The resistance of the toaster is

$$R = \frac{V}{I} = \frac{115 \text{ volts}}{8.7 \text{ amperes}} = 13.2 \text{ ohms.}$$

The energy converted in kilowatt-hours is

$$E = 1 \text{ kilowatt} \times 2 \text{ minutes} \times 1 \frac{\text{hour}}{60 \text{ minutes}}$$

$$= 0.033 \text{ kilowatt-hour}$$

$$= 0.033 \text{ kWh.}$$

Companies that provide the voltage for forcing electrons through our appliances are often referred to as power companies. It is tempting to expect that they are paid for power. They are not. They are paid for energy. Perhaps this is not obvious but a little thought should convince you.

Power is the rate of converting energy. A 100-watt light bulb requires energy at a rate of 100 joules per second regardless of how long it is turned on. However, the cost of operation depends on how long the bulb is lit. Using Eq. 4.5 it follows that energy, power, and time are related by

$$\text{energy} = \text{power} \times \text{time},$$

$$W = Pt.$$

So any unit of power multiplied by a unit of time yields a unit of energy. Watts (or kilowatts) and hours are units of power and time. The watt-hour (or kilowatt-hour) is a unit of energy. It is a little peculiar because the units of time (hours) do not cancel the time units of seconds in power.

$$W = P \text{ (watts)} \times t \text{ (hours)}$$

$$= P \frac{\text{joules}}{\text{second}} \times t \text{ (hours).}$$

Note carefully that the units of hours do not cancel the units of seconds.

Table 4.4 lists the power requirements for several household appliances. Note that those involving the generation or removal of heat require the most power. These devices tend to have low resistance.

The energy consumed by a 1100-watt (1.1 kilowatt) toaster for 1 hour would be

$$E = 1.1 \text{ kilowatts} \times 1 \text{ hour} = 1.1 \text{ kWh.}$$

In 1987 residential consumers paid an average of 7.8 cents per kWh for electric energy. At the average price the cost of operating the toaster for one hour would be

$$\text{Cost} = 1.1 \text{ kWh} \times 7.8 \frac{\text{cents}}{\text{kWh}} = 8.6 \text{ cents.}$$

TABLE 4.4
Power Requirements (in watts) of Some Common Household Appliances

APPLIANCE	POWER (watts)
Cooking range (full operation)	12,000
Heat pump	12,000
Clothes dryer	5,000
Oven	3,200
Water heater	2,500
Air conditioner (window)	1,600
Microwave oven	1,500
Broiler	1,400
Hot plate	1,250
Frying pan	1,200
Toaster	1,100
Hand iron	1,000
Electric space heater	1,000
Hair dryer	1,000
Clothes washer	500
Televison (color)	330
Food mixer	130
Hi-fi stereo	100
Radio	70
Razor	14
Toothbrush	7
Clock	2

4.7 Electrical Shock

A train approaching a crossing of the track with a highway actuates a switch that causes a gate to block cars from crossing the track. An electrical signal has triggered a mechanical operation. Analogous operations occur in the human body. A visual signal stimulates electric currents that travel to the brain, where electrical signals are transmitted to an arm, which causes the arm to flex. Respiration, muscular activity, and beating of the heart are all controlled electrically. Both an electrically operated train warning system and the human electrical system can be damaged by excessive electric currents. For the human system the most susceptible parts are the brain, the heart, and the chest muscles and nerves that control respiration.

A current is produced in the body whenever a voltage appears between two parts of the body. The size of the current depends on the voltage and resistance between the two points. When the skin is dry the resistance is appreciable, around 100,000 ohms. But if the skin is moist the resistance may drop to around 1000 ohms. One thousand ohms connected to the common household voltage of 115 volts produces a current of about 0.1 ampere. One-tenth of an ampere is small compared to the current in a desk lamp. But one-tenth of an ampere in a human heart would likely produce uncontrolled stimulation of the heart muscles, resulting in no blood being pumped. This effect, called *ventricular fibrillation*, persists even after the electric current is removed. Ventricular fibrillation seldom stops of its own accord. It takes only a couple of minutes for ventricular fibrillation to weaken the heart muscles to the point where the normal operation of the heart cannot be restored and death results. Interestingly, one method of defibrillating the heart is to pass a large current of about 10 amperes through the heart for a few thousandths of a second.

Irregular breathing and respiratory paralysis may result from electric currents in the body in the range of 0.02 to 0.1 amperes. Respiratory paralysis is usually treated by artificial respiration. Electric currents of a few thousandths of an ampere in the hand will cause the finger and hand muscles to contract. If the source of the voltage is in the palm or fingertips, the hand clamps onto the source and the victim cannot let go. If for some reason a person must touch a wire to see if it is "hot," this should be done with the back of the hand. Then, when the muscles contract, the fingers pull away from the source rather than toward it. Lest you take offense at this morbid discussion, realize that about 2000 people are electrocuted each year in the United States.

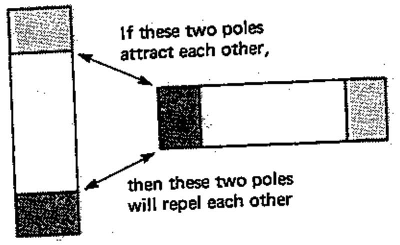
4.8 Magnetic Force and Magnetism

We have discussed electric current and the idea that an electrical "pressure" is required to establish current. Nothing has been said about how the power company generates the pressure, or how it is transmitted to homes and factories. To understand this important aspect of producing electricity we must grasp some fundamentals of magnetic force and magnetism.

Magnets are as useful as they are fascinating. They hold notes on the kitchen refrigerator. Homeowners use magnets to hold quilted window insulation in place. For centuries navigators have relied on magnetic compasses to find their way. Materials containing iron are attracted to magnets. A magnet is attracted to a refrigerator door because the door has some iron content. Most metal paper clips contain iron and are attracted to a magnet. Either end of a magnet such as in a compass will attract a paper clip. But there is a relatively broad region between the ends that will not attract a paper clip. The magnetic properties of a magnet are concentrated near the ends. Years ago these regions were labelled as *poles*. The earth possesses magnetic poles located near the north and south geographic poles. If a pole of a magnet is placed near the poles of another magnet it will be attracted to one pole and repelled by the other pole (Fig. 4.5). We describe the fundamental difference between the two poles by calling one N and the other S. An N pole is the pole of a freely suspended magnet, such as a compass, that points toward the geographic north pole. The tip labeled N on a compass needle is an N magnetic pole. Any other

FIGURE 4.5

A pole of a magnet is attracted to one of the poles of a nearby magnet but is repelled by that magnet's opposite pole.



pole repelled by an N pole is itself an N pole, and any pole attracted by an N pole is an S pole.

Ordinarily, metal paper clips do not behave like magnets. But they can be magnetized by placing them across the poles of a magnet. Once magnetized they behave like other magnets. A useful model views unmagnetized iron as having a vast number of tiny atomic magnets oriented at random. The effect of an atomic magnet pointing in one direction is canceled by another atomic magnet pointing exactly opposite. Consequently, the randomness of the large number of atomic magnets produces no net magnetic effect (Fig. 4.6).

When a magnet is brought near unmagnetized iron (Fig. 4.7), the poles of the atomic magnets experience a magnetic force and align. The repulsive force between S poles causes atomic magnets to align with their S poles away from the S pole of the magnet. Inside the iron, adjacent N and S poles neutralize their magnetism. But at one end there is an accumulation of N poles, and at the opposite end there is an accumulation of S poles. The unmagnetized iron is now magnetized and is attracted to the magnet that induced the magnetism. In some types of iron-based materials, the magnetism remains long after the inducing magnet is removed.

FIGURE 4.6

An unmagnetized bar of iron is viewed as containing a vast number of randomly oriented tiny magnets. The magnetism of any one magnet is canceled by neighboring magnets having different orientation.

FIGURE 4.7

When unmagnatized iron is brought near a magnet, magnetic forces align the tiny magnets in the iron, leaving the iron with N and S poles.

Tiny pieces of magnetized iron make small compasses. Sprinkle these bits on a glass plate covering a magnet and almost magically they align in a strikingly symmetric pattern (Fig. 4.8). The space around the magnet seems to be filled with something instructing the bits of iron to align. We say there is a magnetic field around the magnet. The imaginary lines along which the bits of iron align are called magnetic field lines. The direction assumed by the N pole of a bit of iron determines the direction of the magnetic field line at the position of the bit. Although there is nothing material about a magnetic field line, it is a useful model to visualize a magnetic field as being filled with magnetic field lines. If a wire moves in a magnetic field, we say the wire "cuts" the magnetic field lines.

FIGURE 4.8

Tiny bits of iron sprinkled near a magnet align along the magnetic field lines of a magnet. Here you see the projection of the outlines of bits of iron sprinkled on top of a glass plate resting on top of a bar magnet.

