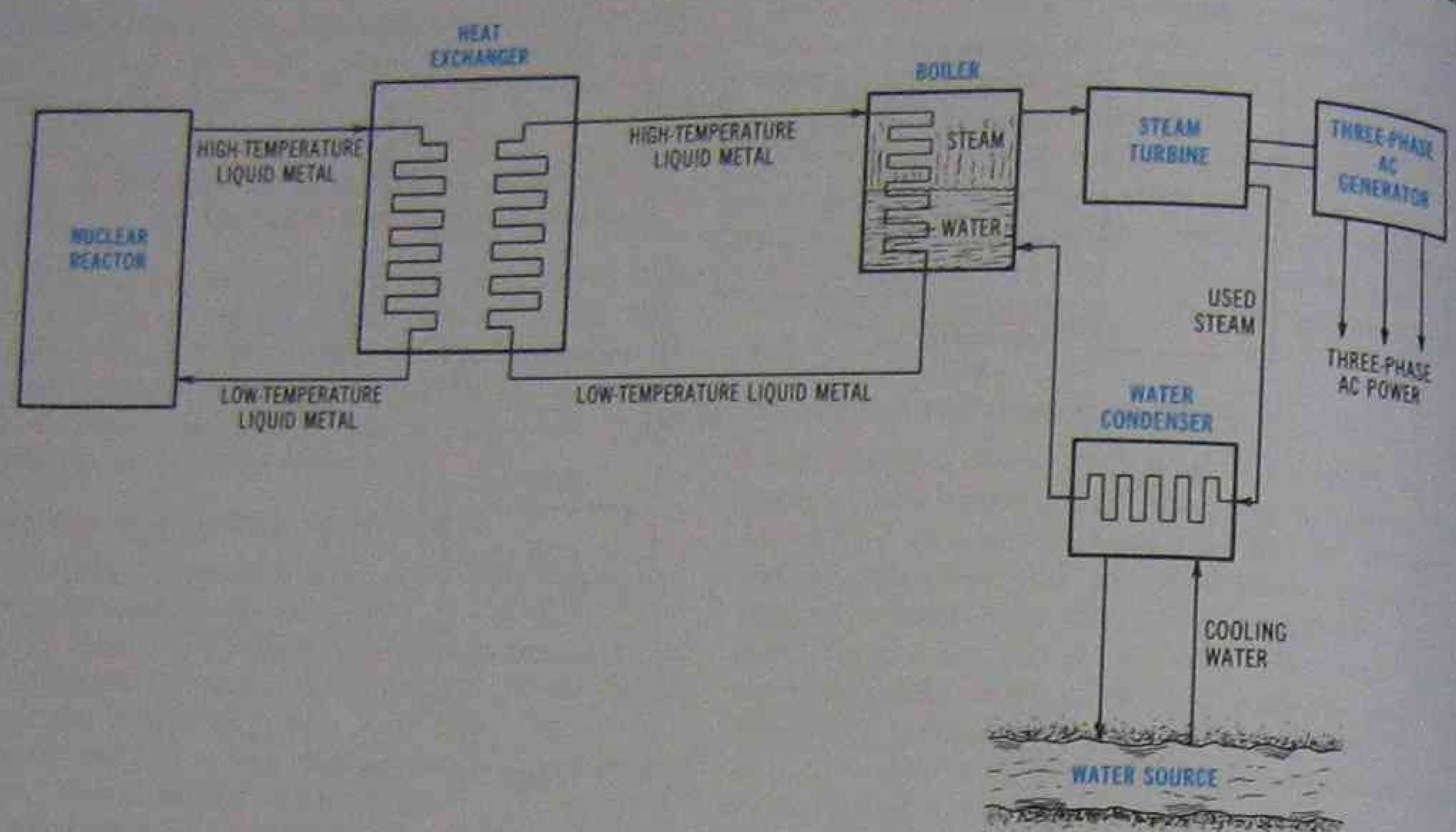


Fig. 2-31. Simplified diagram of the liquid-metal fast-breeder reactor (LMFBR).

when residential, industrial, and commercial systems are supplied by the utilities companies.

Industrial use of electrical power accounts for over 40% of the total kilowatt-hour (kWh) consumption and the industrial use of electrical power is projected to increase at a rate similar to its present rate in the near future. The shortage of natural gas should not significantly affect electrical power consumption by industry. Most of the conversions of gas systems will be to the usage of oil systems in their place.

The major increases in residential power demand have been due to an increased use by customers. A smaller increase was accounted for by an increase in the number of customers. Such variables as the type of heating used, the use or nonuse of air conditioning, and the use of major appliances (freezers, dryers, ranges), affect the residential electrical power demand. At present, residential use of electrical power accounts for over 30% of the total consumption. The rate of increase will probably taper off in the near future.

Commercial use of electrical power accounts for less than 25% of the total kWh usage. Commercial power consumption includes usage by office buildings, apartment complexes, school facilities, shopping establishments, and motel or hotel buildings. The prediction of the electrical power demand by these facilities is somewhat similar to the residential demand. Commercial use of electrical power is also expected to increase at a declining rate in the future.

Electrical Load-Demand Control

As the costs of producing power continue to rise, power companies must search for ways to limit the maximum rate of energy consumption. To cut down on power usage, industries have begun to initiate programs which will cut down on the load during peak operating periods. The use of certain machines may be limited while other large power-consuming machines are operating. In larger industrial plants and at power-production plants, it would be impossible to manually control the complex regional switching systems, so computers are being used to control loads.

To prepare the computers for power-consumption control, the peak demand patterns of local industries and the surrounding region supplied by a specific power station must be determined. The load of an industrial plant may then be balanced according to area demands with the power station output. The computer may be programmed to act as a switch, allowing only those processes to operate which are within the load calculated for the plant for a specific time period. If the load drawn by an industry exceeds the limit, the computer may deactivate part of the system. When demand is decreased in one area, the computer can cause the power system to increase power output to another part of the system. Thus, the industrial load is constantly monitored by the power company to insure a sufficient supply of power at all times.

PROBLEMS

1. The average load for a power plant during a 12-hour period is 500 megawatts. The peak load for the same time period is 620 megawatts. The output capacity of the power plant is 780 megawatts. Calculate:
   a. The load factor of the plant.
   b. Capacity factor.
2. Calculate the load factor and capacity factor of a power plant which has the following output characteristics—an average load (24 hours) of 210 megawatts, a peak load of 290 megawatts, and a plant capacity of 300 megawatts.

PROBLEMS

1. A 20-μF capacitor and a 1000-ohm resistor are connected in series with a 120-volt 60-Hz ac source. Calculate:

   a. X_C
   b. Z
   c. I
   d. E_C
   e. E_R
   f. True power
   g. Apparent power
   h. Reactive power
   i. Power factor

   Draw an impedance triangle, a voltage triangle, and a power triangle for the circuit and label each value.

2. A circuit converts 12,000 watts of power. The applied voltage is 240 volts and the current is 72 amperes. Calculate:

   a. Apparent power
   b. Power factor
   c. Phase angle of the circuit

   Draw a power triangle for the circuit and label each value.

3. A 240-volt single-phase ac motor draws 20 amperes of current. Its power factor is 0.7 at the rated load. What is the true power converted? What is the value of reactive power? Draw a power triangle for the circuit and label each value.

4. A series circuit with 20 volts applied has a resistance of 100 ohms, a capacitance of 40 μF, and an inductance of 0.15 henry. Calculate:

   a. X_C
   b. X_L
   c. X_T
   d. Z
   e. I
   f. E_C
   g. E_L
   h. E_R
   i. The phase angle θ

   Draw an impedance triangle and a voltage triangle for the circuit and label each value.

5. Use the same values that were given for R, C, and L in Problem 4. Connect them in a parallel circuit that has 10 volts applied to it. Calculate:

   a. I_R
   b. I_C
   c. I_L
   d. I_T
   e. Z
   f. Conductance
   g. Susceptance
   h. Admittance
   i. Phase angle

   Draw a current triangle and an admittance triangle and label each value.

6. Use the series circuit of Problem 4. Calculate:

   a. True power
   b. Apparent power
   c. Reactor power
   d. Power factor

   Draw a power triangle and label each value.

7. Use the parallel circuit of Problem 5. Calculate:

   a. True power
   b. Apparent power
   c. Reactive power
   d. Power factor

   Draw a power triangle and label each value.

8. The meters on an industrial motor control panel show the following readings:

   Voltage = 120 volts
   Current = 12 amperes
   Power = 1 kW
   Frequency = 60 Hz

   Calculate:

   a. Apparent power
   b. Power factor
   c. The amount of capacitance which could be connected to the power lines to cause a power factor of 1.0.
   d. Circuit current after the capacitors are added.

9. A wye-connected three-phase ac generator has a phase voltage of 277 volts, line currents of 22 amperes per phase, and a power factor of 0.85. Calculate:

   a. Line voltage
   b. Power per phase
   c. Total power

10. A delta-connected three-phase ac generator has a line voltage of 240 volts, line currents of 12 amperes per phase, and a power factor of 1.0. Calculate:

    a. Phase current
    b. Power per phase
    c. Total power

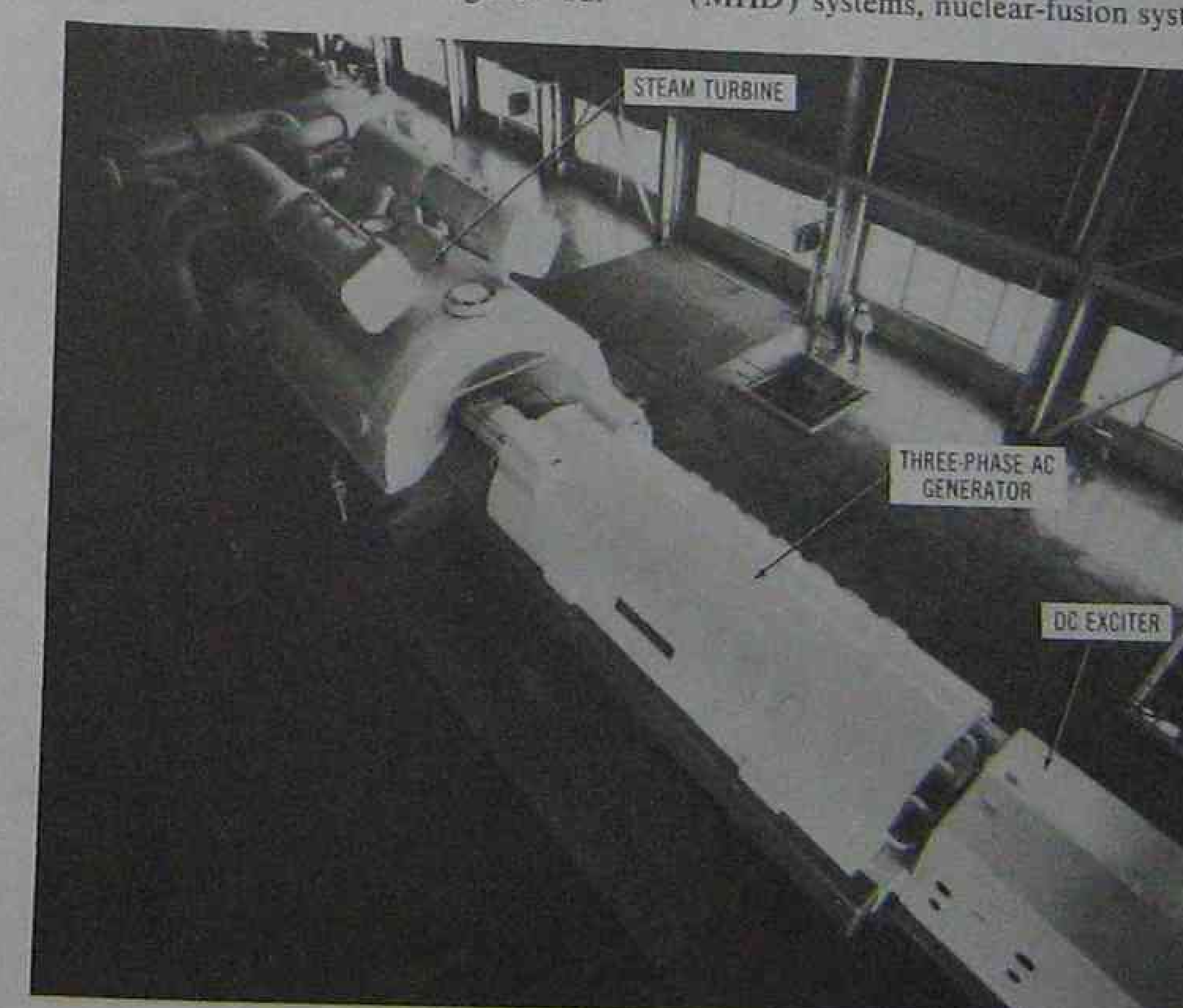
CHAPTER 2

Modern Power Systems

There are well over 80,000,000 customers of electrical utilities companies in the United States today. To meet this demand for electrical power, power companies combine to produce about two million-million (2,000,000 × 10^6) kilowatt-hours of electrical power. This vast quantity of electrical power is supplied by about 4000 power plants. Individual generating units which supply over 1200 megawatts of electrical power are now in operation at some power plants.

Electrical power can be produced in many ways, such as from chemical reactions, heat, light, or mechanical energy. The great majority of our electrical power is produced by power plants located throughout our country which convert the energy produced by burning coal, oil, or natural gas, the falling of water, or from nuclear reactions into electrical energy. Electrical generators at these power plants are driven by steam or gas turbines or by hydraulic turbines, in the case of hydroelectric plants. This chapter will investigate the types of power systems that produce the greatest majority of the electrical power used today.

Various other methods, some of which are in the experimental stages, may be used as future power production methods. These include solar cells, geothermal systems, wind-powered systems, magnetohydrodynamic (MHD) systems, nuclear-fusion systems, and fuel cells.



Courtesy Westinghouse Electric Corp.

Fig. 2-1. A steam turbine generator unit.

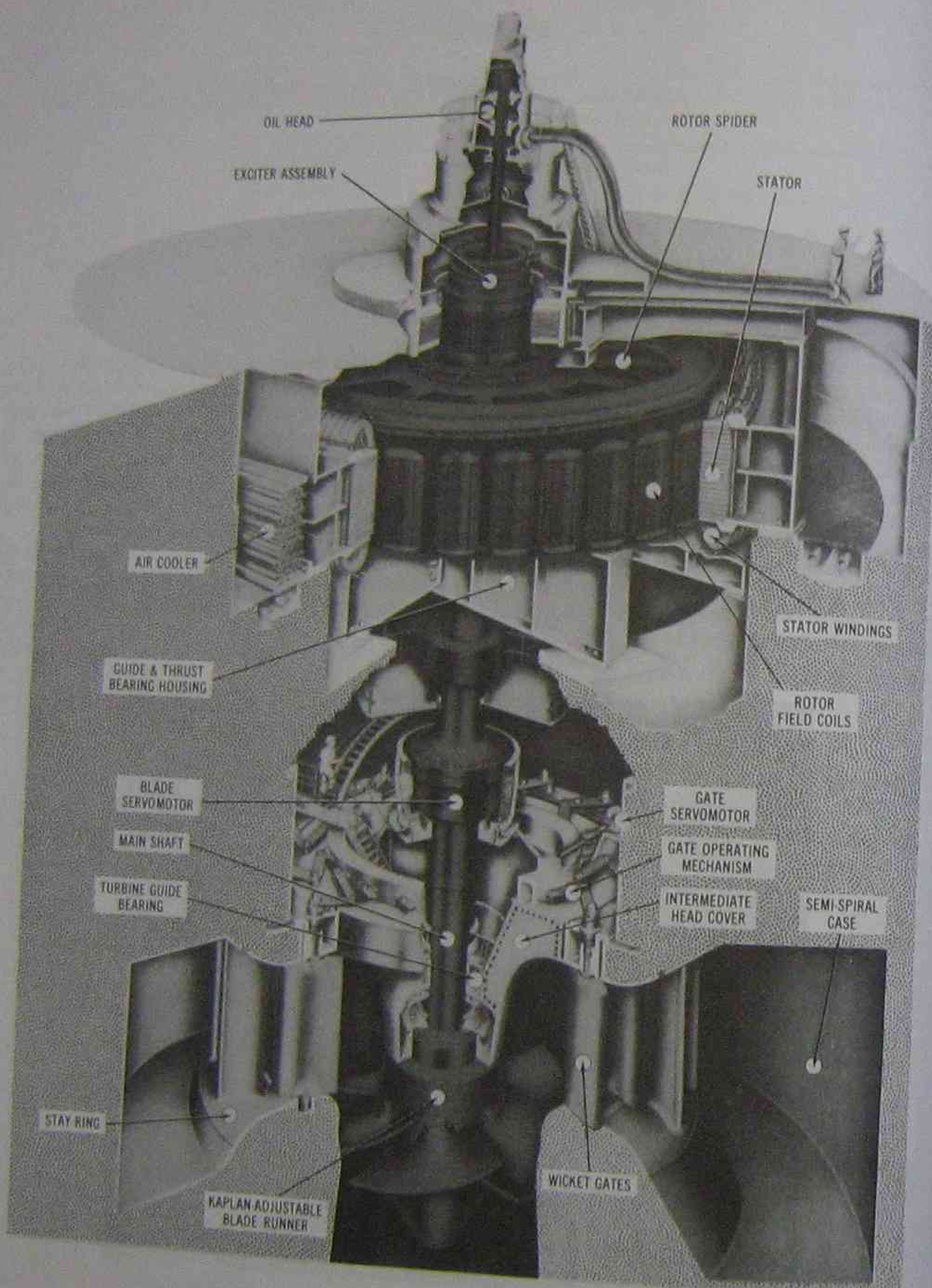


Fig. 2-2. Hydraulic turbine generator unit. Courtesy Allis-Chalmers Co.

These alternative power systems will be discussed in greater detail in Chapter 3.

ELECTRICAL POWER PLANTS

Most electrical power in the United States is produced at power plants that are either fossil-fuel steam plants, nuclear-fission steam plants, or hydroelectric plants. A 390-megawatt steam turbine generator unit located at the Baltimore Gas and Electric Company is shown in Fig. 2-1. Fossil-fuel and nuclear-fission plants utilize steam turbines to deliver the mechanical energy needed to rotate the large three-phase alternators which produce massive quantities of electrical power. Hydroelectric plants ordinarily use vertically mounted hydraulic turbines, such as the one shown in Fig. 2-2. These units convert the force of flowing water into mechanical energy to rotate three-phase alternators.