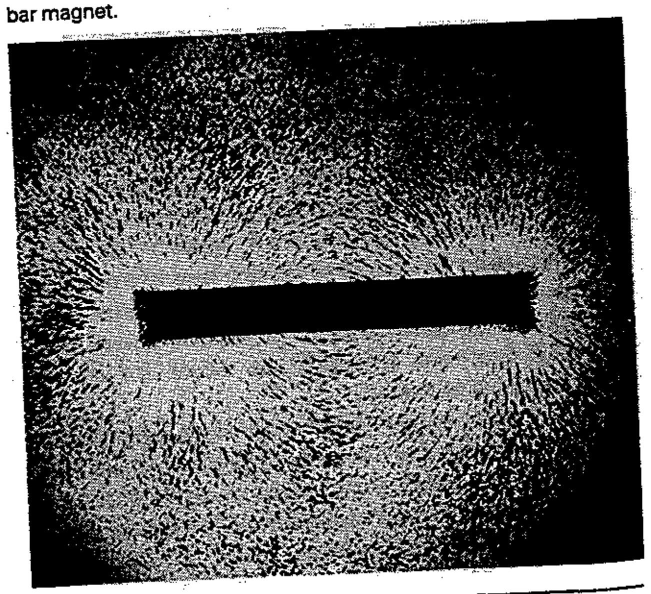
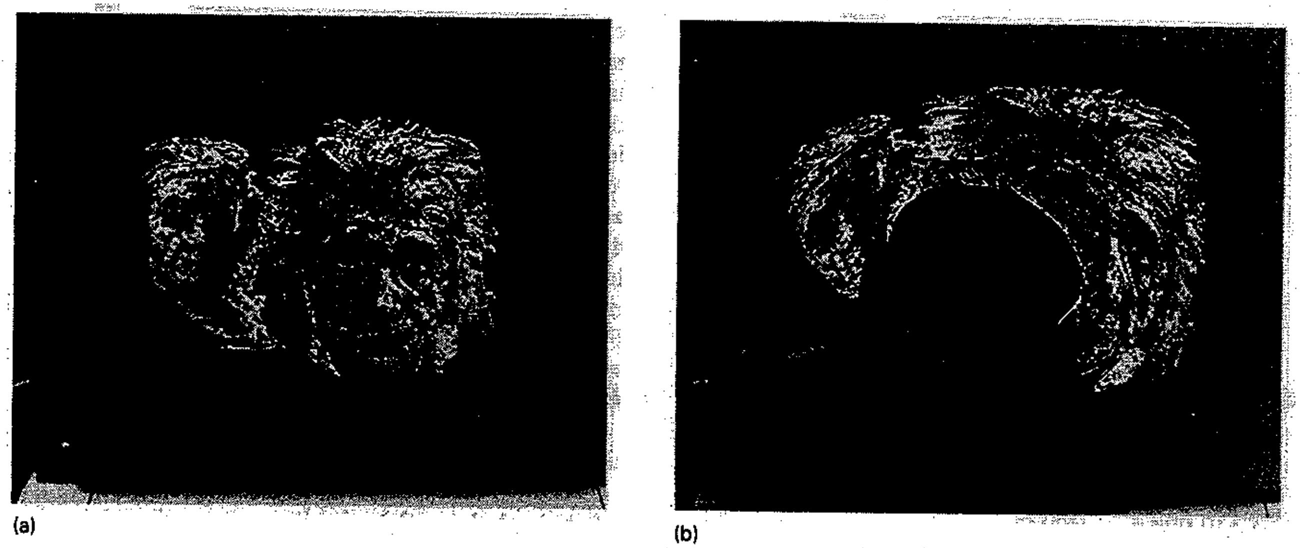


FIGURE 4.9

(a) A computer-generated sketch of Albert Einstein. **(b)** The magnetic field from a U-shaped magnet interacts with electrons streaming toward the computer screen and distorts Einstein's image. Don't do this experiment with a color television; the magnetic field can produce misalignment of the color projection apparatus.


(a)
(b)

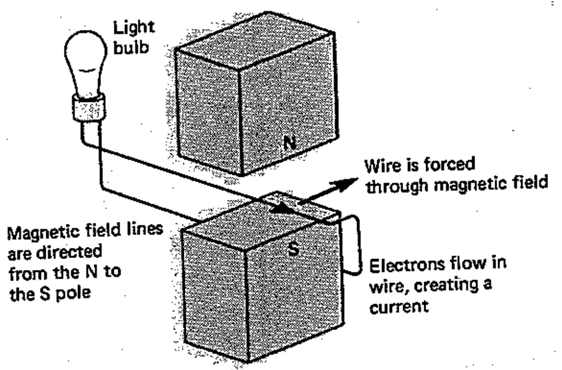
Images on a television set are produced by electrons impacting with the screen. If you place a magnet near the face of a black-and-white television set or computer monitor, the picture distorts (Fig. 4.9). The distortion results from an interaction of the moving electrons with a magnetic field produced by the magnet. As a general principle, any moving charge "cutting" magnetic field lines experiences a magnetic force. In Fig. 4.10, magnetic field lines are directed downward from the N pole to the S pole. A wire moved horizontally in the magnetic field "cuts" the magnetic field lines, and all charges in the wire experience a force by virtue of moving in a magnetic field. However, only the free electrons acquire motion in the wire. If the ends of the wire are connected to a light bulb, for example, an electric current is produced in the circuit. Had the wire been moved vertically parallel to the magnetic field lines there would have been no current in the circuit. Work done by the agent moving the wire accounts for the energy acquired by the electrons. This is the principle of an electric generator such as you might find on a bicycle or in an electric power plant. On a bicycle generator the agent moving the wire is a wheel rotating wires mounted on the shaft of the generator. A large steam turbine is the agent in an electric power plant.

We have illustrated the generator principle by holding a magnet fixed and moving the wire in the magnetic field. A current would also be produced if the wire were held fixed and the magnet moved. As long as the wire "cuts" the magnetic field lines, a current results.

If the wire moves in a direction opposite to that shown in Fig. 4.10, the electron current changes direction. Cutting magnetic field lines with an oscillatory motion produces a current whose direction alternates. Such a current is called an *alternating current* (AC). The current produced by a battery (Fig.

FIGURE 4.10

A current is established in a wire when it moves in a magnetic field so as to "cut" the magnetic field lines. If the wire were moved directly from the N to the S pole, no magnetic field lines are cut and no current results.



4.11a) is called *direct current* (DC) because the charge flows in one direction only.

4.9 Electric Generators

A practical electric generator contains a coil of wire that is rotated in a magnetic field. To understand the operation, let us examine a single loop as shown in Fig. 4.12. Metallic slip rings are bonded to the ends of the wire loop. The brushes are metal contacts touching the slip rings mounted on the shaft of the rotating coil. The coil, slip rings, brushes, and connected electrical device form an electrical circuit for a current. The magnet produces a magnetic field whose field lines are directed from the N pole to the S pole. Only the sides of the loop labeled A and B are able to "cut" magnetic field lines. The two segments of the coil labeled A and B always move in opposite directions. Accordingly the current is always in opposite directions in these two segments. The maximum current results when the wires move perpendicular to the magnetic field lines. There is no current in the circuit when the wire segments move parallel to the magnetic field lines. When the segment designated A is at the top of its rotational path, it is moving horizontally to the right. Because the magnetic field lines are directed to the right, the wire is instantaneously moving parallel to the magnetic field lines. At this instant there is no current in the circuit. As the loop rotates, the segments begin "cutting" the magnetic field lines and a current develops in the circuit. When the portion of the loop designated A has moved down to the position shown in Fig. 4.12b, it instantaneously is moving perpendicular to the magnetic field lines. In this position the electron current is at maximum and has the direction shown by the arrows in the loop. The electron current decreases to zero when the coil reaches the position shown in Fig. 4.12c. As the coil rotates further, the electron current increases but also changes direction. It reaches maximum when the coil achieves the position shown in Fig. 4.12d. Finally the electron current drops to zero when the coil returns to the initial starting position. A plot of electron current versus position of the coil, or equivalently time, since the position depends on time, is shown in Fig. 4.12e.

When a toaster, for example, is plugged into an AC household outlet, the current produced in the wires of the toaster continually changes in size and direction. Nevertheless, the current causes the

FIGURE 4.11

(a) When a device such as a light bulb is connected to a battery, electrons flow out of the negative (–) terminal, through the device, and into the positive (+) terminal. This type of current is called direct current and is denoted DC. **(b)** When a device such as a light bulb is connected to an AC household outlet, electrons oscillate back and forth in the conductors.

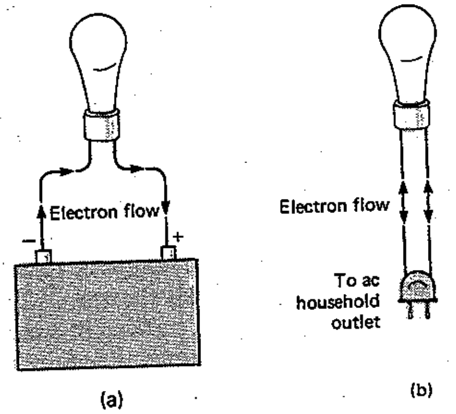
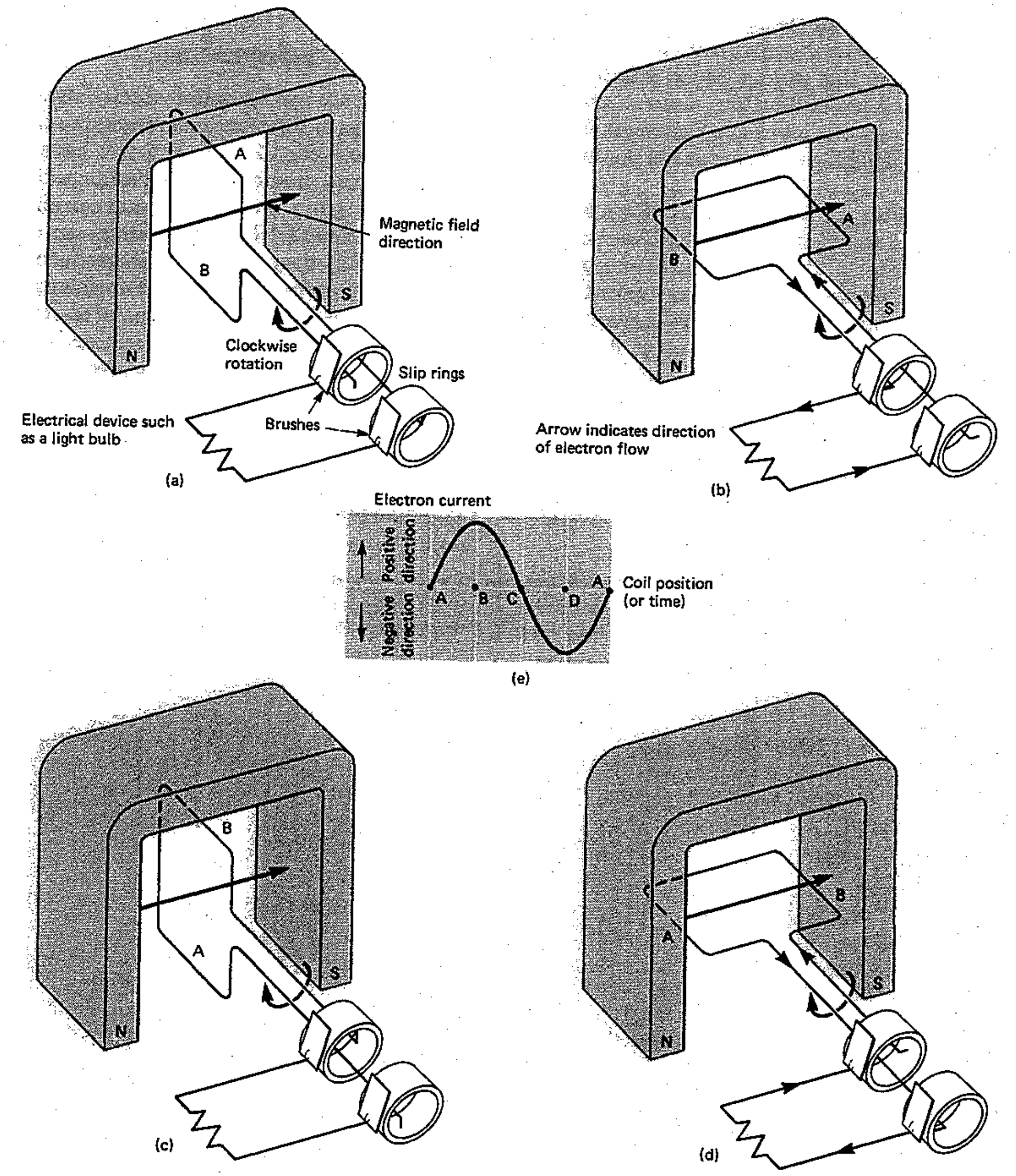


FIGURE 4.12

(a-d) Principle of operation of an AC generator. A current develops in the rotating coil when it moves through the magnetic field created by the magnet. The slip rings rotate with the coil and make electrical contact with the brushes that are connected to an electrical device such as a light bulb or a motor. **(e)** A plot of induced current in the rotating coil of an AC generator. Positive and negative currents are used to distinguish the two directions of charge flow. The letters (A, B, C, D) on the horizontal axis refer to the coil positions designated by parts **(a)**, **(b)**, **(c)**, and **(d)**.



toaster wires to warm. Otherwise we would not be able to toast bread. A household voltage is usually quoted as 120 volts even though we know that the voltage is continually changing in size. This 120-volt rating means that the voltage is as effective at producing heat as a 120-volt battery connected to the toaster. The 120-volt AC label on a light bulb is the effective value of an AC voltage needed to power the bulb.

A generator that provides electricity for a headlamp on a bicycle functions very much like the one illustrated in Fig. 4.12. Mechanical energy is provided by the bicycle wheel rubbing against and rotating a shaft connected to the coil of the generator. The magnetic field is provided by a magnet. A generator like this produces about 5 watts of electric power. While the generator in a commercial electric power plant is enormously larger in physical size and often produces a billion watts of electric power, the basic physical principle is the same. The commercial generator uses a steam turbine for the input mechanical energy and a massive stationary coil with a circulating electric current to provide the magnetic field.

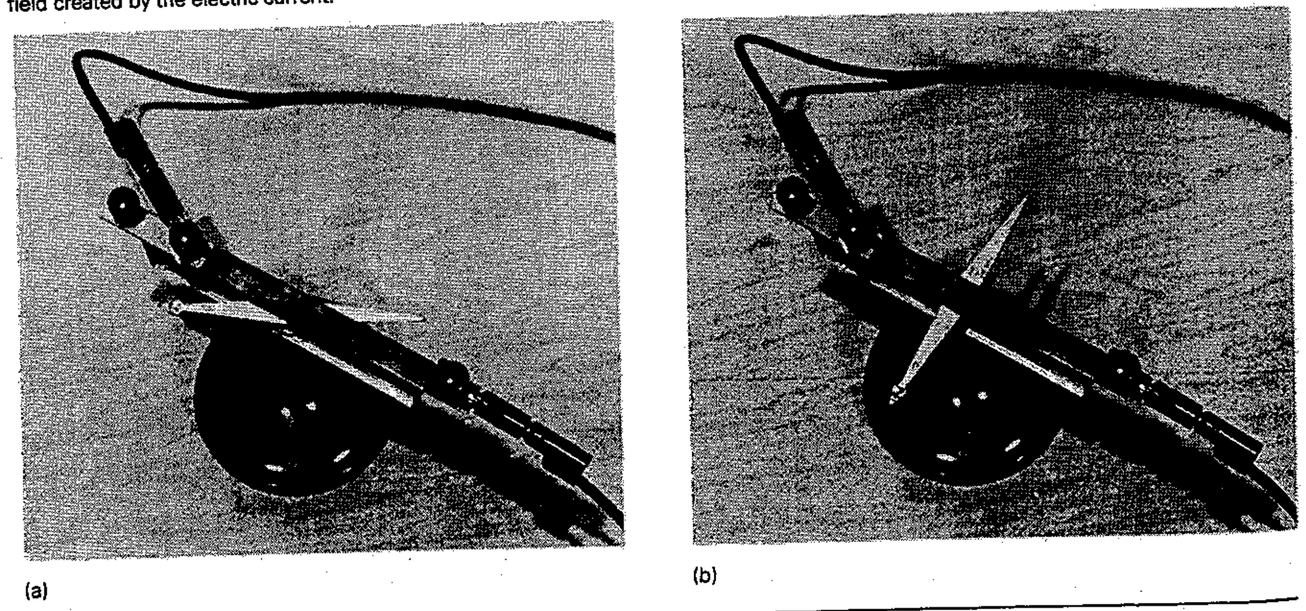
4.10 Transformers

An AC generator and a battery both deliver energy to such things as light bulbs connected to them. If a light bulb requires 12 volts and you have a single battery that can provide 2 volts, it is fairly difficult to use the battery to power a device that can change the voltage from 2 to 12 volts. If AC voltages are involved, it is reasonably easy to tailor voltages using an apparatus called a *transformer*. Transformers play very important roles in the transmission of electric power and in adapting voltages for industrial and household uses. The transformer principle is straightforward.

Figure 4.13a shows a compass below a metal strip in which there is no current. As expected, the N pole of the compass points toward geographic north. When current is established in the strip the compass needle rotates and aligns perpendicular to the strip (Fig. 4.13b). The current in the strip has produced a magnetic field, and the compass needle aligns in the direction of a magnetic field line at the position of the compass. The drawing in Figure 4.14 shows the shape and direction of one of the magnetic field lines. Changing the battery connections reverses the current direction as well as the direction assumed by the compass. Reversal of the compass signals a change in the direction of the magnetic field line. If the battery that produces a current in only one direction is replaced by an AC voltage, the current changes direction periodically and the magnetic field lines change accordingly. If a loop of wire is placed in this changing magnetic field, an alternating current develops in it because, as they change, the magnetic field lines "cut" the wire of the loop. It is just as if the magnetic field lines were put in motion by moving a magnet. This principle is used in transformers to change the size of an AC voltage. The little black box you often see connected to an electrical outlet and to a portable computer to recharge the computer's battery is a transformer that reduces the outlet voltage from 115 volts to around 12 volts.

FIGURE 4.13

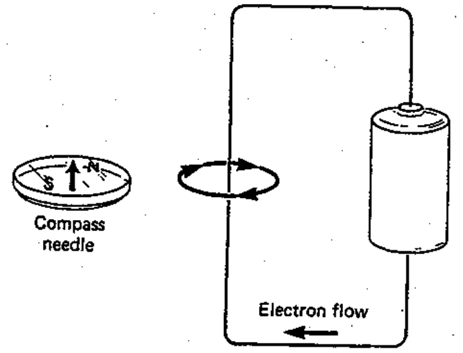
(a) A ribbonlike metal strip is located above the compass needle. With no electric current in the strip the needle aligns with its N pole pointing toward the north geographic pole. **(b)** With sufficient current in the strip, the needle orients perpendicular to the strip because of a magnetic field created by the electric current.



A transformer has two distinct coils of wire wound onto an iron core (Fig. 4.15). One of the coils, called the primary, is connected to an AC voltage such as at the outlet in a house. The other coil, called the secondary, is connected to an electrical device such as a light bulb. The AC current in the primary coil produces magnetic field lines that are guided into the secondary coil by the iron core. The interception of the magnetic field lines by the secondary coil produces a current in the secondary coil. Experiment shows that the ratio of the primary and secondary voltages is equal to the ratio of the number of turns of wire in the primary and secondary coils of the transformer. In symbols,

FIGURE 4.14

An ordinary compass used to determine the presence and direction of a magnetic field around a current-carrying wire. If the direction of the current is changed, the compass needle will point in the opposite direction.



$$\frac{V_S}{V_P} = \frac{N_S}{N_P}. \tag{4.6}$$

To see the utility of the transformer, let us use Eq. 4.6 to relate the primary and secondary voltages by

$$V_S = \frac{N_S}{N_P} V_P.$$

Door chimes in houses often require 6 volts for their operation. Suppose the voltage available at an outlet is 120 volts. If a transformer has twenty times more turns on the primary than on the secondary so that $N_S/N_P = 1/20$, then the secondary voltage will be 6 volts when the primary voltage is 120 volts. The primary is connected to the available 120 volts and the secondary is connected to the chimes.

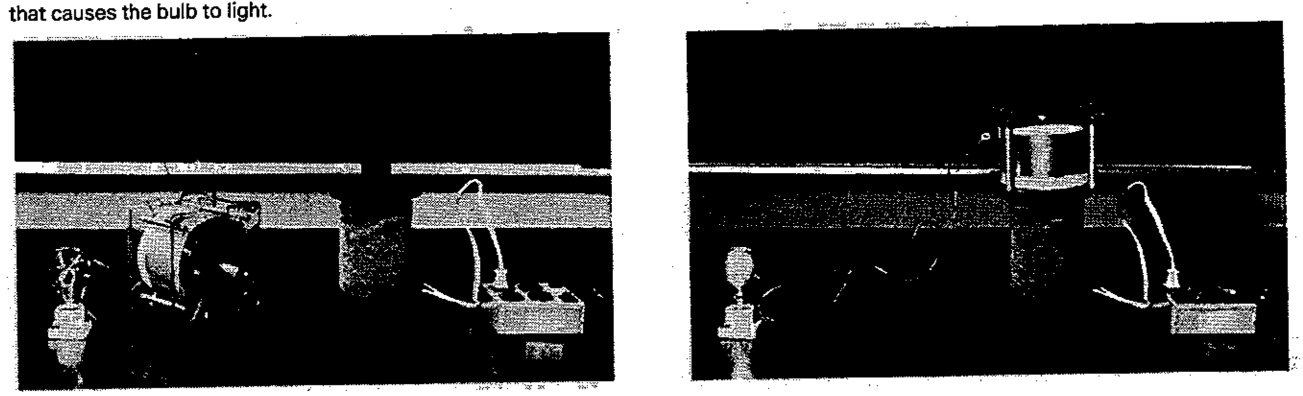
The secondary of a transformer delivers electric power to whatever is attached to it. This electric power has its origin in the source connected to the primary. Conservation of energy prohibits obtaining more power in the secondary than was supplied in the primary. Transformers tend to warm, indicating that some of the power supplied in the primary appears as heat so that the secondary power is always less than that in the primary. In a well-designed transformer the efficiency for energy transfer is around 99%. The ability of a transformer to tailor voltages and its very high efficiency makes it an extremely useful device.