The power plants may be located near the energy sources, near cities, or near the large industries where great amounts of electrical power are consumed. The generating capacity of power plants in the United States is greater than the combined capacity of the next four leading countries of the world. Thus, we can see how dependent we are upon the efficient production of electrical power.

Supply and Demand

The supply and demand situation for electrical energy is much different from other products which are produced by an organization and, then later, sold to consumers. Electrical energy must be supplied at the same time that it is demanded by consumers. There is no simple storage system which may be used to supply additional electrical energy at peak demand times. This situation is quite unique and necessitates the production of sufficient quantities of electrical energy to meet the demand of the consumers at any time. Accurate forecasting of load requirements at various given times must be maintained by utilities companies in order that they may recommend the necessary power plant output for a particular time of the year, week, or day.

Plant Load and Capacity Factors

There is a significant variation in the load requirement that must be met at different times. Thus, the power plant generating capacity is subject to a continual change. For the above reasons, much of the generating capacity of a power plant may be idle during low demand times. This means that not all the generators at the plant will be in operation.

There are two mathematical ratios with which power plants are concerned. These ratios are called load factor and capacity factor. They are expressed as:

$$\text{Load factor} = \frac{\text{Average load for a time period}}{\text{Peak load for a time period}}$$

$$\text{Capacity factor} = \frac{\text{Average load for a time period}}{\text{Output capacity of a power plant}}$$

It would be ideal, in terms of energy conservation, to keep these ratios as close to unity as possible.

FOSSIL FUEL SYSTEMS

Millions of years ago, large deposits of organic materials were formed under the surface of the earth. These deposits, which furnish our coal, oil, and natural gas, are known as fossil fuels. Of these, the most abundant fossil fuel is coal and coal-fired electrical power systems produce about one-half of the electrical power used in the United States. Natural-gas-fired systems are used for about one-fourth of our electrical power, while oil-fired systems produce around 10% of the power at the present time. These relative contributions of each system to the total electrical power produced in the United States are subject to change due to the addition of new power generation facilities and fuel availability. At the present time, over 80% of our electrical energy is produced by fossil-fuel systems.

A basic fossil-fuel power system is shown in Fig. 2-3. In this type of system, a fossil fuel (coal, oil, or gas) is burned to produce heat energy. The heat from the combustion process is concentrated within a boiler where circulating water is converted to steam. The high-pressure steam is used to rotate a turbine. The turbine shaft is connected directly to the electrical generator and provides the necessary mechanical energy to rotate the generator. The generator then converts the mechanical energy into electrical energy. A commercial steam turbine-generator system is shown in Fig. 2-4. A gas turbine, which is used much less than the steam turbine, is shown in Fig. 2-5.

Fossil Fuels

Fossil fuels are used to supply heat by means of their chemical reactions for many different purposes. Such fuels contain carbon materials that are burned as a result of their reaction with air or oxygen. These fossil fuels are used as a direct source of heat when burned in a furnace and are used as a heat source for steam production when used in a power-plant boiler system. The steam that is generated is used for rotating the steam turbines in the power plants.

Fossil fuels vary according to their natural state (solid, liquid, or gas), according to their ability to produce heat, and in the type of flame or heat that they produce. Coal and coke are solid fossil fuels, with coal used extensively for producing heat to support elec

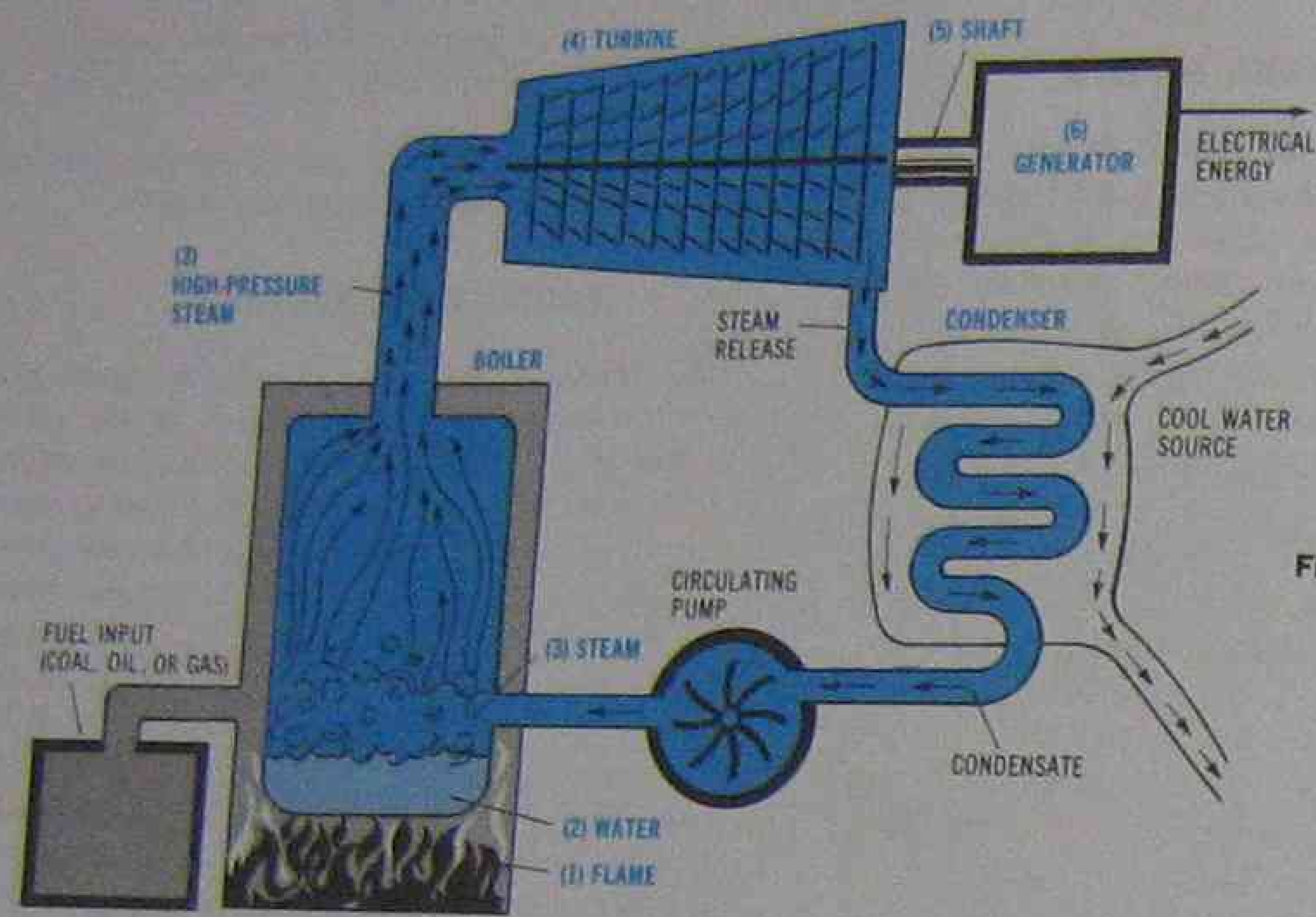


Fig. 2-3. A basic fossil fuel power system.

Heat from burning fuel (1) changes water in boiler (2) into steam (3), which spins turbine (4) connected by shaft (5) to generator (6), producing electrical energy.

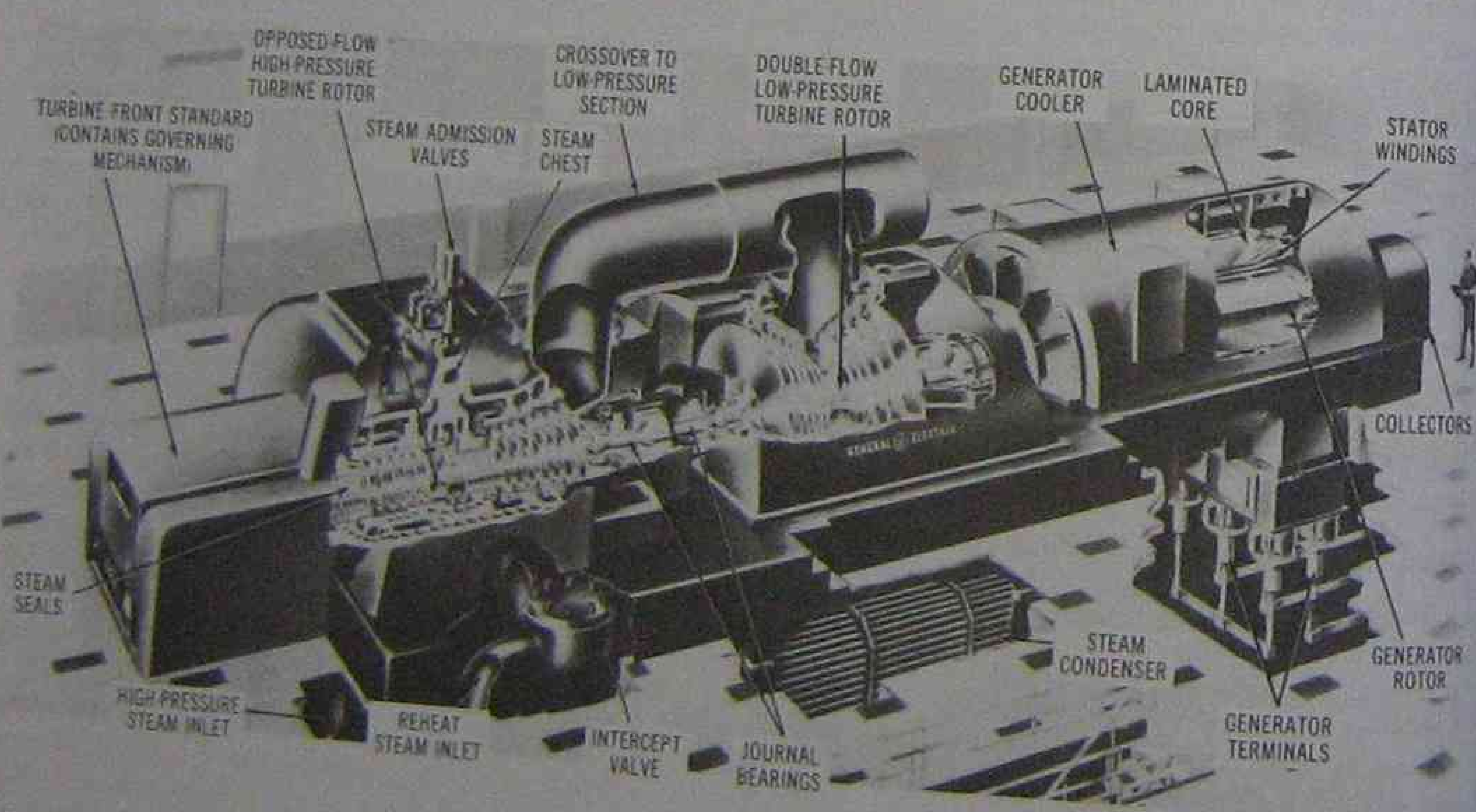


Fig. 2-4. A commercial steam turbine/generator system.

Courtesy General Electric Co.

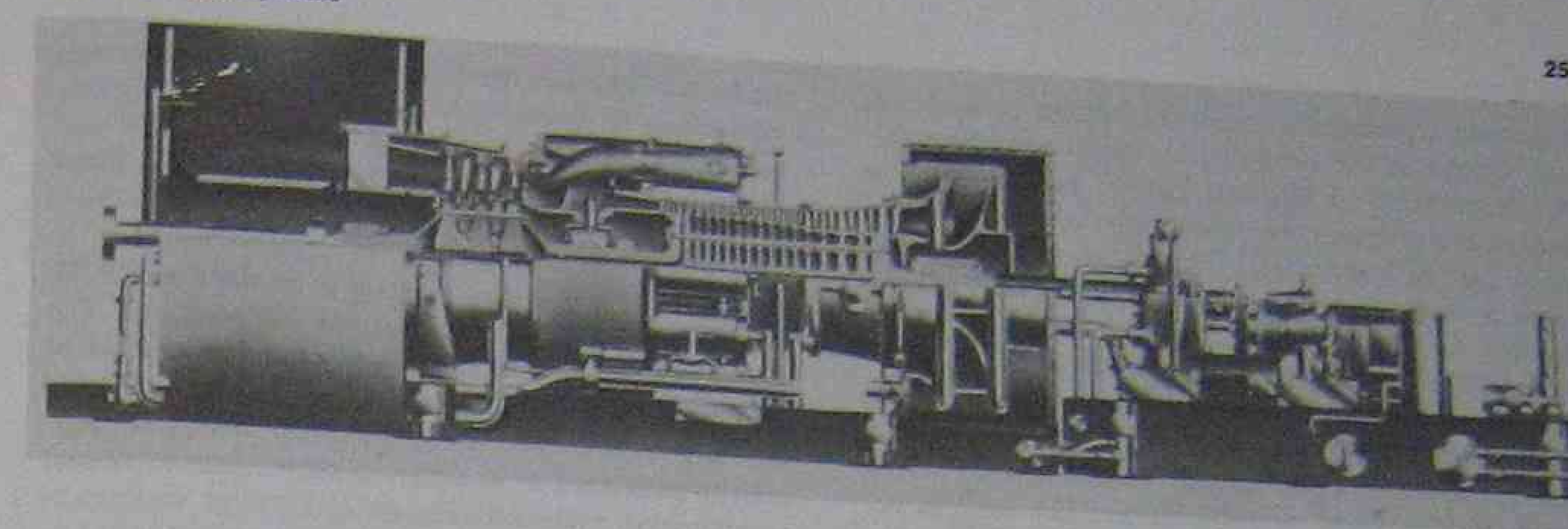


Fig. 2-5. Cutaway illustration of a gas turbine.

Courtesy General Electric Co.

trical power production. Oil, gasoline, and diesel fuel, which are liquid fossil fuels derived by petroleum processing, are used mostly in conjunction with internal combustion engines. However, oil is used as a heat source for many power plants. Natural gas is the primary gaseous fuel used for electrical power production.

Coal-Fired Systems

The use of coal as a fuel to supply the necessary heat energy at a power plant requires the use of specialized stokers or grating units. These units reduce the size of the lump coal. Most of these units are mechanical systems which agitate the coal to reduce it into smaller lumps. The coal used at a power plant usually is sent through a stoker or grating unit by conveyor belts. A large gravity-feed hopper is often used to route very small lumps of coal into a pulverizing unit.

The pulverizer looks very similar in construction to a large ball-bearing unit. The coal is routed into the pulverizer unit where large rotating steel balls crush the coal until it is in particles about the same size and consistency as face powder. These fine particles are routed into the furnace by air pressure caused by forced-draft fans. The coal is held in suspension until it is ignited. It, then, releases a large amount of heat energy. The suspended powder-fine coal particles allow sustained combustion to take place in the furnace. The pulverized coal speeds up the combustion process.

Coal-Fired Plant Operation

Since the majority of electrical power produced today is from coal-fired systems, we will discuss the basic operation of this type of system. In a steam plant which produces electrical power, most of the operations are used for rotating the steam turbine. Remember, that in any steam plant, heat must be produced. This heat produces steam, which moves the steam turbine, which produces a rotary motion, and which, finally, produces electric power. The maximum efficiency of the coal-fired plant of today is approximately 40% when using a powdered-coal spraying process.

Coal requires extensive handling equipment. The coal itself must be handled and, then, the ash and dust particles must be removed. The coal is moved at the power plant to overhead hoppers by means of conveyor belts. These hoppers can be as large as eight stories high. The coal usually is fed into pulverizing mills by gravity. It is ground to a consistency similar to face powder using the method discussed previously. The powdered coal is then dried using plant exhaust gases and is then blown into a furnace. The coal is ordinarily blown through a tangential or "T" burner into the furnace. These burners are placed in the four corners of a square furnace to create the needed turbulence for complete combustion.

Another method of firing the furnace is the fluidized bed. An advantage of the fluidized bed is that it produces less pollution and can burn a lower quality coal. In a fluidized bed, coal is crushed to form ⅛-inch to ¼-inch diameter particles. When air is blown through a layer of this coal, the particles will float on a cushion of air. The pressure has to be adjusted very accurately so that the particles are fluidized without being blown away from the bed. The fluidized bed is the basis of a direct-combustion process. If the bed is hot enough, the flow of air through the bed leads to almost total combustion, and can provide a greater efficiency with less ash and dust.

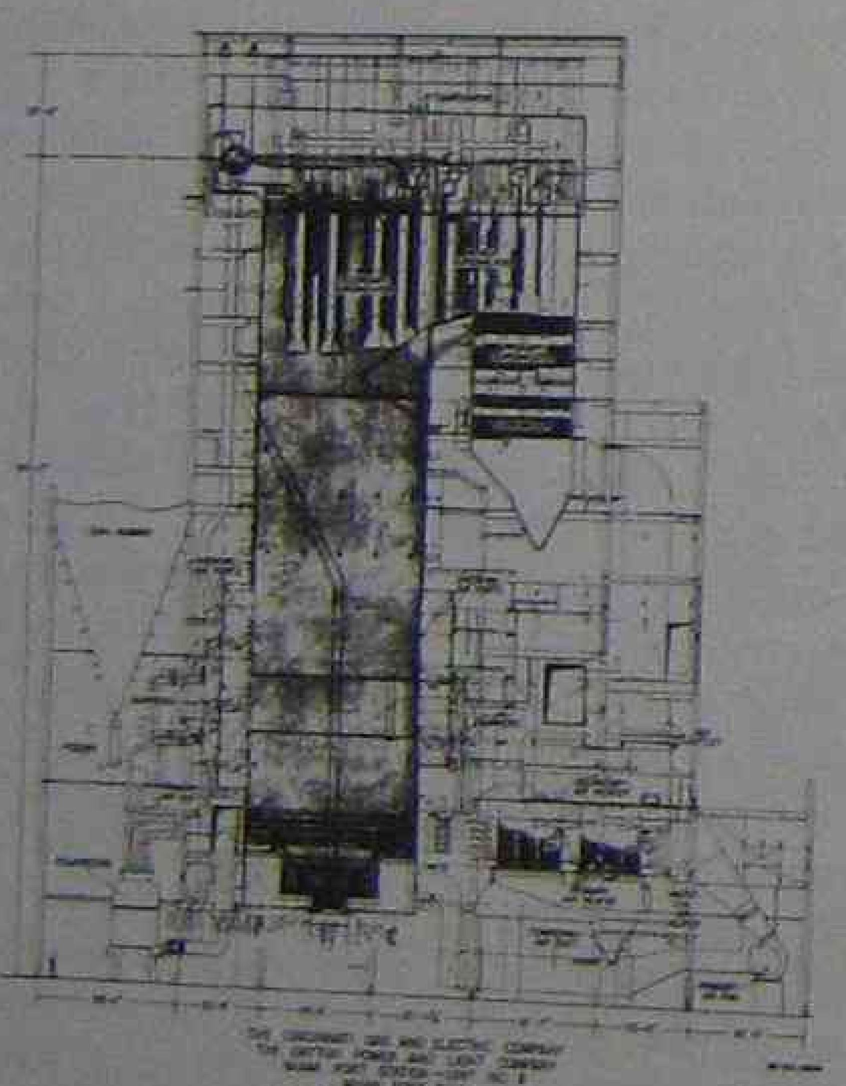
Power plant boilers, such as the one shown in Fig. 2-6, incorporate several special units to improve their thermal efficiency and economy of operation. An *economizer* is placed at the exhaust exit to preheat the water coming into the boiler. The economizer also preheats the air blowing into the furnace. A *superheater* is a bank of tubes located at the hottest spot of the furnace. These tubes take the steam after it leaves the boiler and before it enters the turbine. The purpose of the superheater is to raise the temperature of the steam.

Increased superheat decreases the percent of water per unit volume in the steam, which increases turbine life. A *desuperheater* is the next part of the system. The desuperheater brings the steam down to a temperature so it can be condensed. The *feedwater* in a power plant is used over and over with water added only to account for losses. The feedwater must be very pure to ensure long life of the boiler tubes.

After steam has been produced, a rotary motion must be developed. This rotary motion is produced by a steam turbine. A steam turbine, shown in Fig. 2-4, is made up of as many as 1500 blades. The rotor is usually divided into two parts—the high-pressure rotor and the low-pressure rotor. The low-pressure rotor is larger in diameter than the high-pressure rotor. Steam is channeled to the high-pressure rotor and it is then routed to the low-pressure rotor.

Steam turbines ordinarily achieve a maximum efficiency of between 20% to 28%, but only when run at very high speeds. Some turbines can produce as much as 160,000 horsepower. A speed of 3600 rpm is needed to develop a 60-Hz electrical power output. Large three-phase ac generators are connected to dc exciters. Generators are often cooled with hydrogen because hydrogen has less than 1/10 the density of water. Therefore, much less energy is required to recirculate the hydrogen for cooling purposes.

The process just described summarizes the operation of a steam power plant. There are several variations to the basic process; however, most plants use similar methods. The individual parts of a steam-generating system will be discussed in more detail in the following sections.



Courtesy Babcock & Wilcox Co.

Fig. 2-6. Natural circulation radiant boiler used by the Cincinnati Gas and Electric Company.

STEAM TURBINES

Steam turbine systems are used to produce over 80% of the electrical power used in the United States. The force of steam produces a rotary motion (mechanical energy) in a steam turbine. This mechanical energy is converted to electrical energy by using three-phase generators connected by a common shaft. Both fossil-fuel systems and nuclear-fission systems utilize steam turbines as prime movers (rotary motion producers).

A reaction turbine, such as the one shown in Fig. 2-4, channels high-velocity steam through a set of blades mounted on a rotary shaft. The reaction turbine usually has more than one set of blades, with each set having a different diameter. As the steam passes through the first section of blades, its pressure is reduced and its volume is increased. Due to the increased volume, the additional sections of blades must be of larger diameters and with longer sets of blades. These combined sections of blades direct the high-velocity steam in such a way that a maximum rotational force is produced by the turbine.

The design of a steam turbine is very critical for the efficient production of electrical power. Several characteristics of steam turbines cause design problems. Steam turbines must be operated at high rotational speeds, so the blades must be designed to withstand a tremendous amount of centrifugal force. The rotor and blade assemblies for steam turbines are usually machined from a forged piece of chromium and steel alloy. This assembly must be very precisely balanced before the machine is put into operation. The leakage of steam from the enclosed rotor and blade assembly must be prevented. Solid seals cannot be used along the rotor shaft so so-called "steam-seals" are used to provide a minimum clearance between the seals and the shaft. The bearings of a steam turbine must be carefully designed to withstand both axial and end pressures of high magnitudes.

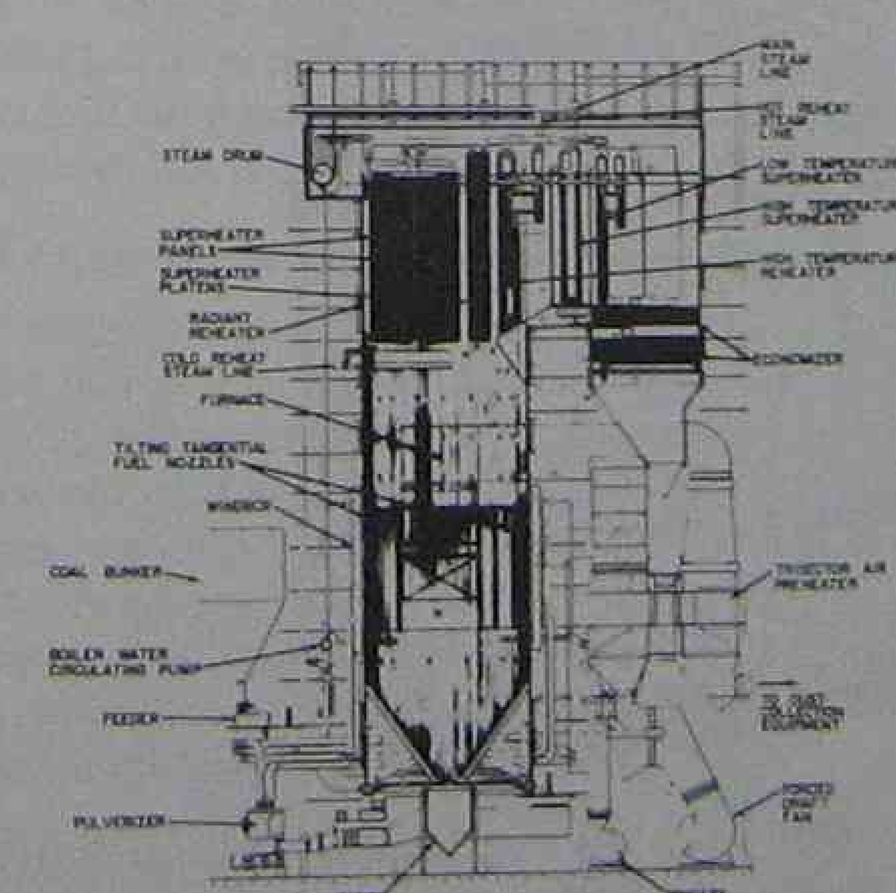
Steam turbines used in electrical power production must be rotated at a constant speed. If turbine speed changes, the frequency of the generator output voltage will be changed from the standard 60-Hz value. Therefore, a system of governors is used in a steam turbine to regulate its speed. The governor system adjusts the turbine speed by compensating for changes in generator power demand. As more load is placed on the generator (increased consumption of electrical power), the generator offers an increased resistance to rotation. Thus, power input to the turbine must be increased accordingly. The governor system of the turbine automatically adjusts the steam input to the turbine blades to compensate for increases and decreases in the load demand placed upon the generator which it drives.

BOILERS

Boilers (as shown in Figs. 2-7 and 2-8) are an important part of steam power production systems. The function of a boiler is to provide an enclosure in which pressurized water can be heated to a high temperature to produce steam. The heat from burning fossil or nuclear fuels is transferred to an area through which pressurized water flows and the water is converted to steam through this procedure.

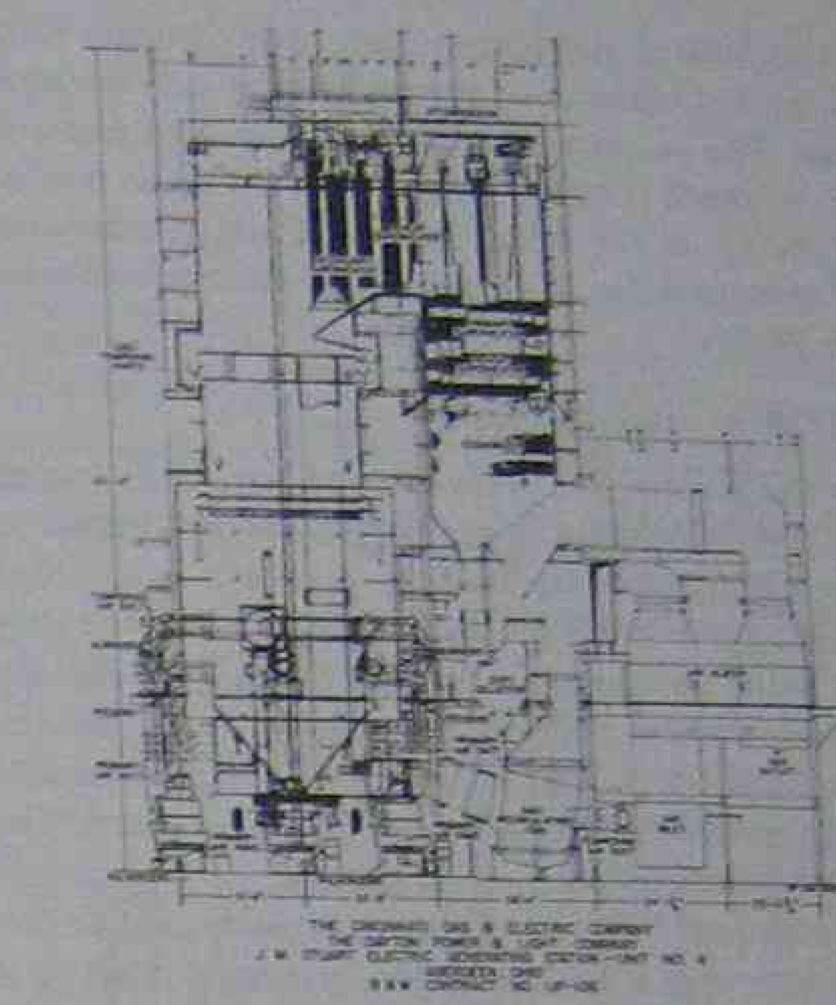
The transfer of heat within a boiler utilizes the three methods of heat transfer—radiation, convection, and conduction. The radiation method involves the movement of heat energy from a warm area to a cool area, and is dependent upon temperature difference and the ability of materials to absorb heat. The conduction method requires contact between the heat source and the heated area and relies upon the heat conductivity of the heated material. Convection is the movement of heat from a hot area to a cooler area by means of an intermediate substance, such as a gas. Each of these three methods of heat transfer occur in an operating boiler. However, they occur in varying amounts dependent upon boiler design.

A boiler which functions properly is a very critical part of the power production system as the boiler operation determines the quantity of steam available to produce the rotary motion of the turbine. When more power input for the generating process is required due to an increased load on the system, the boiler must deliver more steam to the turbine. Boilers must be able to provide effective water circulation, efficient fuel combustion, and maximum heat transfer to the circulating water. The boilers used in most steam power plants today are called water-tube boilers. Their design consists of banks of tubes, separated by heat insulation, through which water is circulated under high temperature and high pressure. Boiler design is very important for an efficient steam power-plant operation.



Courtesy Combustion Engineering, Inc.

Fig. 2-7. Tangentially-fired boiler.



Courtesy Babcock & Wilcox Co.

Fig. 2-8. Once-through universal boiler used at Dayton Power and Light Company.

Boiler Auxiliary Systems

There are several auxiliary systems used in a steam power plant to increase the operation and efficiency of the boilers. Some of these systems were mentioned briefly in previous sections. One auxiliary system is called an *economizer*. Economizers utilize the hot exhaust gases from the fuel reactions within a boiler to preheat the cold feedwater which is pumped into the boiler. Thus, the economizer uses the waste gases, which would otherwise be emitted through the exhaust stack, for an important purpose. This improves the efficiency of the power plant.

In addition to the economizer, feedwater *heaters* and *preheaters* are used to increase the water temperature before its entry into the boiler. These systems heat the pumped feedwater by means of steam which is circulated through the unit. In some plants, systems called *superheaters* are used. These units consist of banks of tubes located at the hottest area of the boiler. Steam flows through these tubes before its entry into the steam turbine. The purpose of the superheater is to cause the steam to reach a higher temperature so as to produce more energy in the steam turbine. Each of these auxiliary systems helps to improve the efficiency of steam power plants.

Condensers and Purifiers

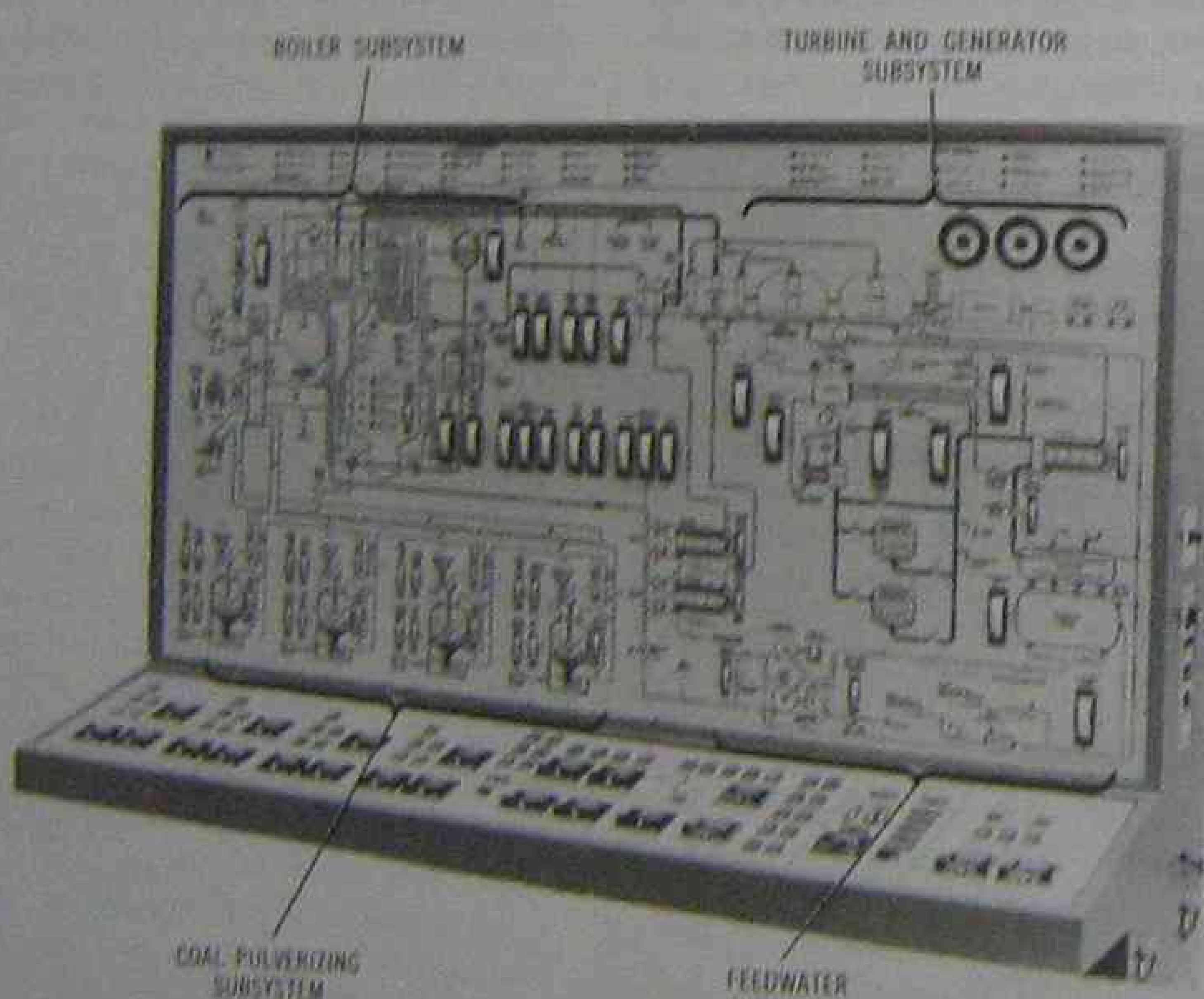
The condensers and feedwater purifiers used at steam power plants are also important in the production of energy. Condensers are used to cool the used steam which has passed through the steam turbine. The condensed water is continuously recirculated through the system. Feedwater purifiers are used to clean the impurities from the feedwater which is obtained from a water source located adjacent to the power plant. The feedwater purifiers play an important part in power plant operation. Without them, the metal used in the construction of the boiler would corrode, producing a slag build-up on the boiler walls, and eventually would destroy the boiler. Also, impurities in the steam can cause damage to the precision blades used in the steam turbines. In addition, the gases which are contained in the feedwater must also be removed. These gases are removed by a unit called a *deaerator*.

The quantity of feedwater which reaches the steam turbine in the form of steam is based on the amount of evaporation which takes place in the system. In the power plant, a comparative analysis must be made of the quantity of water entering the boiler and the quantity of steam coming out of the steam turbine. Adjustments in feedwater flow are based on this comparison.