4.11 Transmission of Electric Power

A large generator in an electric power plant may deliver 1 billion watts at a voltage of 10,000 volts.

FIGURE 4.15

Essentially, a transformer consists of two coils of wire (the primary and the secondary) and an iron core to guide the magnetic field lines from the primary coil to the secondary coil. In **(a)** the secondary coil, which has a light bulb connected to the ends of the coil, is isolated from the iron core of the primary coil, which has its ends connected to a 120-volt electrical outlet. There is no current in the secondary coil and the bulb is not lit. In **(b)** the secondary coil is placed over the iron core. A changing magnetic field within the secondary coil induces an electric current that causes the bulb to light.



(a) (b)

Using the relation between power, voltage, and current ($P = VI$), it follows that the current is about 100,000 amperes in the wires leading from the generator. Current in a wire produces heat that depends on the current and resistance according to $P = I^2R$. The resistance of a transmission line is relatively large because its length may be hundreds of miles. A current of 100,000 amperes in such a line would produce significant heat, which amounts to a loss in energy. A power company can maintain the same power in the transmission lines and reduce the heat losses by placing a transformer between the generator and the transmission lines (Fig. 4.16). The transformer steps up the voltage to as much as 75 times the 10,000-volt generator output. The current in the transmission lines as well as the heat losses drop accordingly. Energy saved this way in transmission is energy available to consumers.

At a home where electric power is used, the voltage is stepped down to 230 volts by a series of transformers. By tapping the secondary of the transformer at the midpoint of the windings (Fig. 4.17), 115 volts are obtained between the center tap and either of the outer connections to the secondary. The center tap becomes the ground connection (see Section 4.4). The 230-volt connection provides power for large applications such as electric stoves, water heaters, clothes dryers, and air conditioners. The 115-volt connections are used for such things as light bulbs, mixers, vacuum cleaners, and toasters. Homeowners often use small transformers to reduce 115 volts to 6 volts for operating doorbells and door chimes. In addition to the 115 volts and 230 volts used in a home, a factory will often use still higher voltages for some operations.

4.12 Meeting Consumer Demands for Electricity

Take a look at a bicycle equipped with a small electric generator for powering a headlight and you see two wires leading from the generator to the light. An on-off switch on the headlight completes the electrical circuit when light is desired. As long as the switch is off, there is no current in the light and a rider does no work against electric forces. Turn the switch on and a current develops. Then the rider must do work to supply the energy delivered to the light. The energy is not stored in the generator and delivered on request. Electric energy is produced on demand. If the cyclist requires no light and keeps the switch off, the generator delivers no energy anywhere. An automobile uses a battery to store energy and deliver energy to headlights and other units on demand. A form of electric generator called an alternator replenishes energy to the battery. Although this scheme works very well for an automobile, it is impractical for electric power plants to store large amounts of energy in batteries. Consequently, a large electric power plant produces electricity on consumer demand. If there is no demand, the generators shut down. Once switches are turned on in factories and homes, the electrical connection triggers:

1. the production of heat by burning coal or fissioning uranium,
2. the vaporization of water (boiling) to produce steam, and
3. the injection of steam to a turbine to spin a shaft coupled to an electric generator.

FIGURE 4.16

Elements of an electric power transmission system.

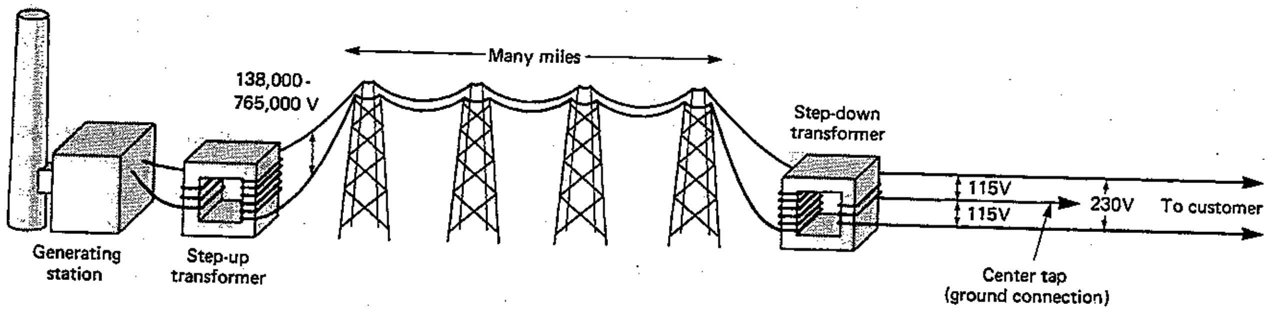
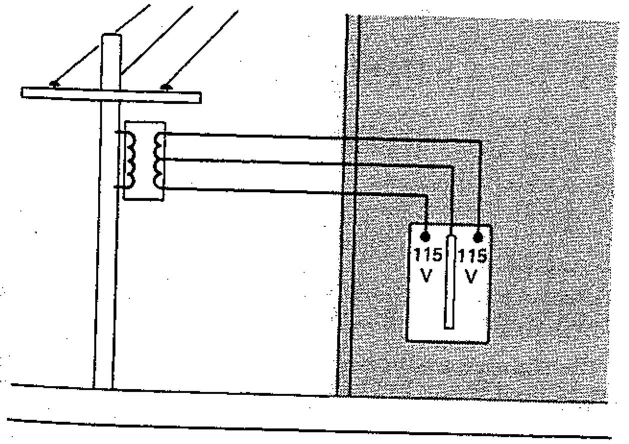


FIGURE 4.17

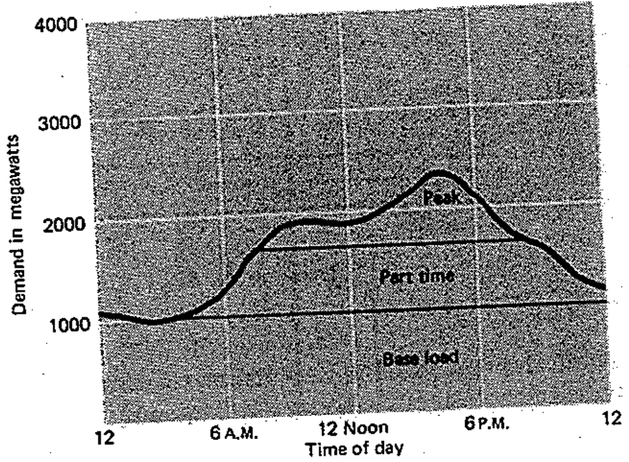
The manner of providing electric power for a household. Near the house there is a transformer usually mounted near the top of a utility pole. Electrical connections are made to the ends and midpoint of the secondary coil of the transformer. Wires from these three connections lead to a circuit-breaker box in the house. The consumer connects wires to the center terminal and either of the two outer terminals to obtain 115 volts; connections to the two outer terminals yields 230 volts.



The utility must be prepared to meet demands that vary throughout the day, the week, and the year. A representative hourly demand is shown in Fig. 4.18. The demand is divided into three parts termed *base load*, *part time*, and *peak*. Base load demand is met with large units having slow response. Usually these units are fueled by coal or uranium. They may be large hydroelectric plants. Base load electricity is the most economical of the three categories. If demand were constant, only base load electricity would be needed. The demand labeled "part time" is generally provided by the large units used for base load. Peak demands requiring fast response are met with oil- and gas-fired turbogenerators, hydroelectricity, pumped-storage hydro systems, purchases from other utilities and, in a few cases, wind-powered generators and solar-powered systems. Peak electricity may cost three to four times more than base-load electricity. Economi-

FIGURE 4.18

Hourly demand for electricity.



cally it is in the interest of both the electric utility and the consumer to make an effort to "flatten out" the demand curve. To do this, a utility sometimes offers a cheaper late nighttime rate for electricity.

4.13 Energy and Emissions Model of a Fossil-Fuel Electric Power Plant

Most commercial electric generators in the United States are driven by steam turbines. Water vaporized by the heat generated from burning fossil or nuclear fuels is forced onto blades attached to the shaft of the turbine (Fig. 4.19). It is akin to rotating a pinwheel by blowing air onto it. With this basic model in mind, we can expand the system to that shown in Fig. 4.20. Several of the major components of this process are identified in the commercial facility shown in Fig. 4.21. These diagrams serve as a flow chart for energy and are useful for obtaining quantitative information. So let us "dump" 1000 pounds of coal (1000 pounds of coal would occupy a cubic space about 3 feet on a side) into the hopper and see how much electric energy comes out and what by-products evolve along the line.

If you have ever started a campfire or a fire in a fireplace, you know that the fire starts most easily with small pieces of wood. This is because a stack of small pieces has more surface area than a single piece of the same weight, and burning takes place at the surface. For this same reason coal is pulverized to a powder to optimize burning. The pulverized product includes unburnable particles (ash) and sulfur along with the burnable carbon-based content. When burned, the sulfur combines with oxygen to form gaseous sulfur oxides. Unless controlled, the sulfur oxides and particulates escape out the smokestack. Assessing power plant performance requires a knowledge of the energy content, sulfur, and unburnables in the coal. These data are rather easy to come by,[*] but there is a large variation in quality.

A "typical" coal from the vast West Virginia coalfields might contain 72% carbon and 2.5% sulfur. For each pound burned, this coal produces about 13,000 Btu of heat, 0.05 pounds of sulfur oxides, 0.1 pound of ash, and 2.6 pounds of carbon dioxide (if all the carbon is converted to carbon dioxide). Let's now follow the 1000 pounds of coal through the power plant assuming the boiler, turbine, and electric generator have energy conversion efficiencies of 88%, 47%, and 99%, respectively.[**]

Boiler

$$\begin{array}{l}\text{Energy}\\ \text{available at}\\ \text{the boiler}\end{array} = \begin{bmatrix}\text{energy}\\ \text{available per}\\ \text{pound of coal}\end{bmatrix} \times \text{number pounds}$$

$$= 13{,}000\,\frac{\text{Btu}}{\text{pound}} \times 1000 \text{ pounds}$$

$$= 13{,}000{,}000 \text{ Btu}$$

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[*] *Handbook of Chemistry and Physics*, CRC Press, 2000 Corporate Blvd. N.W., Boca Raton, FL 33433.