FUTURE OF COAL-FIRED POWER SYSTEMS

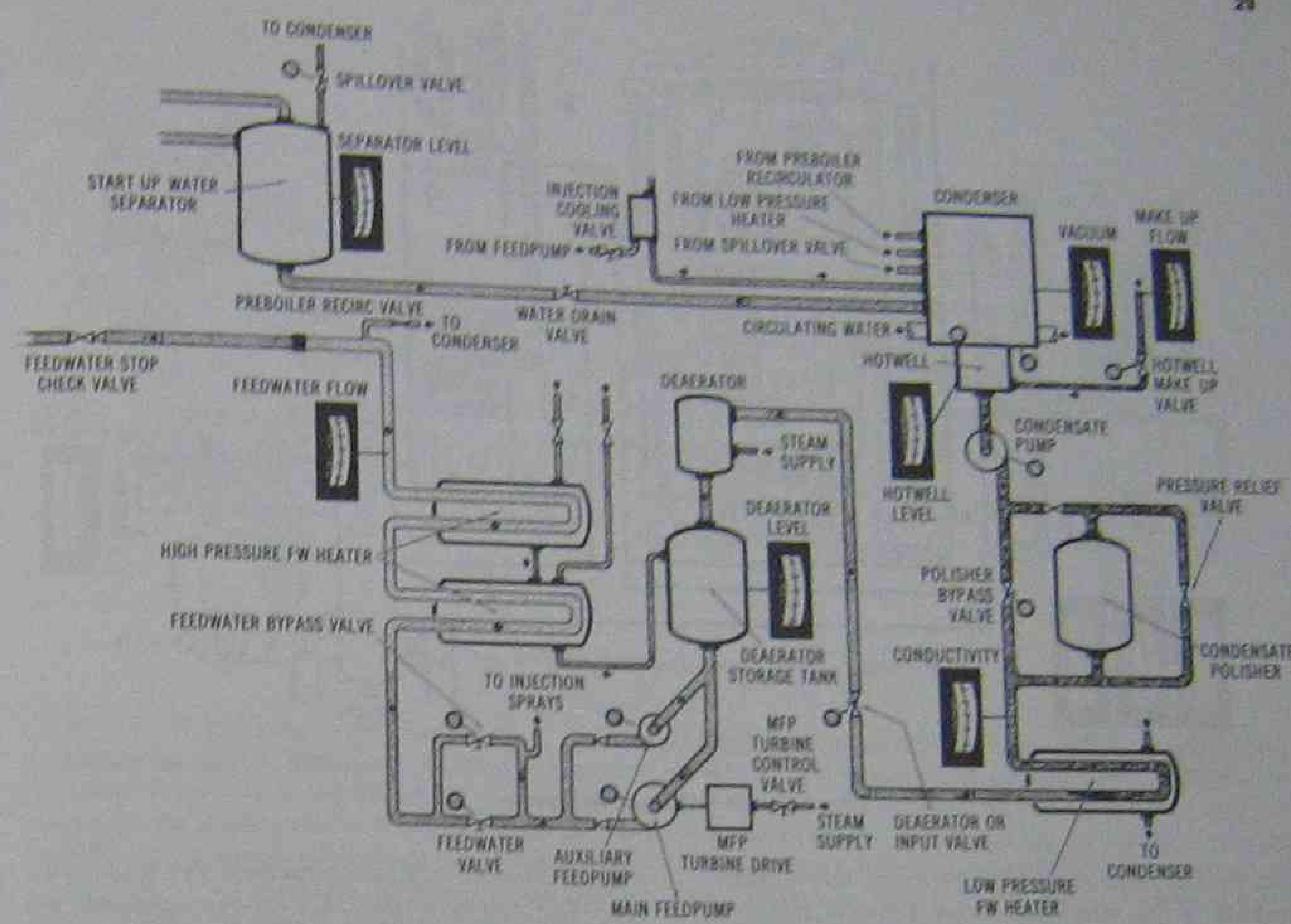
Pulverized-coal systems have been used for many years to produce energy for conversion to electrical power. However, there are now more environmental restrictions on these systems. The major problems are sulphur-dioxide and nitrogen-oxide emission controls for the power plants, particularly sulphur-dioxide controls. More stringent environmental controls increase the capital cost of power system operations. Even though coal is the most abundant fossil fuel, it is also the dirtiest in terms of environmental factors. Thus, a significant problem of electrical power technology is how to utilize coal in an environmentally acceptable way.

Electrical power systems are the largest consumers of coal in the United States. With a decrease in the availability of oil and natural gas fuels, coal must again



Courtesy Omnidata, Inc.

Fig. 2-9. A coal-fired electrical power system simulator.



Courtesy Omnidata, Inc.

Fig. 2-10. The feedwater subsystem.

be relied upon as the prime electrical power source of the future. Power production systems must be designed which will produce electrical energy in the most economical and environmentally attractive way.

Coal-Fired System Simulator

A coal-fired electrical power system simulator is shown in Fig. 2-9. Note how the various subsystems of the coal-fired power plant are interconnected within the overall system. There are basically five subsystems for this type of power plant. These subsystems are the feedwater system, the fuel and air system, the coal-pulverizing system, the boiler-water system, and the steam and turbine system. Each of these five subsystems is shown in the diagrams of Figs. 2-10 through 2-14.

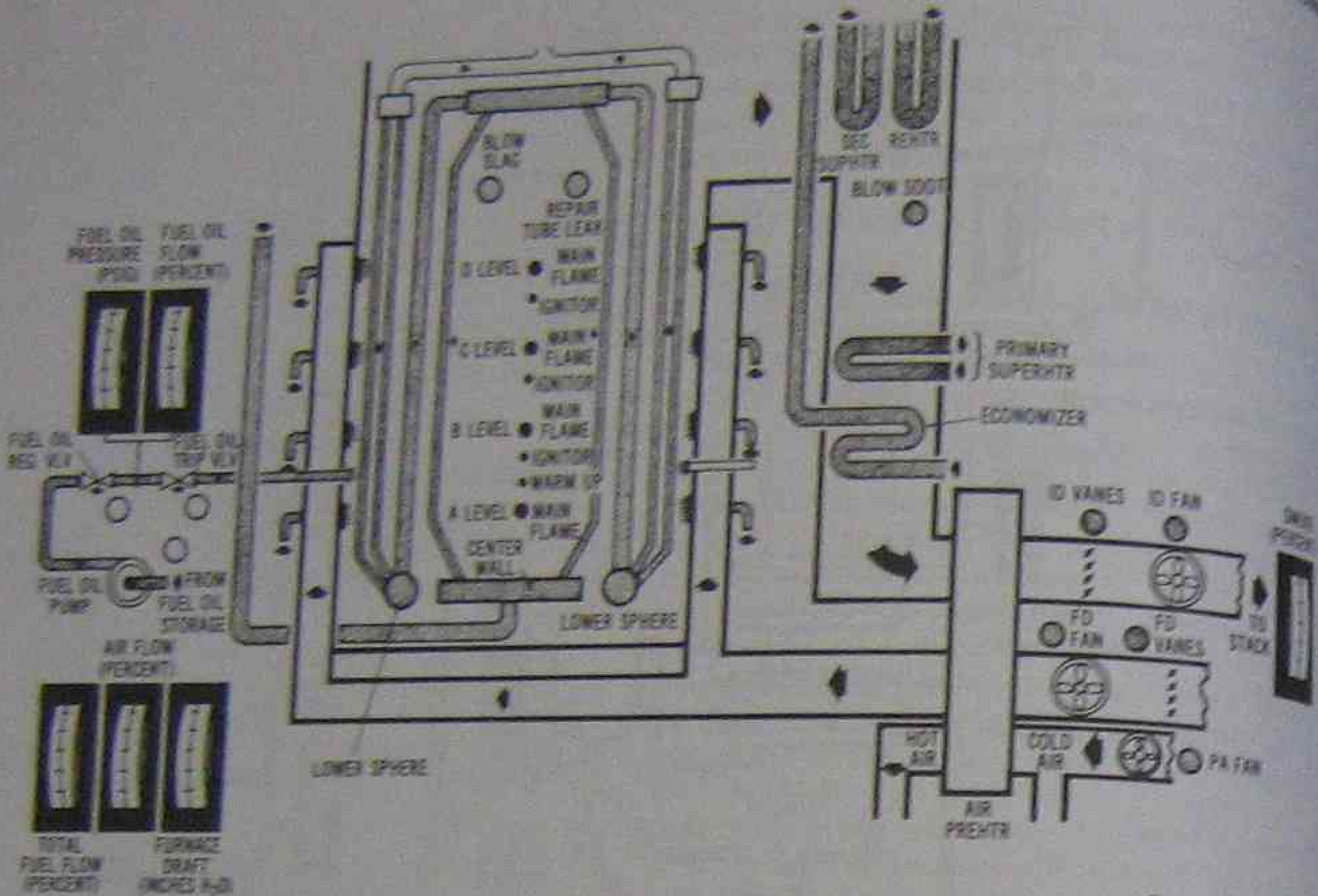
Oil-Fired System Simulator

An oil-fired electrical power system simulator is shown in Fig. 2-15. This system is very similar to the coal-fired system. The subsystems are identical to those used in the coal-fired system except, of course, there is no coal-pulverizing system.

HYDROELECTRIC SYSTEMS

The use of water power goes back to ancient times. It has been developed to a very high degree, but is now taking a secondary role due to the emphasis on other power sources that are being developed in our country today. Electrical power production systems using water power were developed for use in the early 20th Century.

The energy of flowing water may be used to generate electrical power. This method of power production is used in hydroelectric power systems as shown by the simple system illustrated in the diagram of Fig. 2-16. Water, which is confined in a large reservoir, is channeled through a control gate which adjusts the flow rate. The flowing water passes through the blades and control vanes of a hydraulic turbine which produces rotation. This mechanical energy is used to rotate a



Courtesy Omnidata, Inc.

Fig. 2-11. The fuel and air subsystem.

generator that is connected directly to the turbine shaft. Rotation of the alternator causes electrical power to be produced. However, hydroelectric systems are limited by the availability of large water supplies. Many hydroelectric systems are part of multipurpose facilities. For instance, a hydroelectric power system may be part of a project planned for flood control, recreation, or irrigation. Some hydroelectric power systems are shown in Figs. 2-17 through 2-19.

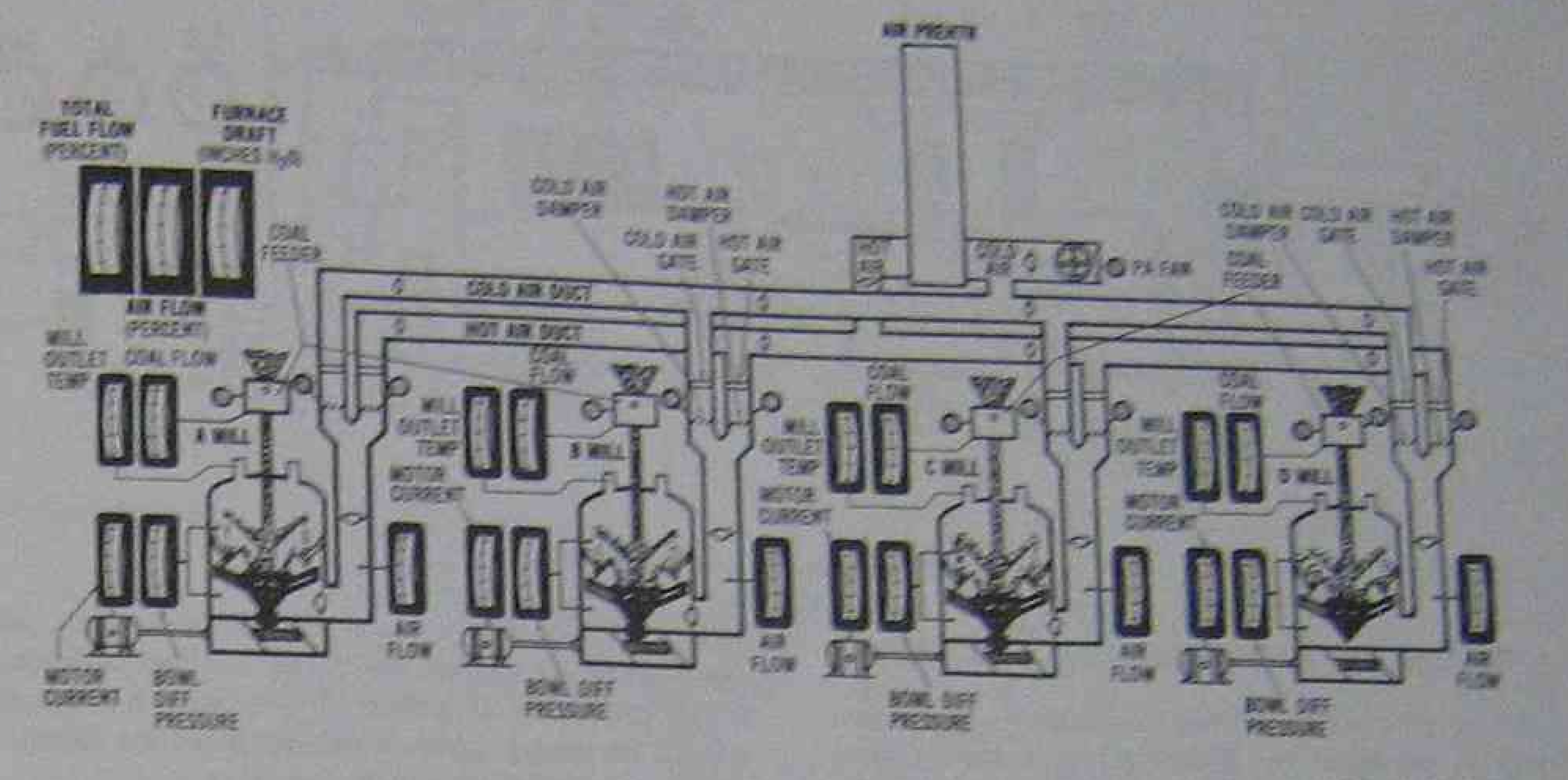
Hydroelectric System Operation

The turbines used as the mechanical-energy sources of hydroelectric systems are very efficient machines. They are ordinarily connected directly to the shaft of a three-phase generator which produces the electrical power. See Figs. 2-2 and 2-20, which show the arrangement of the various parts of a hydroelectric power system.

Water is channeled in from a higher level down into a spiral set of blades on the turbine. The force of water flowing onto these blades causes a rotation of the turbine in the desired direction. The water which flows past the turbine blades is then channeled into a lower-level lake or reservoir area. The angle of the turbine blades can be adjusted to control the speed of rotation of the turbine. Since rotational speed must remain constant to produce a 60-Hz frequency, the blade-angle adjustment and the amount of water channeled onto the blades must be adjusted continuously. Also, varying amounts of force are required to turn the turbine so that different amounts of power are delivered by the turbine to rotate the generator. As the load demand delivered by the generator increases, the power input to the turbine must be increased accordingly. This control is accomplished by adjusting the angle of the blades and the amount of water channeled into the blades. The adjustments are automatically accomplished by servo control systems.

Hydraulic Turbines

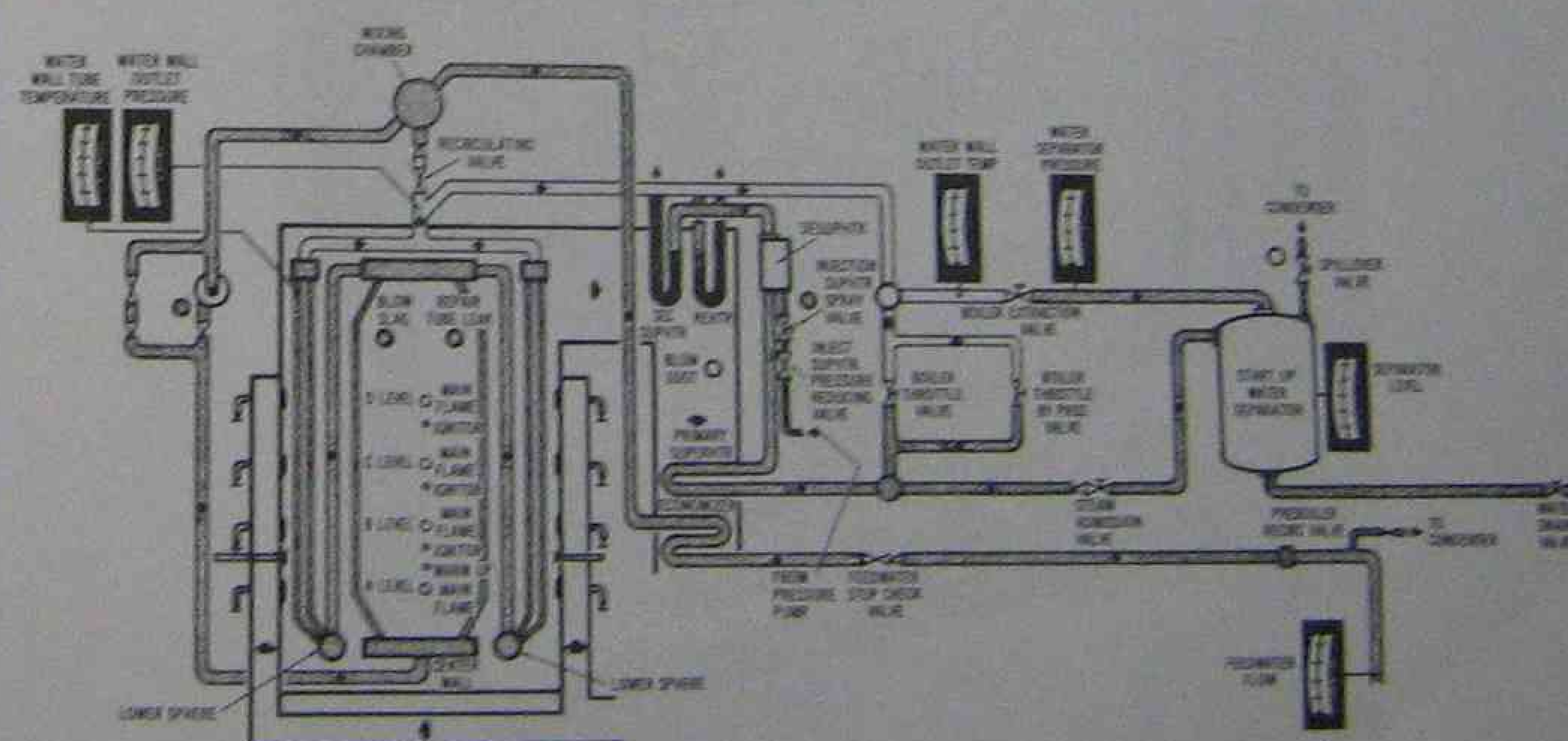
The production of electrical energy by hydroelectric systems is dependent upon the operation of hydraulic turbines. Hydraulic turbines convert the energy produced by the force of moving water into a mechanical energy. This type of turbine is connected to the shaft of a generator at a hydroelectric plant. Some typical generators inside a hydroelectric power plant are shown in Fig. 2-21. Since ac generators at power plants must rotate at a constant speed, the hydraulic turbine must turn at a fixed rate of speed. The efficiency of hydraulic turbines is much greater (in excess of 85%) than most rotating machines.



Courtesy Omnidata, Inc.

Fig. 2-12. The coal pulverizer subsystem.

The type of hydraulic turbine used with a hydroelectric power system determines whether the generators have horizontal or vertical shafts. Vertical shaft designs are the most common. Electrical power is produced by a three-phase ac generator connected directly to the shaft of the hydraulic turbine. Several hydroelectric systems are used as "reserve" systems for peak load times. They may be put into operation much faster than steam-driven power systems. It is also possible for the generators of a hydroelectric system to be operated as three-phase synchronous motors during low demand periods. The motor can rotate the hydraulic turbine which is then capable of pumping water. Water is pumped so that a higher external water level is achieved. The higher water elevation will then assist in the production of power during peak load intervals.



Courtesy Omnidata, Inc.

Fig. 2-13. The boiler-water subsystem.

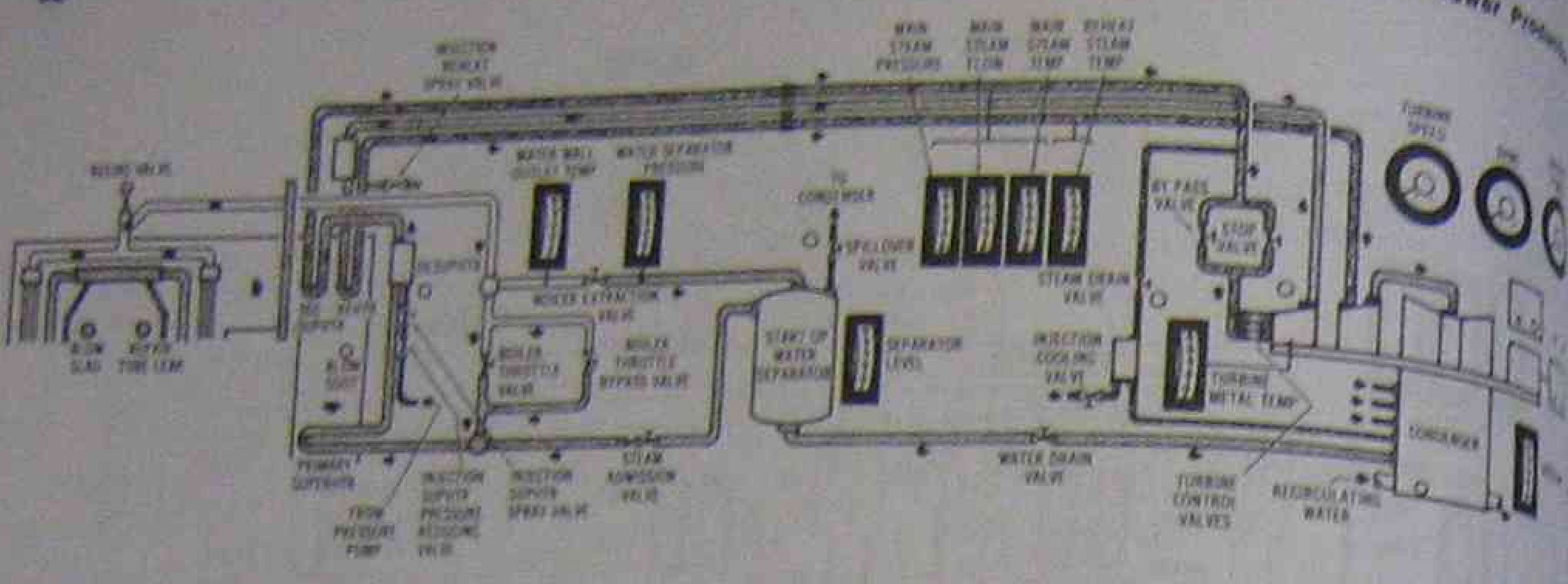


Fig. 2-14. The steam and turbine subsystem.

Courtesy Omnida

FUTURE OF HYDROELECTRIC SYSTEMS

About 10% of the power produced in the United States is produced by hydroelectric power systems. After the initial cost of a hydroelectric generating facility, the electrical power production cost is relatively inexpensive. Hydroelectric systems are easier to start up and stop than are other power production systems in use today. Other advantages of hydroelectric systems are those not associated with the production of electrical power. These benefits, derived from the construction of multipurpose dams, include navigational control of waterways, flood control, irrigation, a development of recreational areas. Another advant is that hydroelectric systems do not cause a consum tion of the energy source which produces the electri power as do other systems in use today.

Hydroelectric generating projects are considered t be low cost and produce little pollution. However, i the United States, we have already used the most de sirable sites for installing hydroelectric systems. Sin the cost of developing other alternative power system such as nuclear and geothermal, has become so grea the development of less desirable hydroelectric sites i

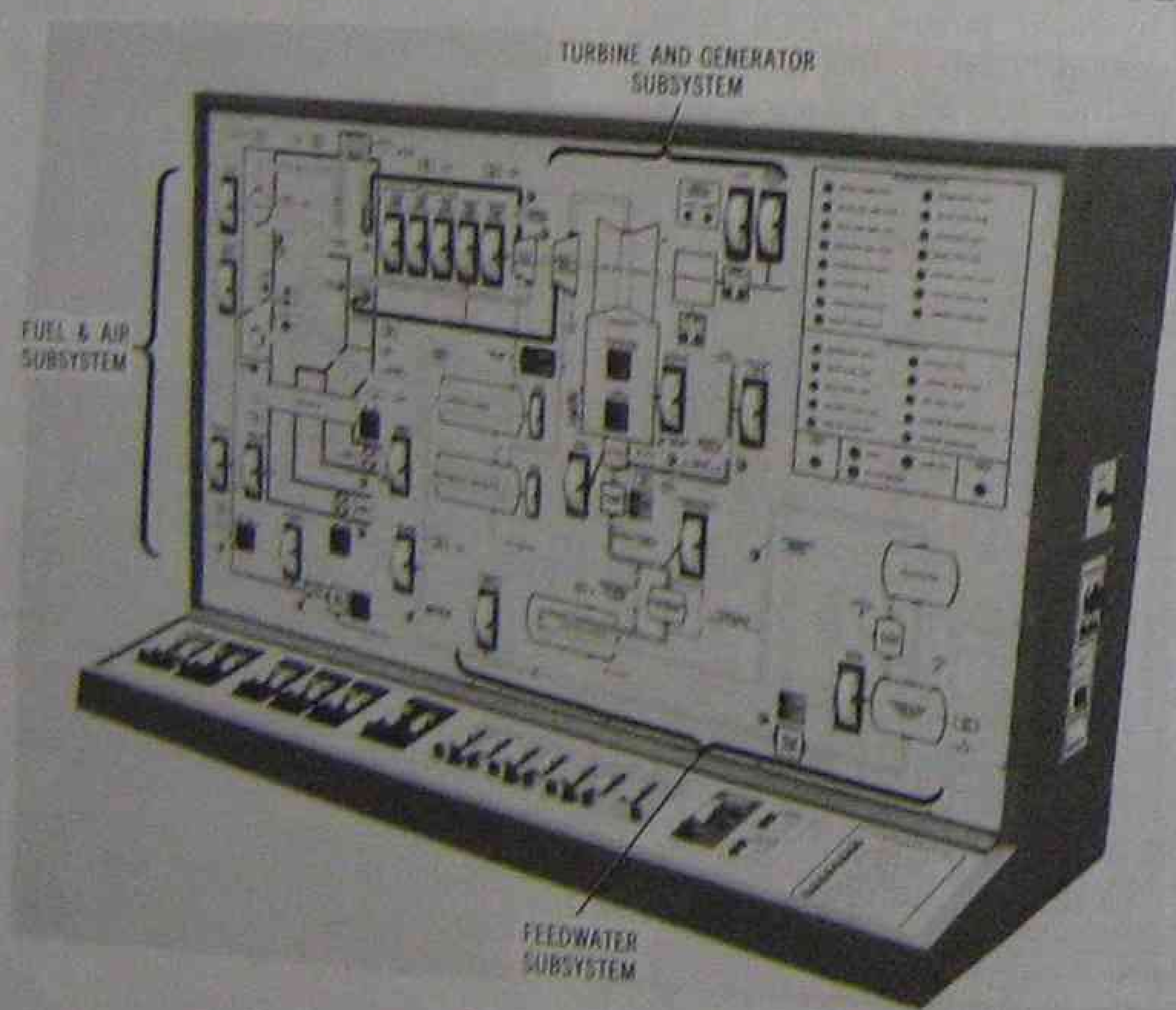


Fig. 2-15. An oil-fired electrical power system simulator.

Courtesy Omnidata, Inc.

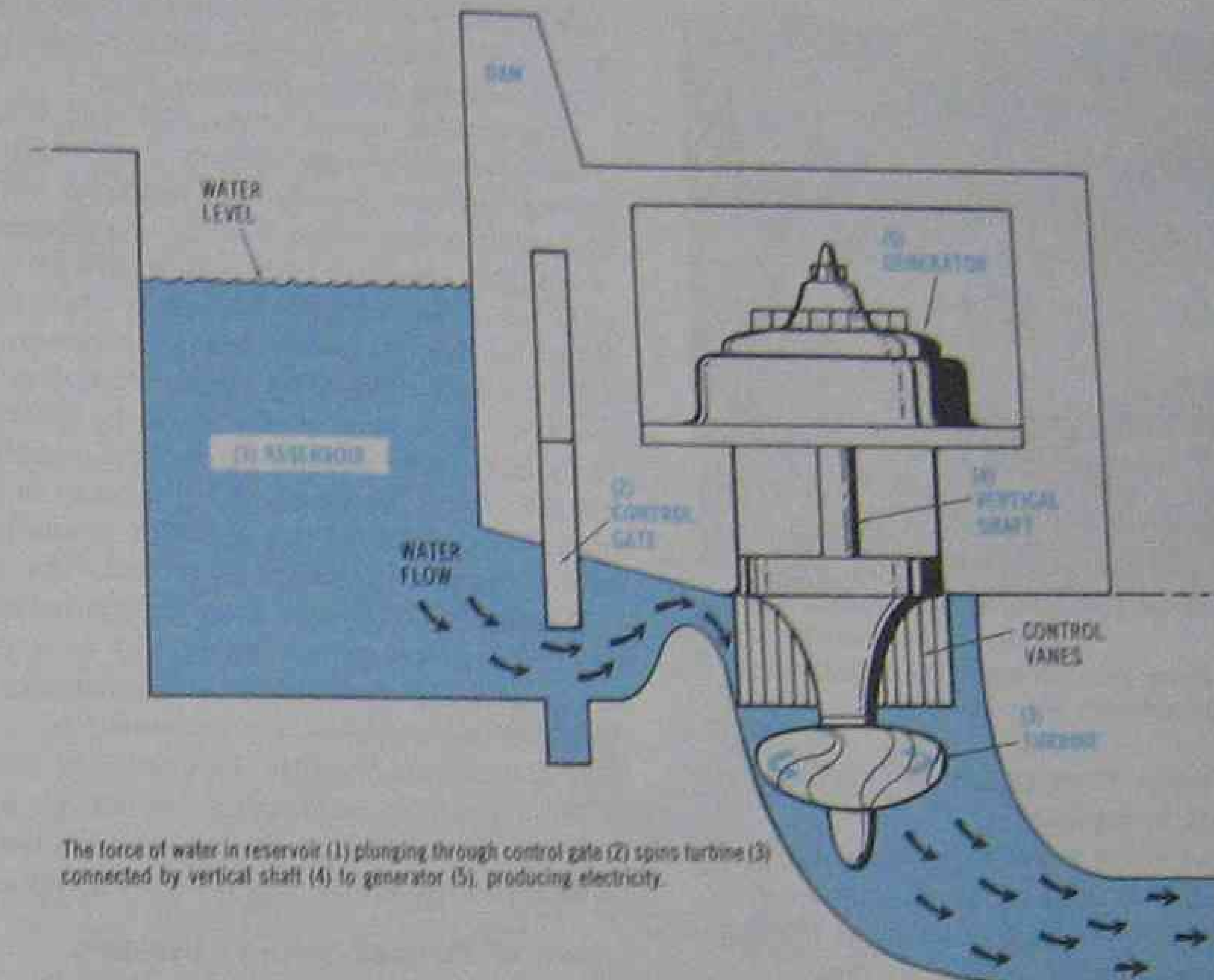
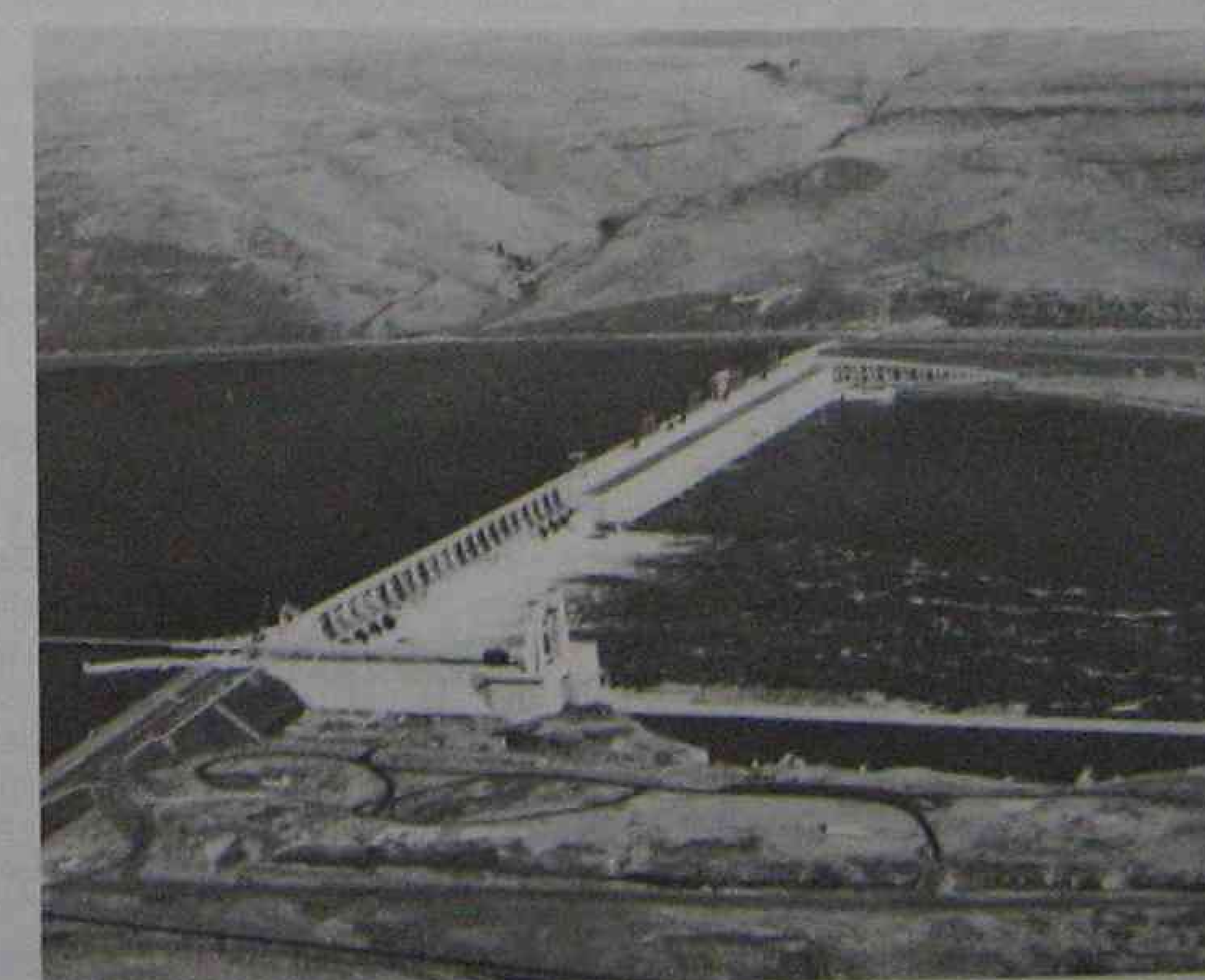
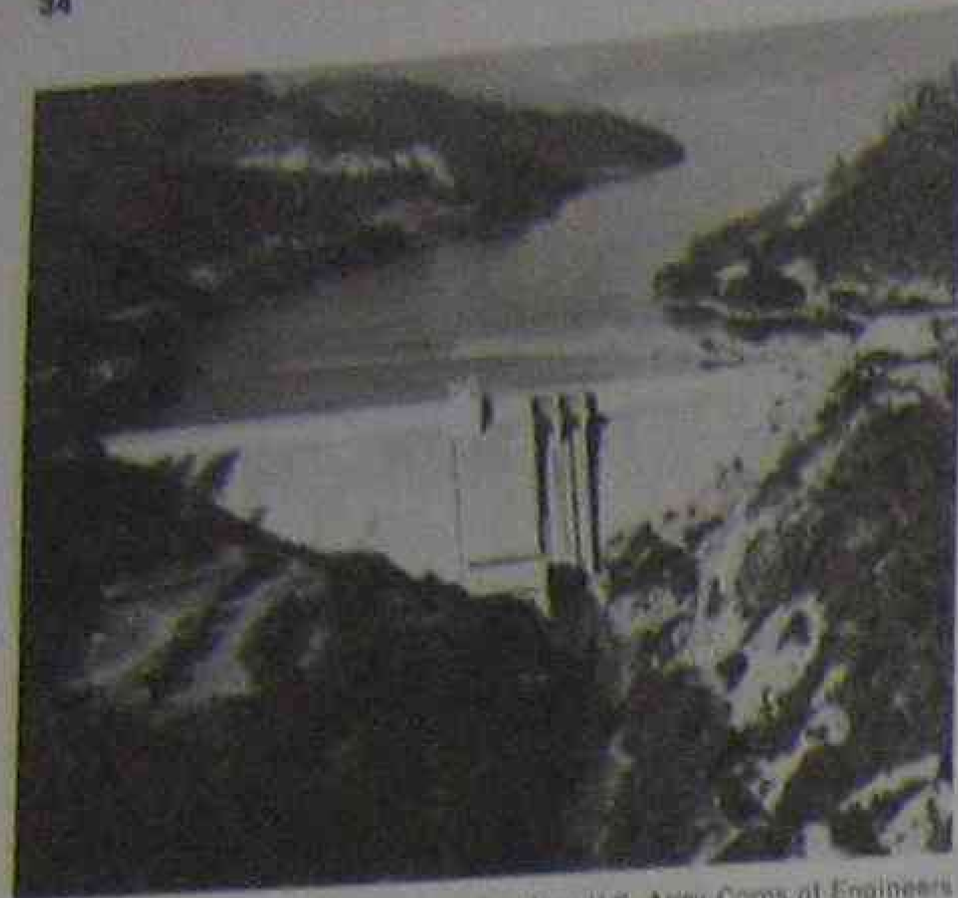


Fig. 2-16. Drawing of a basic hydroelectric power system.