[**] The efficiencies used in these calculations were taken from "The Conversion of Energy" by Claude M. Summers in the book *Energy*, W. H. Freeman, San Francisco, 1979. The definition of efficiency is given in Section 2.10.

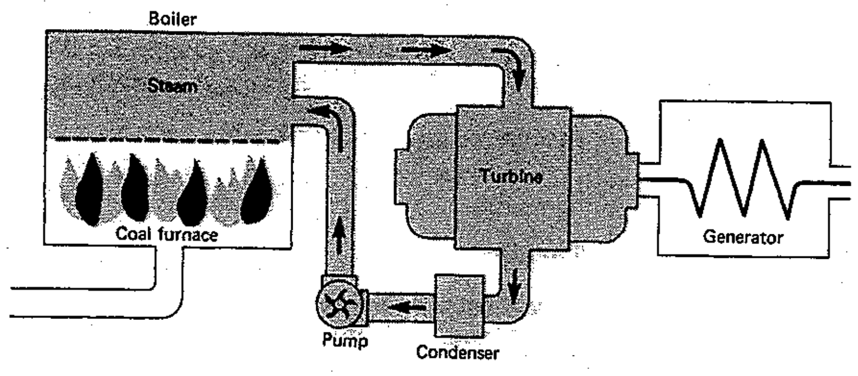


FIGURE 4.19

Schematic representation of the generation of electricity. High-pressure steam impinges on the blades of a turbine producing rotational mechanical energy. The turbine rotates the generator shaft and the mechanical energy is converted to electric energy. The condenser converts the steam back into water and the pump circulates the water through the boiler.

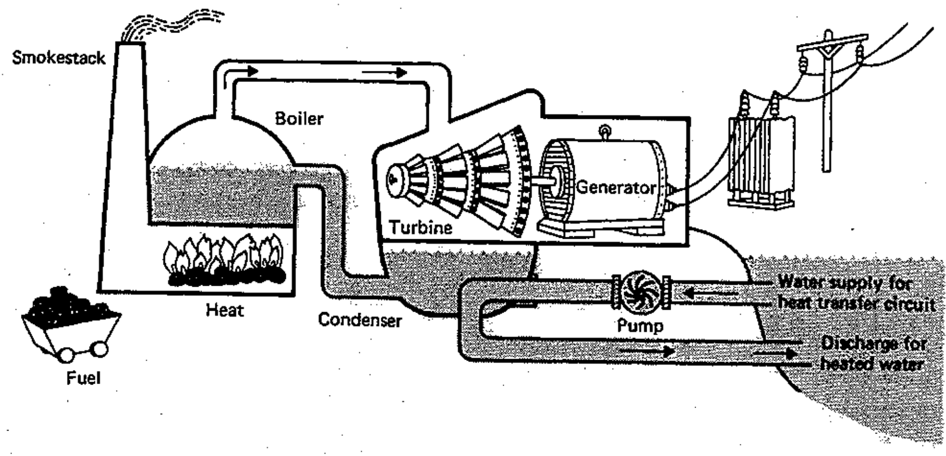


FIGURE 4.20

Major energy components of an electric power plant.

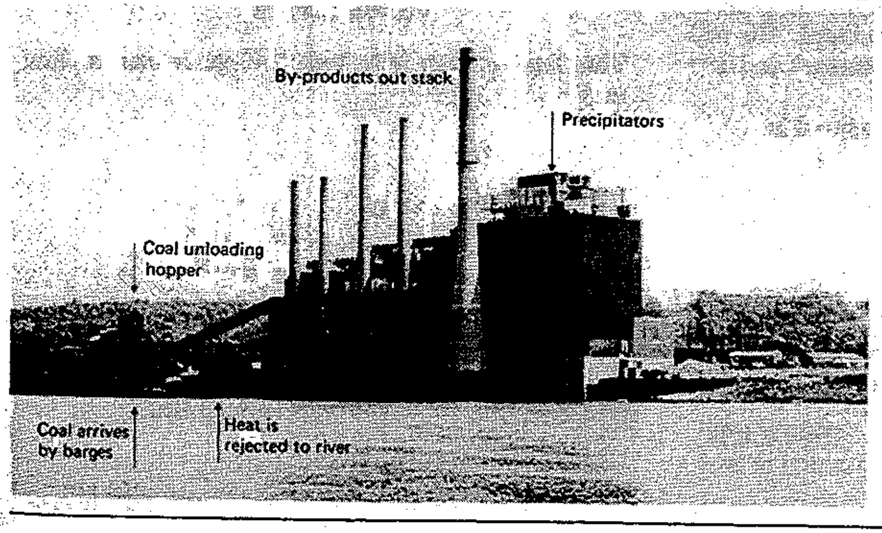


FIGURE 4.21

The Cincinnati Gas and Electric Company Beckjord Station, located on the Ohio River. Several of the components shown schematically in Fig. 4.19 are identified in this photograph. (Photograph courtesy of The Cincinnati Gas & Electric Company.)

$$\text{Energy into the turbine} = \begin{bmatrix}\text{energy}\\ \text{in the}\\ \text{boiler}\end{bmatrix} \times \begin{bmatrix}\text{conversion}\\ \text{efficiency}\\ \text{of boiler}\end{bmatrix}$$

$$= 13{,}000{,}000 \text{ Btu} \times 0.88$$

$$= 11{,}440{,}000 \text{ Btu.}$$

The energy that doesn't enter the turbine escapes, or is released, mostly through the smokestack.

$$\text{Energy out the smokestack} = \begin{bmatrix}\text{energy}\\ \text{into the}\\ \text{boiler}\end{bmatrix} - \begin{bmatrix}\text{energy}\\ \text{into the}\\ \text{turbine}\end{bmatrix}$$

$$= 13{,}000{,}000 \text{ Btu} - 11{,}440{,}000 \text{ Btu}$$

$$= 1{,}560{,}000 \text{ Btu.}$$

The sulfur oxides and carbon dioxide are produced when the coal is burned. The amount of sulfur oxides produced when 1000 pounds are burned is

$$\text{sulfur oxides (pounds)}$$

$$= 1000 \text{ pounds} \times 0.05 \frac{\text{pounds}}{\text{pound of coal}}$$

$$= 50 \text{ pounds.}$$

These oxides do not necessarily escape out the smokestack if there is some mechanism installed to remove them. Modern power plants are equipped to remove about 90% of the sulfur oxides produced. We will assume that 5 pounds go out the smokestack and into the atmosphere.

The amount of carbon dioxide produced is

$$\text{carbon dioxide (pounds)}$$

$$= 1000 \text{ pounds} \times 2.6 \frac{\text{pounds carbon dioxide}}{\text{pound of coal}}$$

$$= 2600 \text{ pounds.}$$

The carbon dioxide is vented to the atmosphere. The ash is an unburnable product in the coal.

$$\text{Ash (pounds)} = 1000 \text{ pounds} \times 0.1 \frac{\text{pounds ash}}{\text{pound of coal}}$$

$$= 100 \text{ pounds.}$$

Most power plants have facilities for removing about 99% of the ash. Hence 1% escapes to the environment.

$$\text{Amount escaping} = 100 \text{ pounds} \times 0.01$$

$$= 1 \text{ pound.}$$

Turbine

$$\text{Energy out the turbine and into generator} = \begin{bmatrix}\text{energy}\\ \text{into}\\ \text{turbine}\end{bmatrix} \times \begin{bmatrix}\text{conversion}\\ \text{efficiency}\\ \text{of turbine}\end{bmatrix}$$

$$= 11{,}440{,}000 \text{ Btu} \times 0.47$$

$$= 5{,}377{,}000 \text{ Btu.}$$

The low value for this efficiency is probably the most difficult thing to accept in this discussion. However, there is a practical limit to the efficiency of a steam turbine imposed by the physical laws of thermodynamics. This is discussed in Chapter 8.

Condenser

$$\text{Heat energy rejected to condenser} = \begin{bmatrix}\text{energy}\\ \text{into}\\ \text{turbine}\end{bmatrix} - \begin{bmatrix}\text{energy}\\ \text{into}\\ \text{generator}\end{bmatrix}$$

$$= 11{,}440{,}000 - 5{,}377{,}000 \text{ Btu}$$

$$= 6{,}063{,}000 \text{ Btu.}$$

This heat energy goes into the condenser cooling water.

Generator

$$\text{Energy out of generator} = \begin{bmatrix}\text{energy}\\ \text{into}\\ \text{generator}\end{bmatrix} \times \begin{bmatrix}\text{conversion}\\ \text{efficiency}\\ \text{of generator}\end{bmatrix}$$

$$= 5{,}377{,}000 \text{ Btu} \times 0.99$$

$$= 5{,}323{,}000 \text{ Btu} \times \frac{\text{kWh}}{3413 \text{ Btu}}$$

$$= 1560 \text{ kWh.}$$

Burning the 1000 pounds of coal would produce enough electric energy to run a 1560-watt (1.56 kW) air conditioner for 1000 hours.

With these numbers, the model of Fig. 4.20 can be quantified as in Fig. 4.22.

This procedure accomplishes several things.

1. Numerical results are obtained for a given set of conditions. This gives a feel for the emissions from a typical power plant.
2. The origin of the emissions in the energy conversion process has been established.
3. Most important, a model applicable to any system of this type has been deduced. Only the numbers are different for another system of the same type.

The magnitude of the emissions cannot be fully appreciated because the element of time has not been considered. A 1000-megawatt unit operating at capacity would use the 1000 pounds of coal in about 5 seconds. This means that about 10,000 tons of coal are used per day and this would produce 500 tons of sulfur oxides, 26,000 tons of carbon dioxide, and 1000 tons of particulates.