Courtesy U.S. Army Corps of Engineers

Fig. 2-17. John Day Dam on the Columbia River. (A 2.7 megawatt hydroelectric power plant.)



Courtesy U.S. Army Corps of Engineers

Fig. 2-18. Green Peter Dam, Oregon. (An 80,000 kilowatt hydroelectric power plant.)

now feasible. Future development of hydroelectric power systems may be inevitable.

To motivate our using water to produce electrical power is the fact that if we used this natural resource to its full potential, it would give us other benefits. These were discussed earlier. Although the cost to produce electrical power with hydroelectric systems depends on a number of factors, it is generally considered to be a very cheap source of energy. The costs are primarily dependent upon the location of the power plant. The desirability of the site is dependent upon its natural characteristics, which affect the cost of development and its regional characteristics, which, in turn, affect the market for the power.

In the late 1930s, water supplied about 40% of the electrical power in the United States. Now, however, water power supplies only about 10% of the nation's electrical power. This is due to the massive development of other power production methods. It is estimated that, in the future, water power will account for an even lower percentage of electrical power generation. Despite this projected decrease, hydroelectric plants are still being built, and the hydroelectric capacity of the United States is still substantial. Hydroelectric systems are not now being developed rapidly; however, with our ever-increasing energy problems and the shortages of our other natural resources, water systems may still have a useful potential.

Pumped-Storage Hydroelectric Systems

Over 10,000 megawatts of electrical power is developed in the United States by pumped-storage hydroelectric systems. This type of system, shown in Fig. 2-22, operates by pumping water to a higher elevation

and storing it in a reservoir until it is released to drop to a lower elevation to drive the hydraulic turbines of a hydroelectric power-generating plant.

The variable nature of the electrical load demand makes pumped-storage systems desirable to operate. During low-load periods, the hydraulic turbines may be used as pumps to pump water to a storage reservoir of a higher elevation from a water source of a lower elevation. The water in the upper reservoir can be stored for long periods of time, if necessary. When the electrical load demand on the power system increases, the water in the upper reservoir can be allowed to flow (by gravity feed) through the hydraulic turbines which will then rotate the three-phase generators in the power plant. Thus, electrical power can be generated without any appreciable consumption of fuel. The pump-turbine and motor-generator units are constructed so that they will operate in two ways: (1) as a pump and motor, and (2) as a turbine and generator. In either case, the two machines are connected by a common shaft and operate together. However, the multiple use of these machines, although economically a very attractive method, limits the amount of time that a pumped-storage system can generate electrical power.

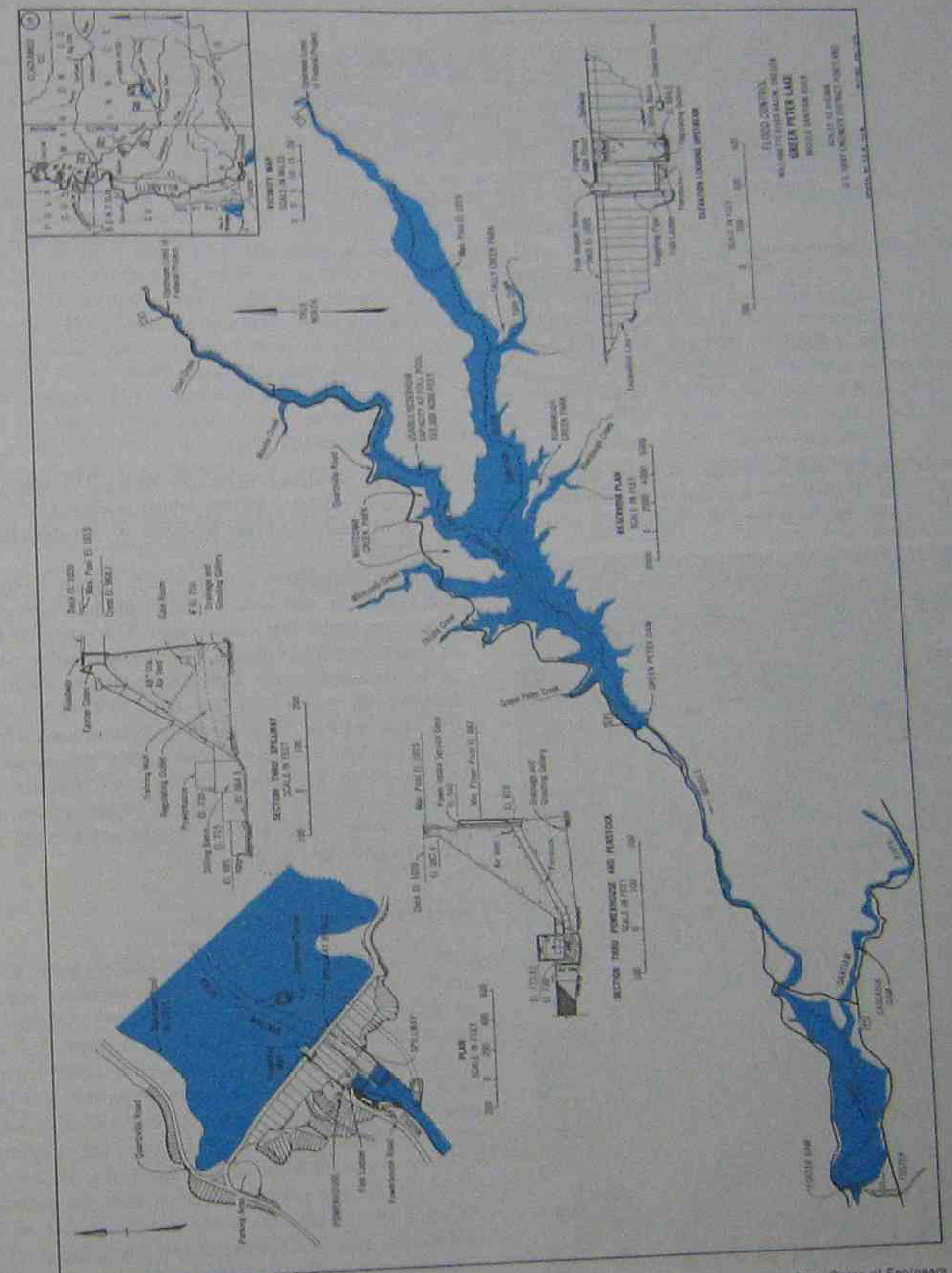
Future of Pumped-Storage Systems

The future of pumped-storage systems depends primarily on economic factors. If fuel and capital construction costs continue to rise, pumped-storage systems might be developed. The conversion of conventional hydroelectric systems to pumped-storage systems has been considered. Also, underground pumped-storage systems have been studied. The underground system would have an upper reservoir at ground level and the lower reservoir underground. The operating principle is the same as in a conventional pumped-storage system.

NUCLEAR-FISSION SYSTEMS

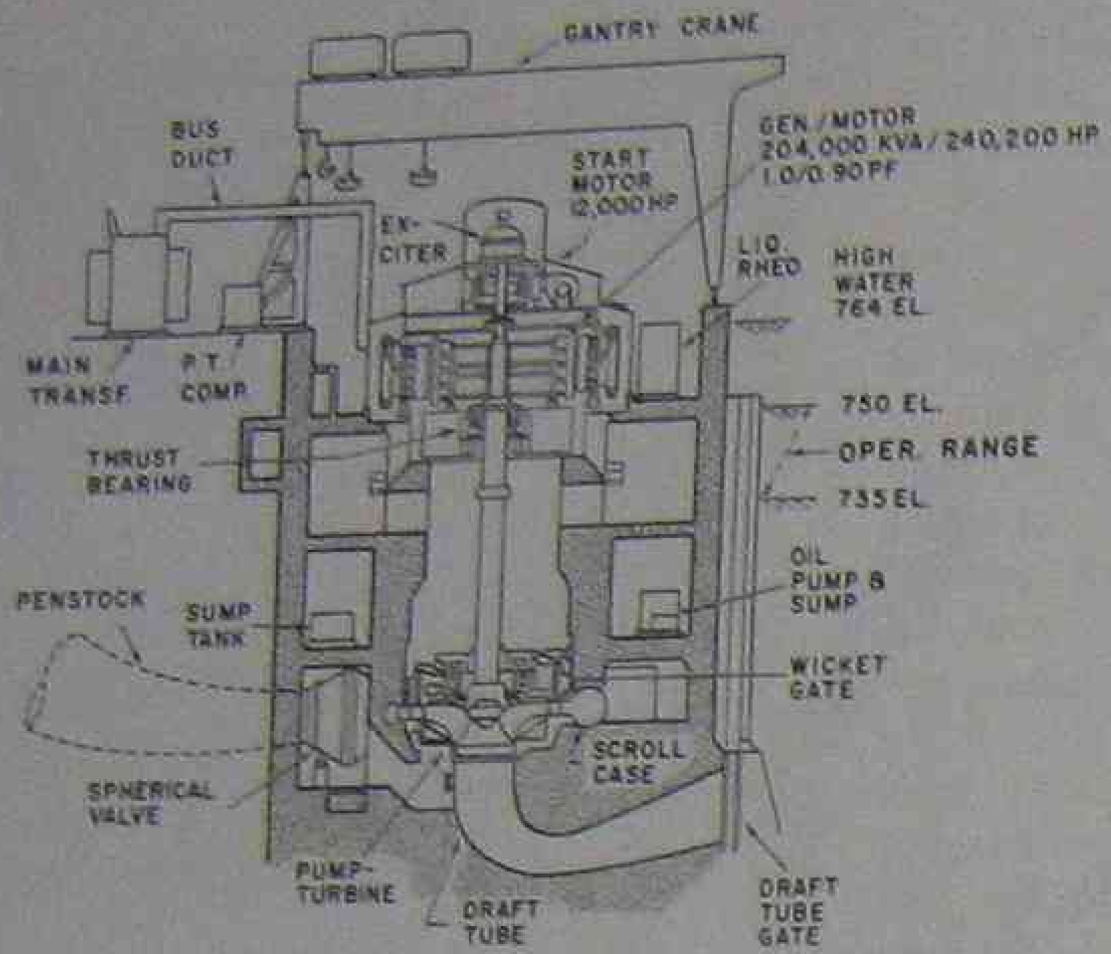
Nuclear power plants in operation today utilize reactors which function due to the nuclear-fission process. Nuclear fission is a complex reaction which results in the division of the nucleus of an atom into two nuclei. This splitting of the atom is brought about by the bombardment of the nucleus with neutrons, gamma rays, or other charged particles and is referred to as induced fission. When an atom is split, it releases a great amount of heat. A nuclear-fission power plant simulator is shown in Fig. 2-23.

In recent years, several nuclear-fission power plants have been put into operation. A nuclear-fission power system shown in Fig. 2-23 relies upon heat produced during a nuclear reaction process. Nuclear reactors



Courtesy U.S. Army Corps of Engineers

Fig. 2-19. Site layout of the hydroelectric project at Green Peter Lake.



Courtesy Allis-Chalmers Co.

Fig. 2-20. Cutaway drawing of a hydroelectric power station section at a main unit showing equipment arrangement.

"burn" nuclear material whose atoms are split causing the release of heat. This reaction is referred to as nuclear fission. The heat from the fission process is used to change circulating water into steam. The high-pressure steam rotates a turbine which is connected to an electrical generator. This is shown in the diagram of Fig. 2-25.


Courtesy U.S. Army Corps of Engineers

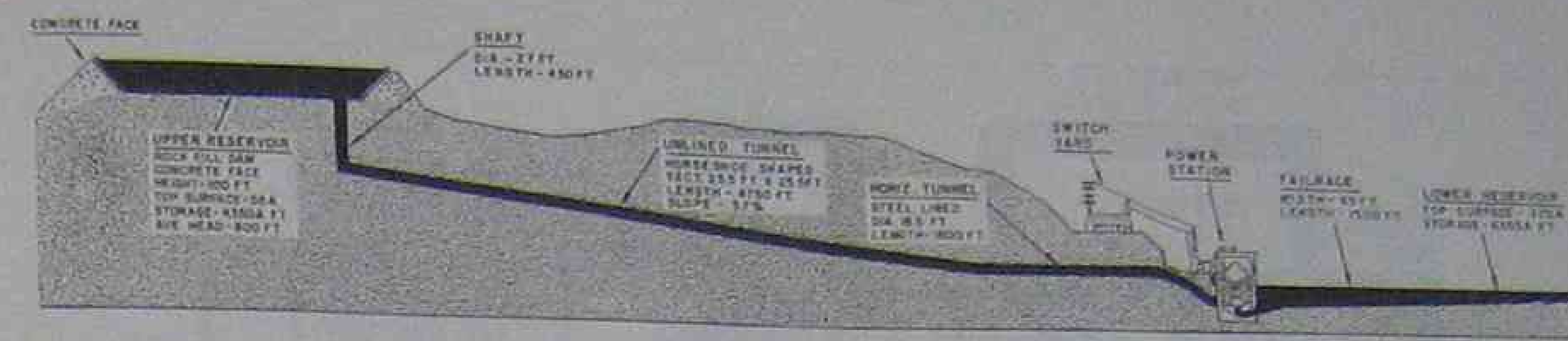
Fig. 2-21. Generators inside a hydroelectric power plant.

The nuclear-fission system is very similar to fossil-fuel systems in that heat is used to produce high-pressure steam which rotates a turbine. The source of heat in the nuclear-fission system is a nuclear reaction while in the fossil-fuel system, heat is developed by a burning fuel. At the present time, less than 10% of the electrical power produced in the United States comes from nuclear-fission sources. However, this percentage is also subject to rapid change as new power facilities are put into operation. An operational nuclear power system is shown in Fig. 2-26. A typical power plant site layout is given in Fig. 2-27.

Nuclear Power Fundamentals

In order to better understand the process involved in producing electrical power by nuclear-fission plants, we should review some basic fundamentals. An atom is the smallest particle into which an element can be broken. The central part of an atom is called its nucleus (this is how the term "nuclear power" was derived). The nucleus of an atom is composed of protons which are positively charged particles and neutrons which have no electrical charge. Electrons, which are negatively charged particles, orbit around the nucleus. An atom of any element is electrically neutral in its natural state since the number of protons in the nucleus is equal to the number of electrons which orbit around the nucleus.

The number of protons (+) and electrons (−) contained by an atom varies from one atom to another. (For further information concerning atomic number, mass, etc., refer to the table of Elements given in Appendix B.) The number of neutrons (0) in an atom is not always the same as the number of protons and electrons. Atoms which have additional neutrons are called isotopes. For instance, a hydrogen atom normally has one electron, one proton, and no neutrons. If one neutron is added to this atomic structure, heavy hydrogen or deuterium is formed. Deuterium is an isotope of hydrogen.

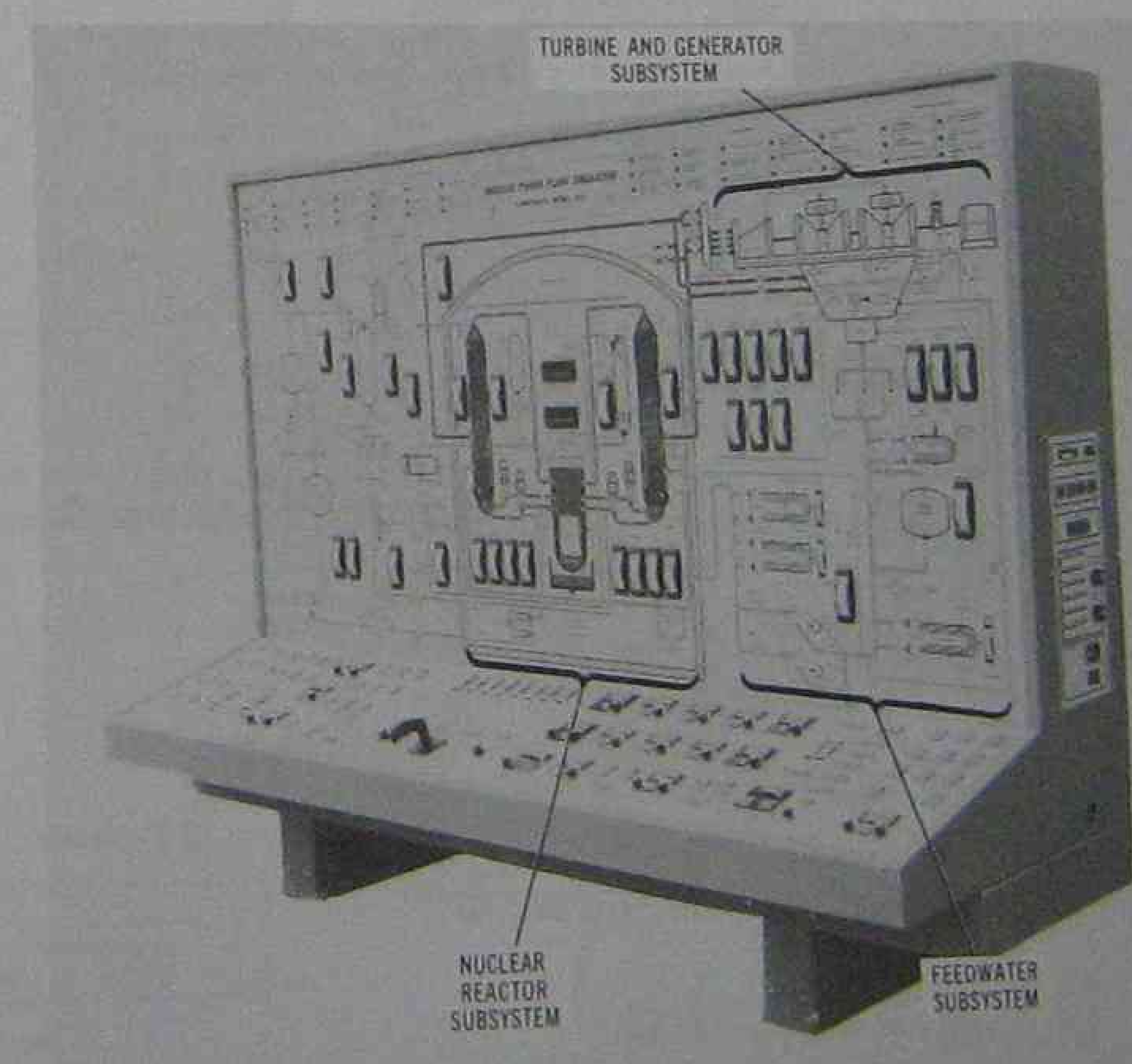


Courtesy Allis-Chalmers Co.