4.14 Coping with Particulate Matter

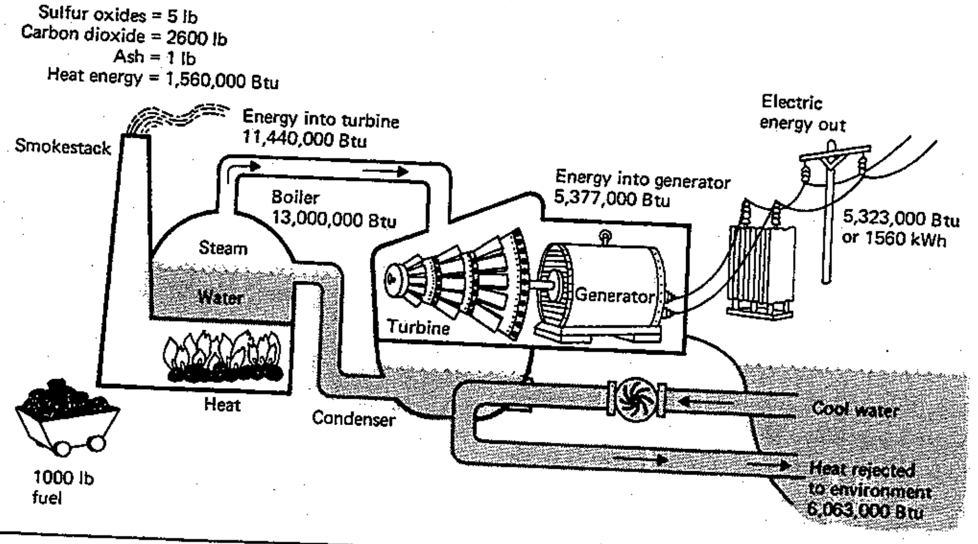
• General Properties

Particulate matter emerging from the smokestack of a coal-burning electric power plant (Fig. 4.23) enters the atmosphere in the form of fine, solid particles.* These particles mix with contributions from many other sources of solid and liquid pollutants. Particulates are classified by a length even though they generally have jagged shapes. The length is associated with an assumed geometric shape. For simplicity, we presume spherical particulates and use the concept of mass density to infer the diameter.

Mass density is defined as

FIGURE 4.22

Typical outputs for conversion of 1000 pounds of coal into electric energy.



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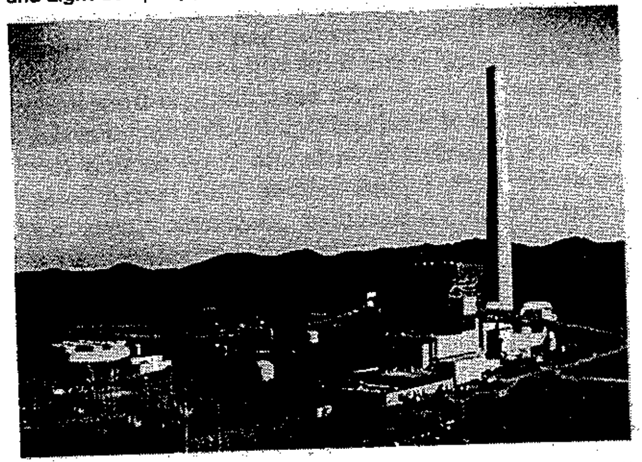
* The word *aerosol* is often used interchangeably with *particulate*. Some scientists, though, prefer to consider aerosols as particulates with diameters less than some specific value, for example, 0.0001 meters.

FIGURE 4.23

The Killen Electric Generating Station near Manchester, Ohio, on the Ohio River is a modern coal-fired electric power plant. More than 99% of the mass of the particulates produced are captured before entering the atmosphere. (Photograph courtesy of Dayton Power and Light Company.)



$$\text{mass density} = \frac{\text{mass of an object}}{\text{volume occupied by the mass}},$$

$$\rho = \frac{M}{V}.$$

One cubic meter of water has a mass of 1000 kilograms. Its mass density is 1000 kg/m^3 or 1 g/cm^3 (1 gram per cubic centimeter). If you measure the mass of a certain amount of water to be 10 grams, then you know its volume is 10 cm^3. Similarly, if the density of particulate matter is 2 g/cm^3 and its mass is known from some measurement, you can compute its volume from the expression

$$V = \frac{M}{\rho}.$$

To illustrate, if a given particulate has a mass of one millionth of a gram (10^{-6} g) and a density of 1 g/cm^3, it has a volume of one millionth (10^{-6}) of a cubic centimeter. Rolled into a tiny ball it would have a diameter of 0.012 centimeters. A dime has a diameter of about 1 centimeter, so the diameter of the particulate would be about one hundredth the diameter of a dime. This is a fairly large particulate. The sizes of particulates range from about 0.000 000 02 cm to 0.05 cm. Rather than work with such very small numbers, it is common to express these lengths in terms of a millionth of a meter (or one ten-thousandth of a centimeter). One millionth of a meter is called a micrometer and is symbolized µm. On the micrometer scale, the particulate range 0.000 000 02 cm to 0.05 cm would be 0.0002 µm to 500 µm.

Particulate concentrations in the atmosphere are reported as the total mass contained in a cubic meter of air. Typical units are micrograms per cubic meter, symbolized µg/m^3. Concentrations range from about 10 µg/m^3 in remote nonurban areas to 2000 µg/m^3 in very heavily polluted regions. Over 1400 stations monitor particulate concentrations throughout the United States. Since 1977 the average concentration has dropped from 63 µg/m^3 to 48 µg/m^3 in 1986. Even though the concentrations vary substantially throughout the country, the percentage having a particular size is essentially the same everywhere. Most of the particulates are very small—less than 0.1 µm in length. Larger particulates account for about 95% of the total mass. Relatively few particulates account for the bulk of the mass. However, smaller-sized particles may be more damaging to people than the larger-sized particles. It may be more important to reduce the number of smaller-sized particles than to reduce the concentration of mass, which favors elimination of the larger particles. The sizes and origin of atmospheric particulates are shown in Fig. 4.24.

Of the several environmental concerns over particulates in the air, the following are noteworthy.

1. Particulates settling to the ground produce annoying grime, requiring energy and money to remove.
2. Particulates produce effects detrimental to materials, plants, and animals, including human beings.
3. Accumulation of particulates in the atmosphere may alter the heat balance of the earth through reflection and absorption of solar radiation.

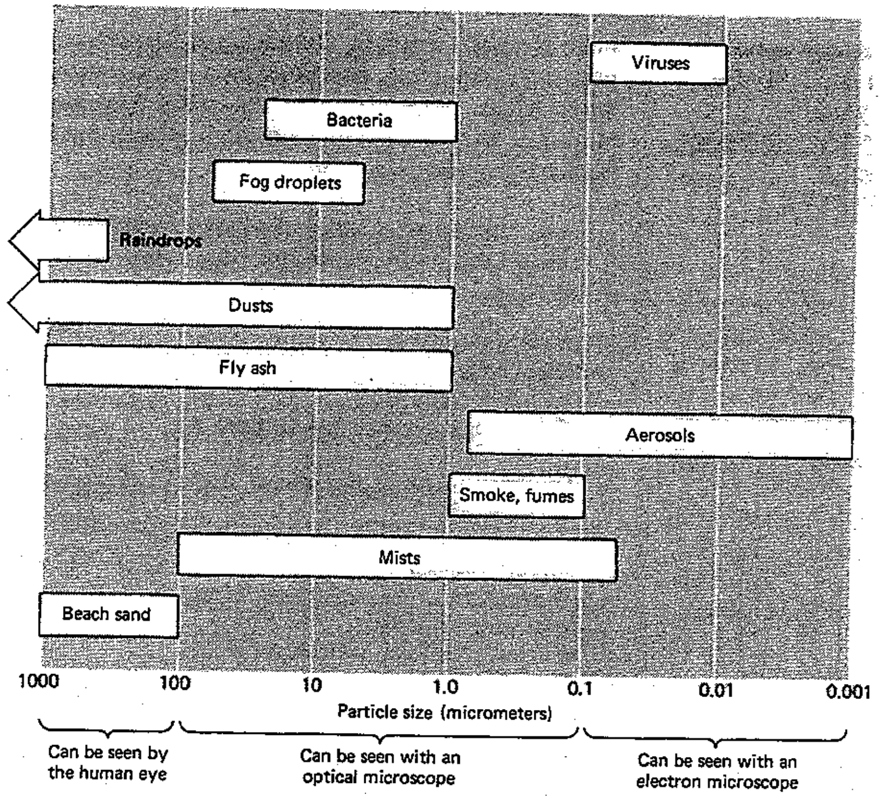


FIGURE 4.24

The sizes and origin of atmospheric particulates. Note that aerosols are labeled as particulates with diameters of less than one micrometer. To obtain a feel for the size scale, think about raindrops and beach sand that can be seen with the naked eye. Baby powder is much finer, each particle ranging from about 0.5 to 50 micrometers.

• Settling of Particulates in the Atmosphere

A solid plastic sphere falling in a fluid such as oil is pulled downward by gravity and held back by (1) a viscous force (drag) exerted by the fluid on the sphere, and (2) a buoyant force tending to float the sphere. The viscous force is akin to that exerted on your hand when you hold it out the window of a moving car. A buoyant force causes a child's helium-filled balloon to rise. The viscous force increases as the falling sphere gains speed. Ultimately the gravitational force is balanced by the opposing viscous and buoyant forces and the sphere descends with constant speed. Any size sphere eventually achieves constant speed, but the limiting speed of spheres made of the same material increases as the diameter increases. This size effect is easily discernible when you drop a handful of sand in a vat of water and observe which grains reach the bottom first. Particulates in the atmosphere are not plastic spheres and their motion is influenced greatly by winds, but the larger ones settle faster for exactly the same reason. Smaller particulates sometimes become permanently airborne and do not settle at all. A simple calculation using the rate concept shows why.