Fig. 2-22. A pumped-storage hydroelectric power plant. (Shown is a diagrammatic section of the Taum Sauk project.)

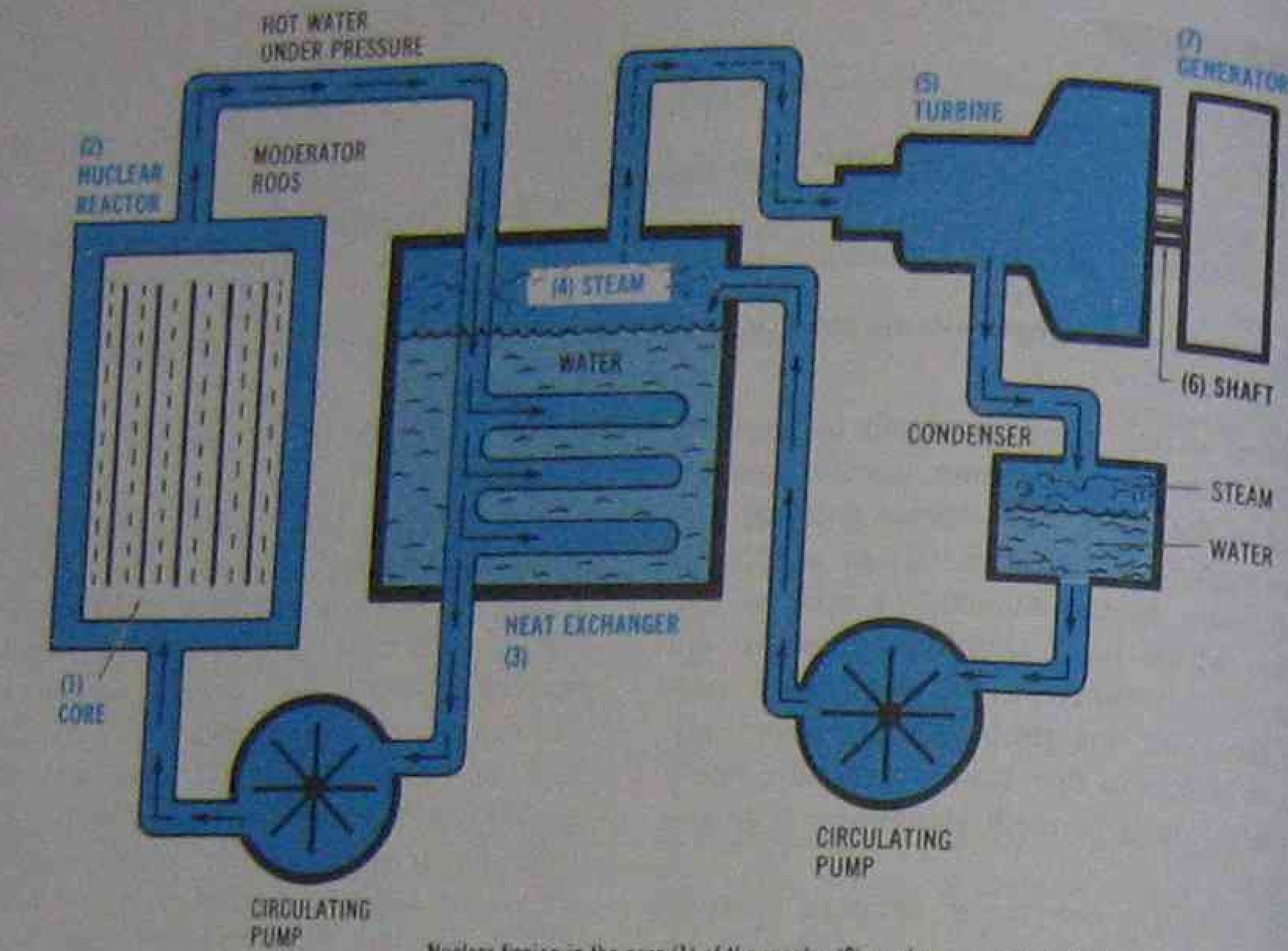
The element uranium has many different isotopes, each of which contains 92 protons. If the isotope has 143 neutrons in the nucleus, uranium-235 is formed. Uranium-235 has proved to be a valuable nuclear fuel, but less than 1% of the uranium metal ore mined is of the uranium-235 type.

The fission or splitting reaction of uranium-235 or other nuclear fuels is an interesting process. It requires separate controlled neutrons, traveling at high velocities, to penetrate the orbiting electrons around the nucleus of the U-235 isotope. Once a high-velocity neutron has struck the nucleus, the nucleus will split into two smaller nuclei. This reaction causes a large quantity of heat to be released. When a nucleus splits, other neutrons from within it are released. These neutrons can cause additional fission reactions in other U-235 isotopes. Thus, the fission reaction occurs as a chain reaction which causes massive amounts of heat energy to be given off.



Courtesy Omnidata, Inc.

Fig. 2-23. Nuclear power plant simulator.



Nuclear fission in the core (1) of the reactor (2) produces energy in the form of heat, which heats water under pressure. The heat from the water in this primary system is transferred to a secondary stream of water in heat exchanger (3) converting it into steam (4), which spins the turbine (5) connected by shaft (6) to generator (7), producing electricity.

Fig. 2-24. Drawing illustrating the principles of a nuclear-fission power system.

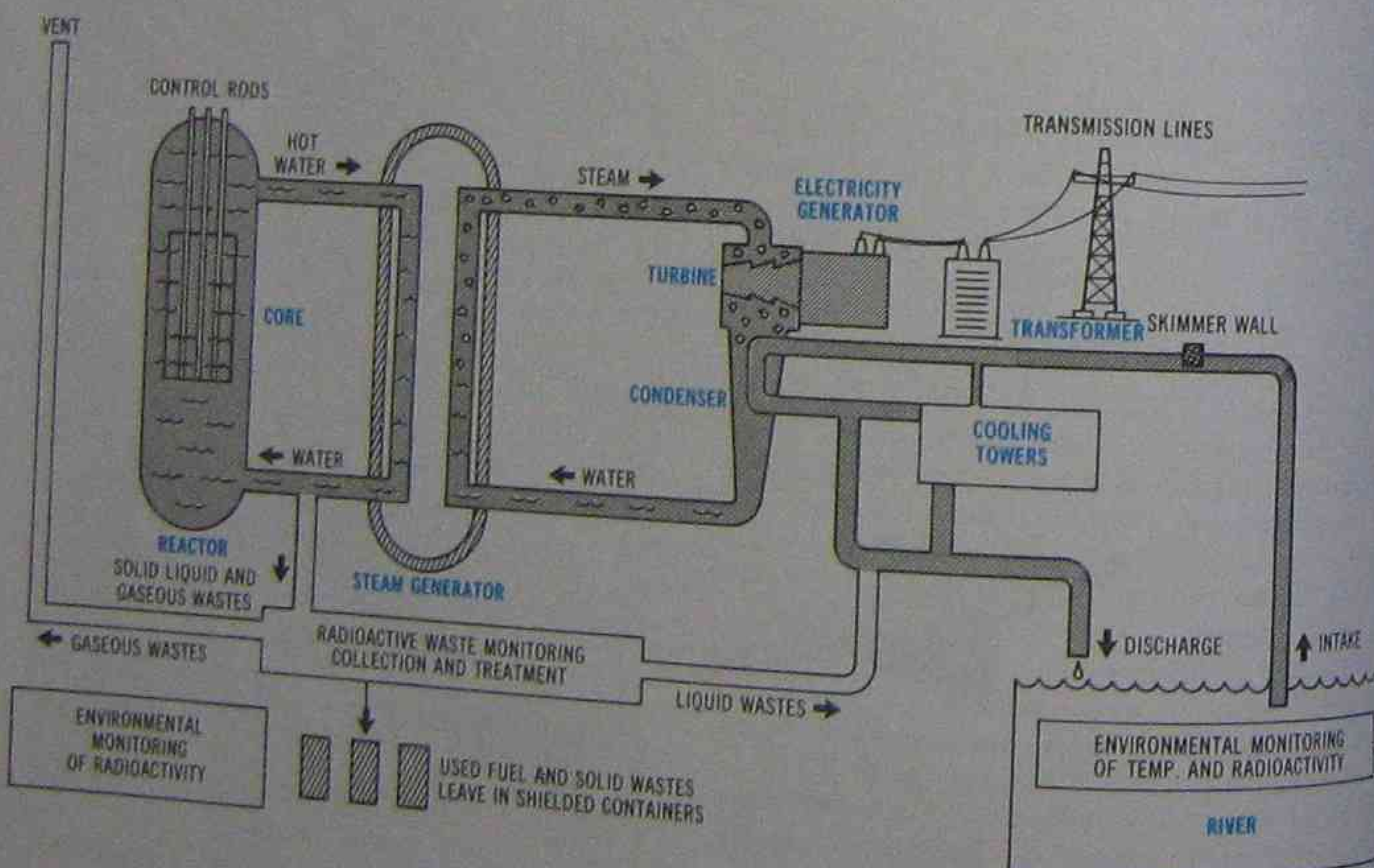
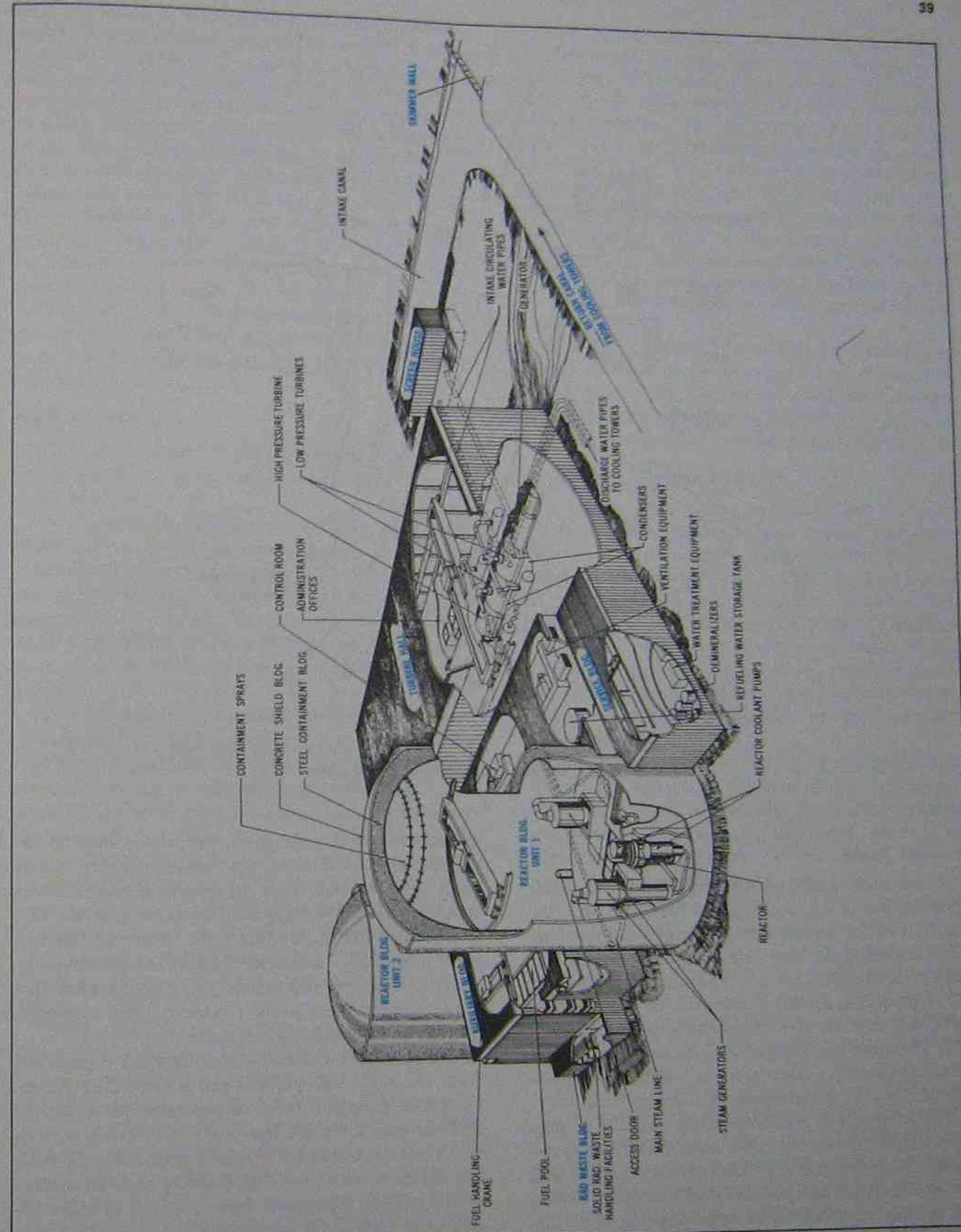


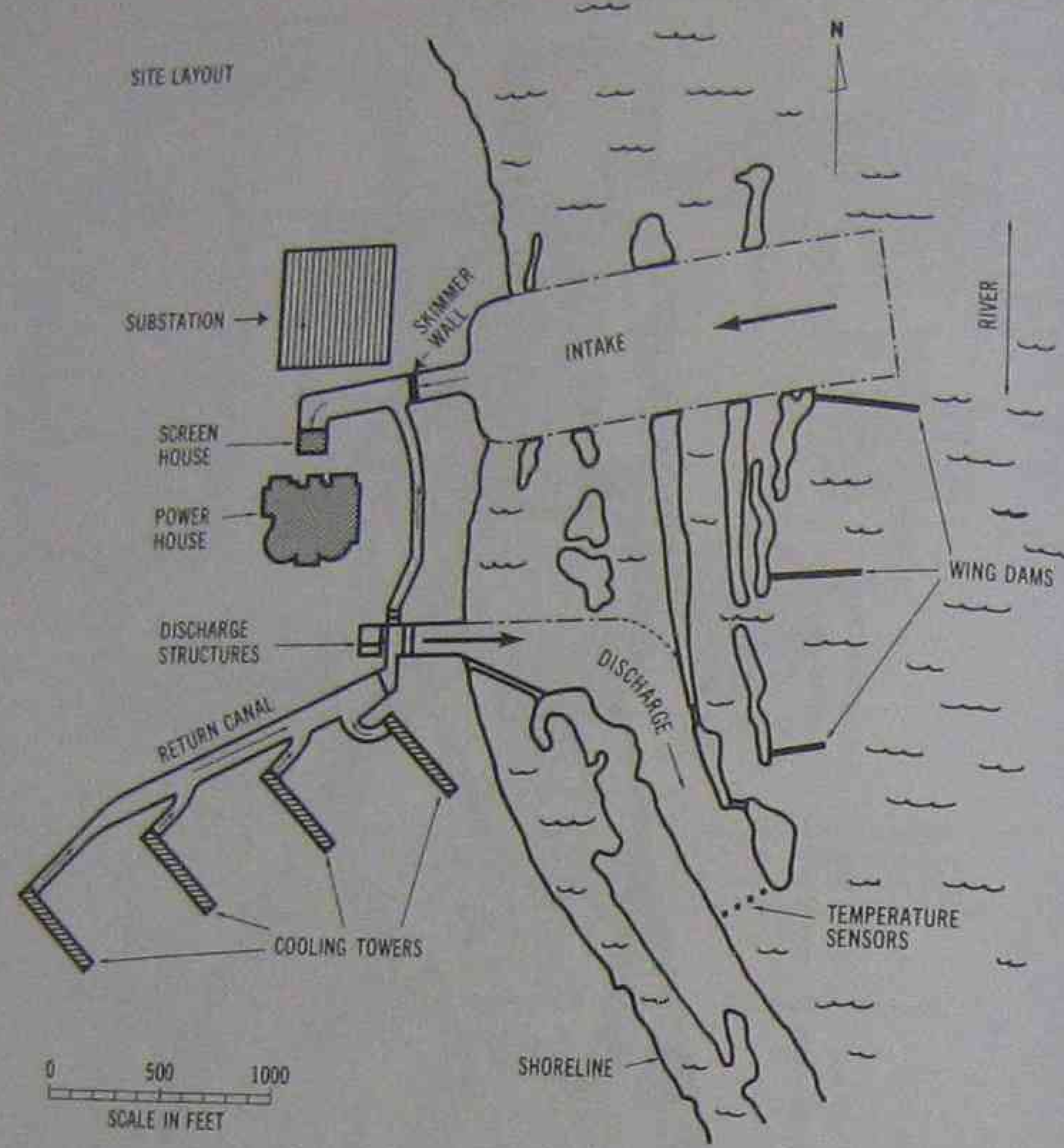
Fig. 2-25. Diagram of the nuclear reaction process.

Courtesy Northern States Power Co.



Courtesy Northern States Power Co.

Fig. 2-26. An operational nuclear-fission power plant.



Courtesy Northern States Power Co.

Fig. 2-27. Typical site layout of a nuclear power plant.

Nuclear Fuels

A sustained nuclear-fission reaction is dependent upon the use of a proper type of fuel. The most desirable fuels for nuclear-fission reactions are uranium-233, uranium-235, and plutonium-239. These three nuclear materials are the only fissionable isotopes capable of producing sustained reactions. Of these nuclear fuels, the only one that occurs naturally is uranium-235. The other two isotopes are produced by artificial means. Ordinarily, nuclear reactors which use uranium-235 as a fuel are called *converter reactors.*

The possibility of a nuclear-fission reaction producing as much or more fuel than is used has been investigated. Such reactors are called *breeder reactors* and use uranium-233 and plutonium-239 as fuels. During the nuclear reactions which take place in a breeder reactor, materials that are used in the reaction process are converted to fissionable materials. The long-range development of nuclear power production may be dependent upon whether or not breeder reactors can be made available soon. Since the types of nuclear reactors which are presently being used consume uranium-235, it is thought that in the future the supply of this fuel will become low, forcing its price to rise substantially. A price increase in this naturally available nuclear fuel would make nuclear power production less economically competitive with other systems.