Table 4.5 shows the relation between settling speed and particulate diameter. Let us determine the time it takes a 1-micrometer-diameter particulate to settle 1 kilometer (0.62 mile). A 1-micrometer diameter particulate has a settling speed of 0.004 centimeters/second. Thus

$$\text{settling time} = \frac{\text{distance traveled}}{\text{settling speed}}$$

$$= \frac{100{,}000 \text{ centimeters}}{0.004 \text{ centimeters / second}}$$

TABLE 4.5

Approximate Settling Speeds in Still Air for Particles Having a Density of 1 g/cm^3

DIAMETER (micrometers)	SETTLING SPEED (centimeters/second)
0.1	0.000 08
1	0.004
10	0.3
100	25
1000	390

From *Air Quality Criteria for Particulate Matter*, National Air Pollution Control Administration publication No. AP-49.

$$= 25{,}000{,}000 \text{ seconds}$$

$$= \frac{25{,}000{,}000 \text{ seconds}}{3600\ (24) \text{ seconds / day}}$$

$$= 290 \text{ days.}$$

Particulates with diameters smaller than 1 micrometer settle so slowly that they tend to migrate thousands of miles before settling to the ground. It is not uncommon to find that dust particles characteristic of the earth in Arizona have migrated as far east as New York. Or to find radioactive debris from nuclear bomb tests migrating across the Pacific Ocean to the west coast of the United States. Permanently airborne particulates cause concern for long-term weather effects (see Chapter 7).

• Federal Standards for Particulate Concentrations

The 1970 Clean Air Act empowered the Environmental Protection Agency to set air quality standards for designated pollutants, and to promulgate and enforce the standards. Primary standards define levels of air quality judged necessary to protect the public health with an adequate margin of safety. Secondary standards define levels of air quality judged necessary to protect public welfare; for example, by protecting property, materials, and economic values. A state may impose more stringent measures but cannot relax the standards. The federal standards for particulates are the following.

The maximum average 24-hour concentration that is not to be exceeded more than once per year is:

primary standard
260 micrograms per cubic meter of air,
secondary standard
150 micrograms per cubic meter of air.

The annual geometric mean[*] concentration cannot exceed:

primary standard
75 micrograms per cubic meter of air,
secondary standard
60 micrograms per cubic meter of air.

To improve and maintain air quality, particulate emission limits are placed on coal-fired boilers. The 1970 Clean Air Act restricted particulate emissions to 0.1 pound for each million Btu of heat derived from burning.[**] An Appalachian coal having 10% unburnable ash and liberating 12,000 Btu of heat per pound when burned produces 8.3 pounds of particulates per million Btu. Thus the act requires capturing over 98% of the particulates generated. Still stricter limits were placed on coal-fired units built after September 18, 1978. These systems can liberate to the environment no more than 0.03 pound of particulates for each million Btu produced. This means that more than 99% of the particulates generated must be collected. Following the Clean Air Act of 1970, annual particulate emissions dropped from 18.5 million tons in 1970 to 10.6 million tons in 1975. By 1986, they had dropped to 6.8 million tons per year.

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[*] The most familiar mean (or average) value is formally called the arithmetic mean and is obtained by summing the quantities of interest and dividing by the number of quantities. For example, the average class grade for an examination is determined by adding all the grades and dividing by the number of students. The geometric mean is obtained by multiplying the quantities of interest and taking the *N*th root of the product where *N* is the number of quantities. For example, if 25 students took an examination, the geometric mean would be the 25th root of the product of all 25 grades.

[**] House bill H.R. 3030 and Senate bill S. 1630 include major revisions to the Clean Air Act that separately have been passed by the two legislative bodies. At the time of this writing mutually-agreeable revisions have not been enacted into law.

• Particulate Collection Devices

No single particulate collection device can capture particulates of all sizes. Accordingly, a utility employs combinations of collectors, each of which works efficiently for a range of sizes. The most common collectors are called *gravitational*, *cyclone*, *electrostatic precipitator*, and *fabric filtration*. We have at hand the basic principles for understanding their operation.

Gravitational Collector. The principle of the gravitational collector is shown in Fig. 4.25. Gases containing a suspension of particulates from fuel combustion enter a large chamber. Like particulates in the atmosphere, they are influenced by the gravitational force of the earth (pulling down) and retarding forces (viscous and buoyant) due to the gaseous medium. Some of the particles settle enough to be collected at the bottom of the container. As expected from our discussion of particulates settling in the atmosphere, the ones of larger diameter settle fastest and are the ones most likely to be collected.

Gravitational collectors are simply conceived and relatively maintenance free, but they function efficiently only for particulate diameters greater than about 50 micrometers.

Cyclone Separator. A rapidly swirling air mass is loosely referred to as a *cyclone*. Such a condition is created with the combustion gases in a cyclone separator. Particulates are forced to the outer edge of the cyclone, where they can be collected. In a cyclonic separator, the gas containing the particulates is forced down through a tapered cylinder to produce cyclonic action (Fig. 4.26). The particulates move toward the walls of the cylinder; some strike the walls and fall into a collection bin. A cyclone separator collects particulates with diameters as small as 5 micrometers.

Electrostatic Precipitator. An electrostatic precipitator is the most efficient device for removing particulates with diameters smaller than 5 micrometers. It is based on the attractive electric force between unlike charges. In principle, the precipitator is a hollow cylindrical container with a wire along the axis of the cylinder (Fig. 4.27). A large voltage is maintained between the central wire and

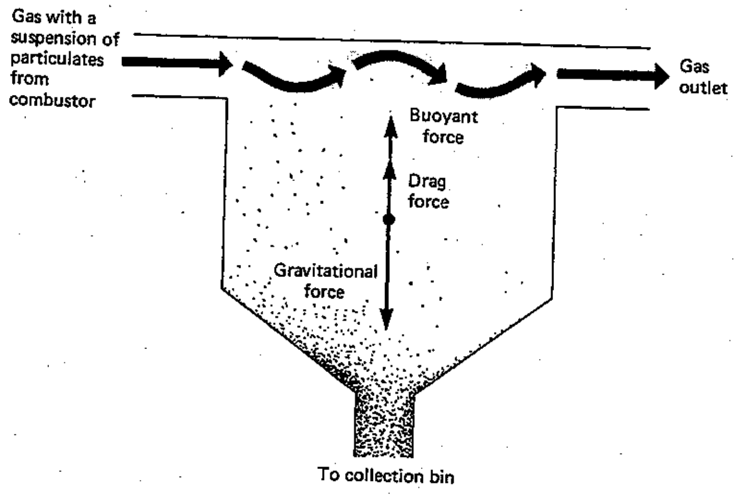


FIGURE 4.25

Basic physics of a gravitational collector. Particulates are influenced by forces exactly like particulates in the atmosphere. The gravitational force pulls them downward; a viscous (drag) force and a buoyant force due to the air oppose the downward motion.

FIGURE 4.26
Basic physics of a cyclone particulate collector. The cyclonic air motion forces particulates toward the walls of the collector. When the particulates strike the wall, they fall into a collection bin.

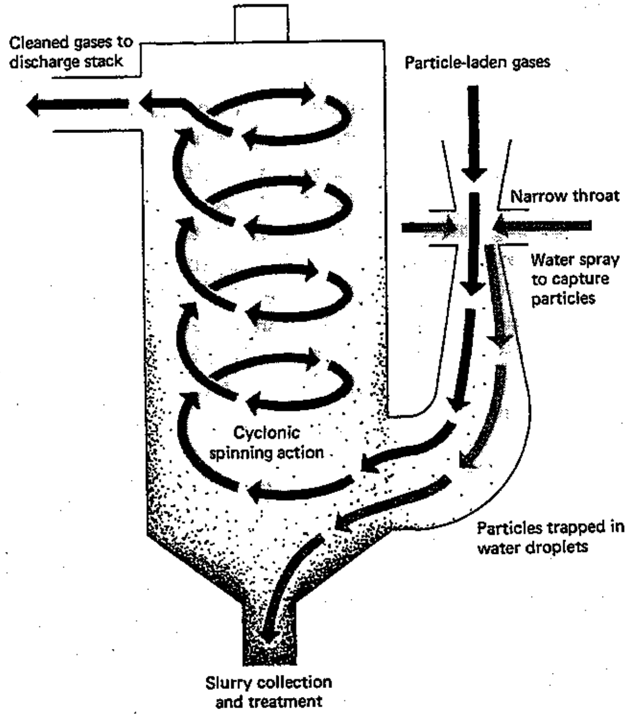
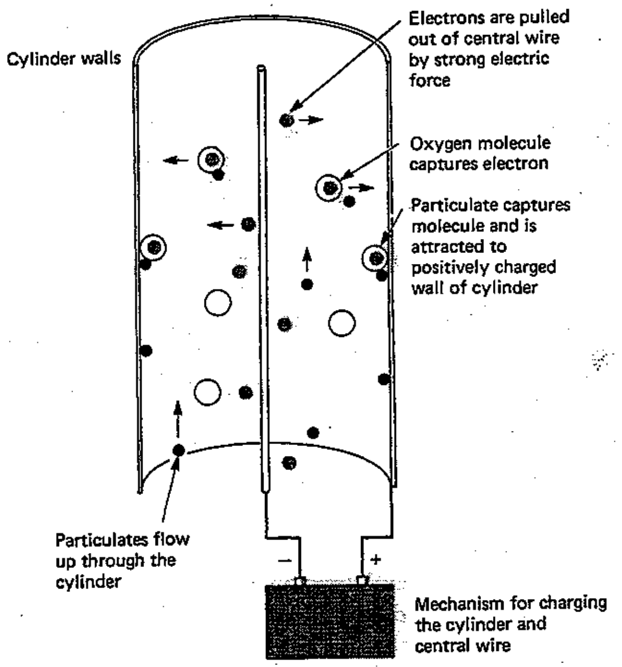


FIGURE 4.27
Basic physics of an electrostatic precipitator. The particulates, having acquired a net negative charge, are attracted toward the wall of the precipitator. When the particulates strike the wall, they become electrically neutral and fall into a collection bin.



outer housing, with the wire being negative. The electric force experienced by electrons in the wire is sufficiently large to pull electrons from the wire. Electrons, being negatively charged, are attracted to the positive cylinder.