Uranium fuel for nuclear-fission reactors is produced from ore and is then purified and converted to the desired state through a series of processes. Most nuclear fuel elements are made into a series of plates or rods which are protected by a cladding of stainless steel, zirconium, or aluminum. The cladding must be capable of withholding the nuclear fuel so as not to allow the release of radioactive materials.

Used fuel is released from the fission reactors when it no longer produces heat effectively during the nu-

clear reaction. It is not depleted at this time; therefore, further processing can bring about the recovery of more fuel from the used fuel. The used fuel, which is released from a nuclear reactor, is usually stored underwater for a period of time to permit cooling and radioactive shielding. This type of storage reduces the radioactivity of the fuel. After the storage period has elapsed, the fuel may be reprocessed more safely and easily. The reprocessing of nuclear fuel is very expensive. A large factor contributing to this cost is the expense of constructing a reprocessing facility. These facilities must be extensively shielded for radiation protection, both internally and externally. The production and use of nuclear fuels in the United States is rigidly controlled. An agency of the federal government keeps a continuous account of all nuclear fuels produced, used, or reprocessed.

Nuclear Reactors

There are a variety of types of nuclear reactors. The major type used in the United States has been the water-moderated reactor.

The fundamental difference between a nuclear power plant and a conventional power plant is the fuel that is employed. Most conventional power plants burn coal, oil, or gas to create heat while the present nuclear plants "burn" uranium. Burning uranium has proved to be a very effective source of power production; however, there is much controversy over this source of power.

It is estimated that burning one ounce of uranium has roughly the same energy output as the burning of 100 tons of coal. The "burning" which takes place in a nuclear reactor is referred to as nuclear fission. Nuclear fission is the method used in nuclear power generation and it is quite different from ordinary combustion. The burning of coal results from the carbon combining with oxygen to form carbon dioxide, along with the release of heat. The fissioning or splitting of the uranium atom results in the uranium combining with a neutron and, subsequently, splitting into lighter elements. This process produces a massive quantity of heat.

The reactors used at nuclear power plants must be capable of controlling fission reactions. When nuclear fuels are bombarded by neutrons, they split and release energy, radiation, and other neutrons. This process is a sustained chain reaction, producing a great amount of heat energy, which is used for the production of steam, which is used to rotate a steam turbine-generator system. The nuclear-fission power-generating system is about the same as a conventional fossil-fuel steam plant, except a nuclear reactor is used to produce the heat energy rather than a burning fuel confined in a furnace.

Within the nuclear reactor, there is a mixture of fuel and a moderator material. There are three known nuclear-fission fuels—uranium-235, uranium-233, and plutonium-239. Moderators are used to slow the speed of fission neutrons. Since the neutrons involved in the fission reaction have high energy levels, they are called fast neutrons. They are slowed by collisions with moderator materials such as water, deuterium oxide, beryllium, and other lightweight materials. Neutrons which have been slowed down possess an energy equilibrium and are referred to as thermal neutrons. These thermal neutrons aid additional fission reactions. Thus, moderators play a significant role in sustaining nuclear-fission reactions.

Nuclear reactors differ in several ways. Differences include the type of fuel and moderator, the thermal output capacity, and the type of coolant. Several classifications of nuclear reactors, according to types of coolant, are discussed in the following sections.

Moderating Nuclear Reactors

A uranium atom undergoes fission when it absorbs a neutron and, at the same time, produces two lighter elements and emits two or three neutrons. These neutrons, in turn, react with other uranium atoms, which will undergo fission and produce more neutrons. Heat is increased in the reactor as the number of neutrons is increased. If a reactor is left uncontrolled, it may destroy itself. Moderating a reactor, therefore, means controlling the multiplication of neutrons in the reactor core. There are several methods used for moderating nuclear reactors.

Boiling-Water Reactor (BWR)—Water is a popular coolant for reactors. In this type of reactor, shown in Fig. 2-28, water is pumped into the reactor enclosure. The water is then converted into steam which is delivered to a steam turbine. The water also serves as the moderator material of the reactor.

Pressurized-Water Reactor (PWR)—The pressurized-water reactor, shown in Fig. 2-29, is similar to a boiling-water reactor except that the coolant water is pumped through the reactor under high pressure. Steam is produced in an adjacent area from a separate stream of water which is pumped through the steam-production system. Just as in the BWR, the water within the reactor serves as the moderator.

High-Temperature Gas-Cooled Reactor (HTGR)—The high-temperature gas-cooled reactor, shown in Fig. 2-30, uses pressurized helium gas to transfer heat from the reactor to a steam-production system. The advantage of helium gas over water is that the helium can operate at much higher temperatures.

Other Types—Other types of reactors, such as the liquid-metal fast-breeder reactor (LMFBR) and the molten-salt cooled reactor, have some potential in electrical power production systems. The LMFBR type is shown in Fig. 2-31.

OPERATIONAL ASPECTS OF MODERN POWER SYSTEMS

There are several operational aspects of modern electrical power production systems which must be considered. These considerations include the location of power plants, electrical load requirements, and electrical load demand control. Each of these will be discussed in the following sections.

Location of Electrical Power Plants

A critical issue which now faces those involved in the production of electrical power is the location of power plants. New federal regulations associated with the National Environmental Policy Act (NEPA) have made the location of power plants more difficult. At present, there is a vast number of individual power plants throughout the country. However, the addition of new generating plants involves such current issues as air pollution, water pollution, materials handling (particularly with nuclear plants), fuel availability and federal, state, and municipal regulations.

These issues have brought about some recent thought about the construction of "energy centers." Such systems would be larger and more standardized than the power plants of today. This concept would reduce the number of plants that are needed to produce a specific quantity of electrical power. Other advantages of the concept include better use of land resources, easier environmental control management, and a more economic construction and management of facilities. These advantages may make centralized power production the best alternative, socially, economically, and technically, for meeting future electrical power requirements.

Electrical Load Requirements

The electrical power which must be produced by our power systems varies greatly according to several factors such as the time of the year, the time of the week and the time of the day. Electrical power supply and demand is much more difficult to predict than most quantities that are bought and sold. Electrical power must be readily available and in sufficient quantity whenever it is required. The overall supply and demand problem is something most of us take for granted until our electrical power is interrupted. Electrical power systems in the United States must be interconnected on a regional basis so that power stations can support one another in meeting the variable load demands.

The use of electrical power is forecasted to increase every ten years at a rate that will cause a doubling of the kilowatt hours required. Some forecasts, however, show the rate of electrical power demand to have a "leveling-off" period in the near future. This effect may be due to a saturation of the possible uses of electrical power for home appliances, industrial processes, and commercial use. These factors, combined with greater conservation efforts, and social and economic factors, support the idea that the electrical power demand will increase at a lesser rate in future years. The forecasting of the present demand by the electrical utilities companies must be based on an analysis by regions. The demand varies according to the type of consumer that is supplied by the power stations (which comprise the system). A different type of load is encountered

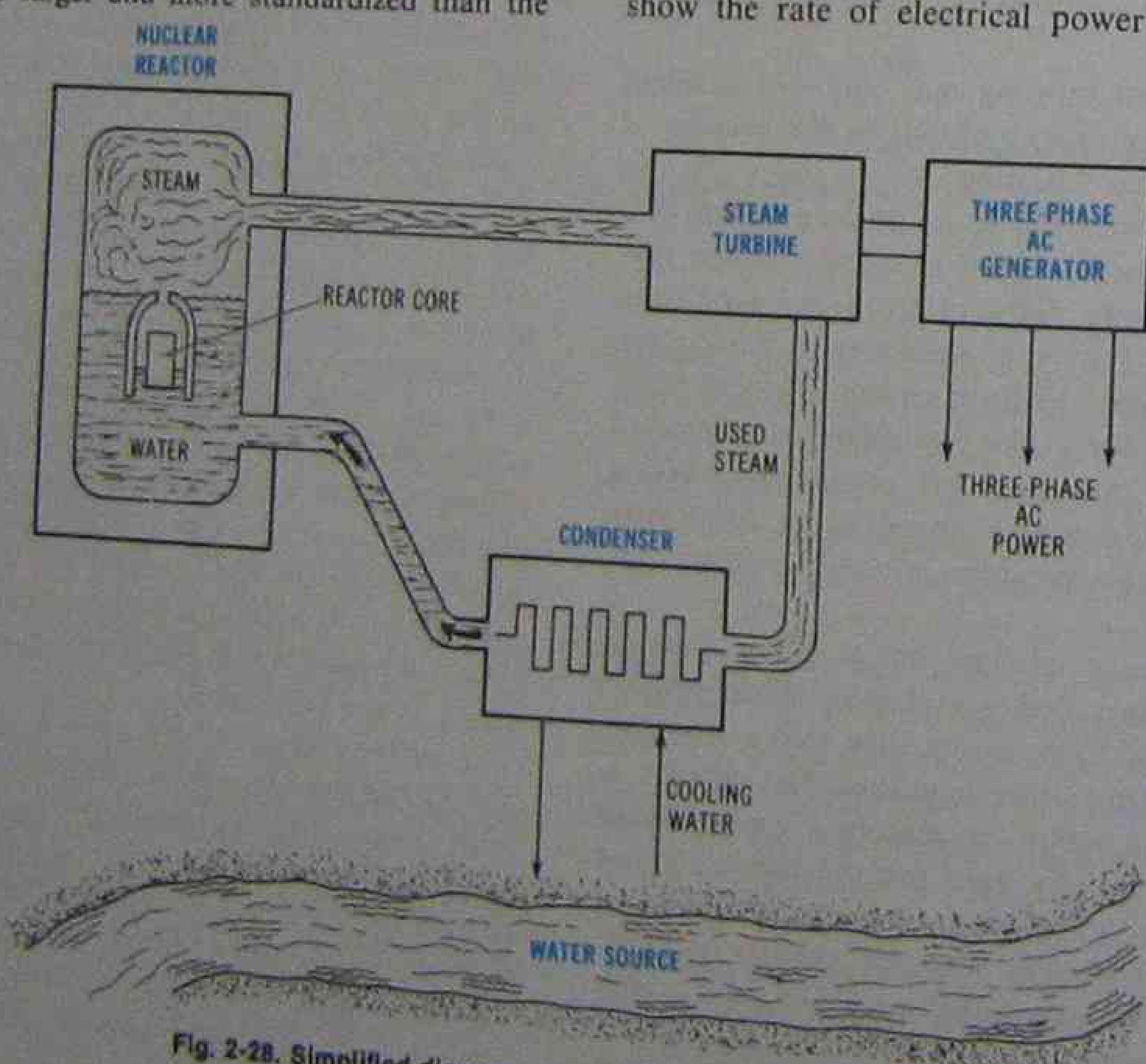


Fig. 2-28. Simplified diagram of a boiling-water reactor (BWR).

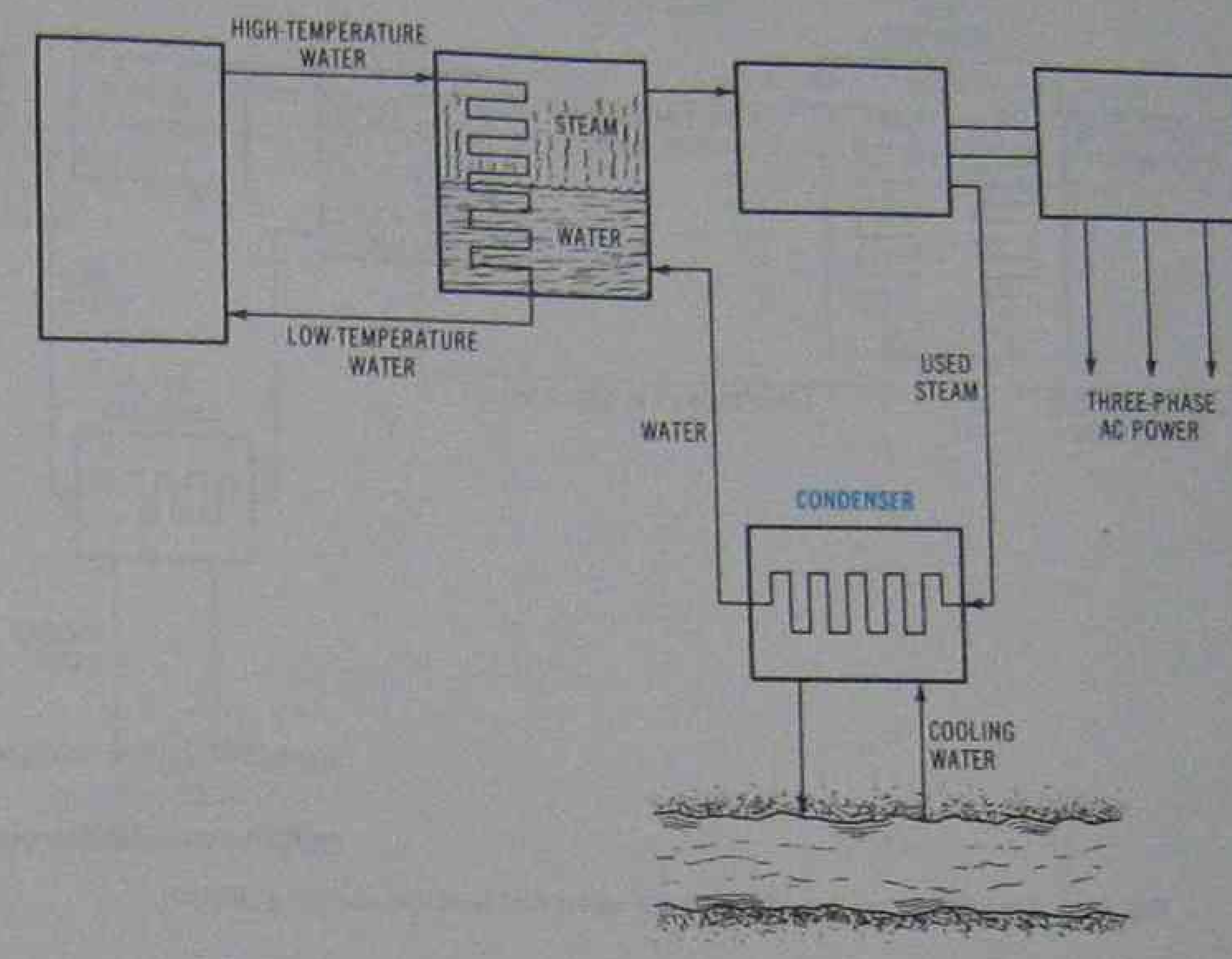


Fig. 2-29. Simplified diagram of a pressurized-water reactor (PWR).

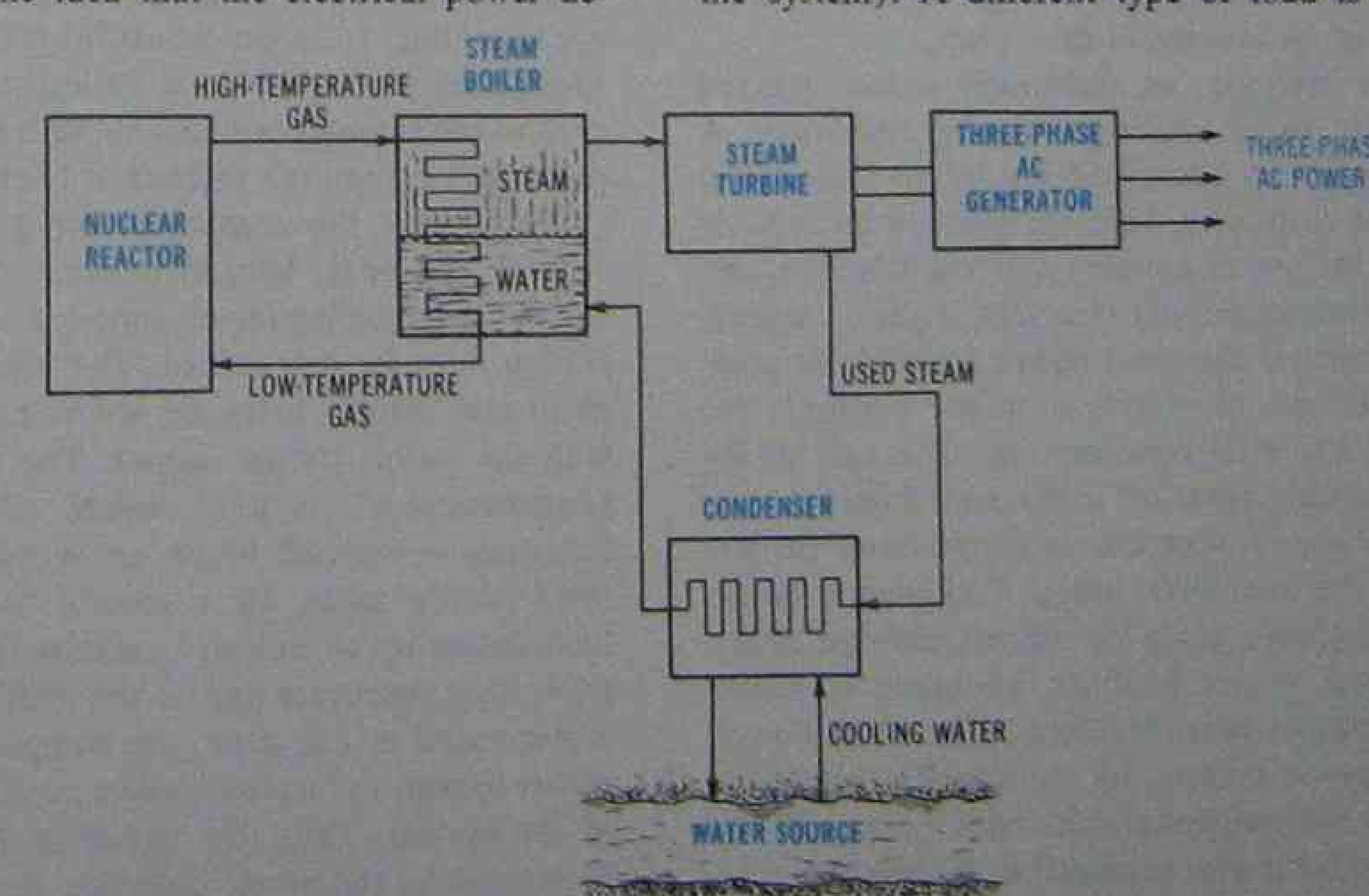


Fig. 2-30. Simplified diagram of a high-temperature gas-cooled reactor (HTGR).