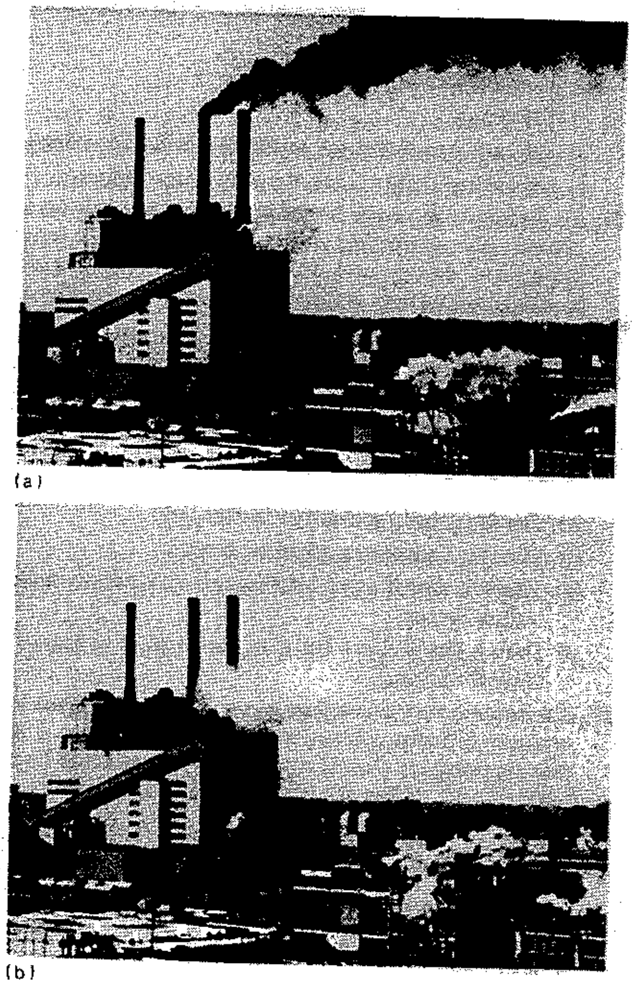
Some gas molecules, such as oxygen (O_2), will capture an electron and acquire a net negative charge (O_2^-). These molecules are accelerated toward the wall of the positively charged cylinder. During transit, the O_2^- ion may cling to a particle and the particle-O_2^- composite migrates toward the wall. Once the composite strikes the wall, it becomes electrically neutral and the electric force vanishes. The particulates are then removed from the walls of the container.

An electrostatic precipator is the most efficient of the systems discussed and is capable of removing 99% of the total mass concentration. However, the efficiency for particulates smaller than 0.1 micrometers in diameter is poor. Even though the precipitator may remove 99% of the mass, only about 5% of the *number* of particulates are accounted for because there are many more smaller particulates. The electrostatic precipitator has difficulty in extracting the small particulates. That electrostatic precipitators are effective is illustrated by Fig. 4.28.

• The Disposal Problem

In 1988 the electric utilities burned about 760 million tons of coal having about 10% unburnable ash. Because the collection efficiency is very good, about 76 million tons of coal ash were collected. For the most part, the ash is taken from the collectors and dumped into ponds where it settles to the bottom. Some commercial use is made of the ash collected but amounts to only about 13% of that collected. Some of the uses are as an aggregate for building bricks, improved traction material for car tires, fire-quenching material for coal mines, and fertility improver for soils.

FIGURE 4.28
The effectiveness of electrostatic precipitators for removing particulates escaping from a smokestack is illustrated in these pictures taken **(a)** without and **(b)** with the electrostatic precipitators in operation. The white clouds appearing in both photographs are composed of water vapor. (Photographs reprinted courtesy of Eastman Kodak Company.)



References

• Electric Energy and Power

Extensive discussions of electricity, electric energy, and electric power are given in most physics and physical science texts. Two useful texts for expansion of the material presented in Chapter 4 are *Physics in Perspective*, Eugene Hecht, Addison-Wesley, Reading, MA, 1980; and *Contemporary College Physics*, Edwin R. Jones and Richard L. Childers, Addison-Wesley, Reading, MA, 1990.

Review

1. Devise an experiment to deduce whether or not a balloon has a net charge.
2. What type of energy is converted by an electric generator? How efficient is the generator in performing its stated function?
3. How is an electric current similar to the flow of water in a pipe?
4. What are the units of electric current, potential difference, power, and energy?
5. Make a sketch of an electrical circuit that includes a household outlet, a switch, and a light bulb.
6. Why are electrical devices producing heat more expensive to operate than household appliances like mixers producing mechanical motion?
7. How does electric power differ from electric energy?
8. What is a kilowatt-hour?
9. Distinguish between alternating current and direct current.
10. What physical principle involving electric charges and a magnetic field is employed in the production of an electric current by an electric generator?
11. Describe in words the function of a transformer. Why is a transformer useful in the transmission of electric power?
12. Why is electric power transmitted at very high voltages?
13. Name the by-products of significance produced by electric power plants using coal for input energy.

14. What is the most inefficient energy conversion device in an electric power plant?
15. Match the equations with the appropriate term and name the quantity going with each symbol.

Ohm's law	$I = Q/t$
voltage	$P = VI$
electric current	$I = V/R$
power	$V = W/Q$
power loss	$P = I^2R$

16. If all lengths can be measured in meters, what is the rationale for introducing the micrometer unit of length for specifying particulate sizes?
17. Why is the settling time for particulates important?
18. Give a reason why a limit on the mass of particulates per cubic meter of air may not be completely appropriate for assessing health effects.
19. Name and describe briefly four devices used to collect particulates in a coal-burning electric power plant.
20. In a certain house, a 100-watt light bulb is normally on for 30 hours each week. If electricity costs 8 cents/kWh and, for conservation reasons, it is decided to keep the bulb lit only half as much, then the savings per week would be
    a) 12 cents b) 6 cents c) \$60
    d) \$120 e) 60 cents
21. If you halve the voltage across a device that obeys Ohm's law, then
    a) the current in the device doubles.
    b) the current in the device halves.
    c) the resistance of the device doubles.
    d) the resistance of the device quadruples.
    e) none of the above are correct conclusions.
22. Homeowners pay their electric utilities bills in units of cents per
    a) watt.
    b) kilowatt.
    c) joule.
    d) Btu.
    e) kilowatt-hour.
23. A typical light bulb is rated at 100 watts. This rating means
    a) the bulb requires 100 watts of energy.
    b) the bulb converts 100 joules of energy each second it is on.
    c) the bulb could also be rated as 1 kilowatt.
    d) the bulb converts 100 watts of energy each second it is on.
    e) if the bulb is on 10 hours, it will use 1000 kilowatt-hours of electric energy.
24. When the switch in an electric circuit is in the off position, the current in the circuit is zero. Therefore, we would say the electric resistance of the switch is
    a) zero.
    b) very large, essentially infinite.
    c) 115 ohms.
    d) impossible to determine without knowing the voltage.
    e) irrelevant. Only wires have electrical resistance.
25. An electric iron draws 10 amperes and operates on a 120-volt electric line for two hours. We could say it used 2.4 kWh of energy and required the same power as twelve 100-watt light bulbs operating at the same time.
    a) true b) false
26. A certain 50-watt light bulb costs 50 cents and, on the average, lasts for 100 hours before burning out. Another longer-lived 50-watt bulb costs \$1.50 and lasts for 250 hours.
    a) The \$1.50 bulb is clearly a poorer buy.
    b) The \$1.50 bulb is clearly a better buy.
    c) The two bulbs are equivalent buys.
    d) There is insufficient information to decide which bulb is better.
    e) Both bulbs will use the same amount of energy in their lifetimes.
27. For water to flow through a pipe, there must be a water pressure difference between the ends of the pipe. For electric charge to flow through a wire there must be a (an) ________ difference between the ends of the wire.
    a) electrical b) current c) potential
    d) power e) charge
28. Different types of light bulbs are connected to a battery. The bulb having the least electrical resistance will produce the
    a) least amount of current.
    b) greatest amount of current.
    c) least amount of energy.
    d) least amount of electric power.
    e) least amount of potential difference.
29. A bird sitting on an electric power line does not get electrocuted because
    a) unless it touches another wire, there is no potential difference across the bird.
    b) its electrical resistance is too high.
    c) its electrical resistance is too low.
    d) the current in the wires is AC rather than DC.
    e) it wears rubber shoes as suggested by a student.
30. A night-light requires five watts of power. If electricity costs 10 cents/kWh, the daily cost of continuous operation is
    a) 50 cents b) 0.5 cents c) \$1.20
    d) \$5 e) 1.2 cents
31. Electric current is generated by forcing a large number of wires to move through a magnetic field.
    a) true b) false
32. A small electric generator is operated by a crank turned by a student. The student must do work to generate electricity because
    a) the magnetic field produced by the current tends to aid the magnetic field needed for the generation process.
    b) of the first law of thermodynamics.
    c) of Newton's third law.
    d) magnetic forces tend to oppose the motion provided by the student.
    e) of the electrical resistance of the wire.
33. Electric energy that your bedside clock uses during the night
    a) comes from electric energy stored by the power company during the day.
    b) is probably provided by solar-powered generators.
    c) comes from batteries.
    d) is produced by generators operating during the night.
    e) probably costs more on a kWh basis than the energy used to run the clock in the daytime.
34. When electric power is transmitted from the generating site to a community, the company tries to keep the electric current small to
    a) keep energy losses small due to heating of the transmission wires.
    b) minimize magnetic energy losses.
    c) make the electrical resistance of the wires small.
    d) speed up the transmission of the electric power.
    e) protect birds that might perch on the transmission wires.

35. An electric power company uses transformers to
    a) transform AC currents to DC currents.
    b) increase the amount of electric power.
    c) prevent electrocution of birds sitting on the transmission lines.
    d) change the sizes of voltages.
    e) transform electric fields to magnetic fields.
36. Electric utilities, in an effort to reduce energy loss in transmission wires, employ ________ to step up the ________ at the power plant to a very high level. (Similar devices are employed at the home to reverse this process.)
    a) transformers, voltage
    b) turbines, voltage
    c) transformers, current
    d) generators, voltage
    e) generators, resistance
37. In a commercial electric power plant, it takes about ________ units of energy to produce one unit of electric energy.
    a) 1 b) 2 c) 3 d) 4 e) 5
38. The commercial production of electric energy requires three energy conversion steps. If two of these steps have efficiencies of 90% and the overall conversion efficiency is 40%, then the efficiency of the third step is (pick the closest answer)
    a) 36% b) 50% c) 44% d) 90% e) 20%
39. Generation of electricity is a multistep process. Match the following converters with the particular energy transformation accomplished by that converter. Assume a coal-burning electric power plant.

1. boiler	a. mechanical energy to thermal energy
2. steam turbine	b. chemical energy to thermal energy
3. generator	c. mechanical energy to electrical energy
	d. thermal energy to mechanical energy

    a) 1-a, 2-b, 3-c
    b) 1-b, 2-d, 3-a
    c) 1-c, 2-b, 3-d
    d) 1-b, 2-d, 3-c
    e) none of the above is a correct match.
40. During the last six years, the particulate concentra-

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