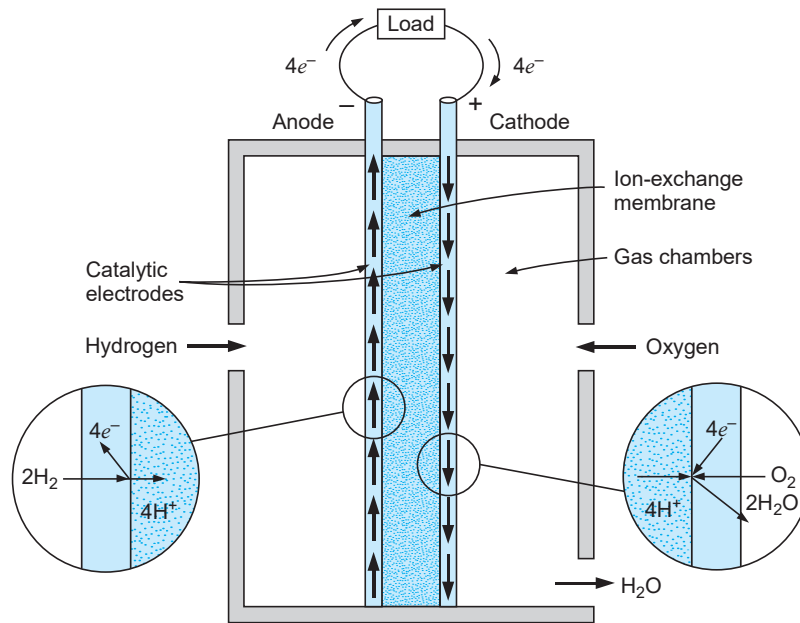


FIGURE 1.5
Schematic arrangement
of an ion-exchange
membrane type of fuel
cell.



large-scale power-generating systems, and although conventional piston engines and gas turbines are still used in most transportation power systems, the fuel cell may eventually become a serious competitor. The fuel cell is already being used to produce power for the space program and other special applications.

Thermodynamics plays a vital role in the analysis, development, and design of all power-producing systems, including reciprocating internal-combustion engines and gas turbines. Considerations such as the increase in efficiency, improved design, optimum operating conditions, reduced environmental pollution, and alternate methods of power generation involve, among other factors, the careful application of the fundamentals of thermodynamics.

1.3 THE VAPOR-COMPRESSION REFRIGERATION CYCLE

A simple vapor-compression refrigeration cycle is shown schematically in Fig. 1.6. The refrigerant enters the compressor as a slightly superheated vapor at a low pressure. It then leaves the compressor and enters the condenser as a vapor at an elevated pressure, where the refrigerant is condensed as heat is transferred to cooling water or to the surroundings. The refrigerant then leaves the condenser as a high-pressure liquid. The pressure of the liquid is decreased as it flows through the expansion valve, and as a result, some of the liquid flashes into cold vapor. The remaining liquid, now at a low pressure and temperature, is vaporized in the evaporator as heat is transferred from the refrigerated space. This vapor then reenters the compressor.

In a typical home refrigerator the compressor is located at the rear near the bottom of the unit. The compressors are usually hermetically sealed; that is, the motor and compressor are mounted in a sealed housing, and the electric leads for the motor pass through this

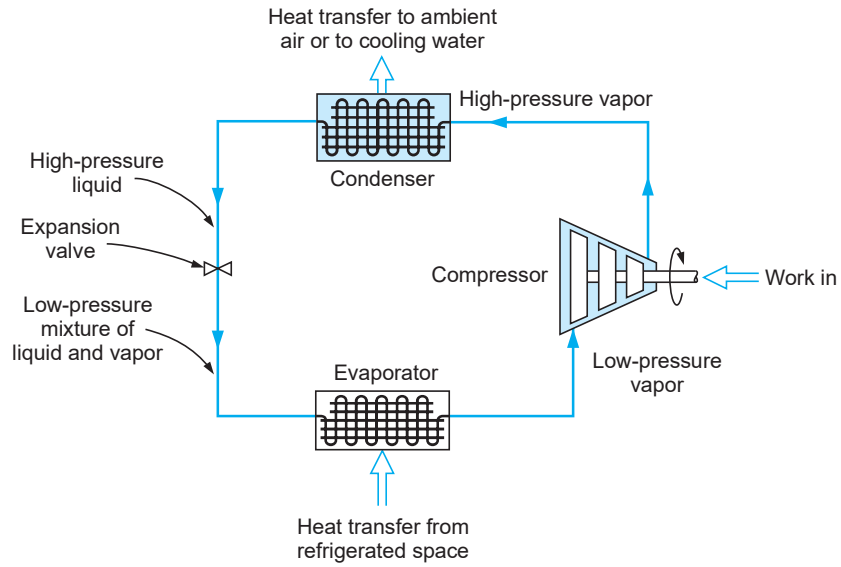


FIGURE 1.6 Schematic diagram of a simple refrigeration cycle.

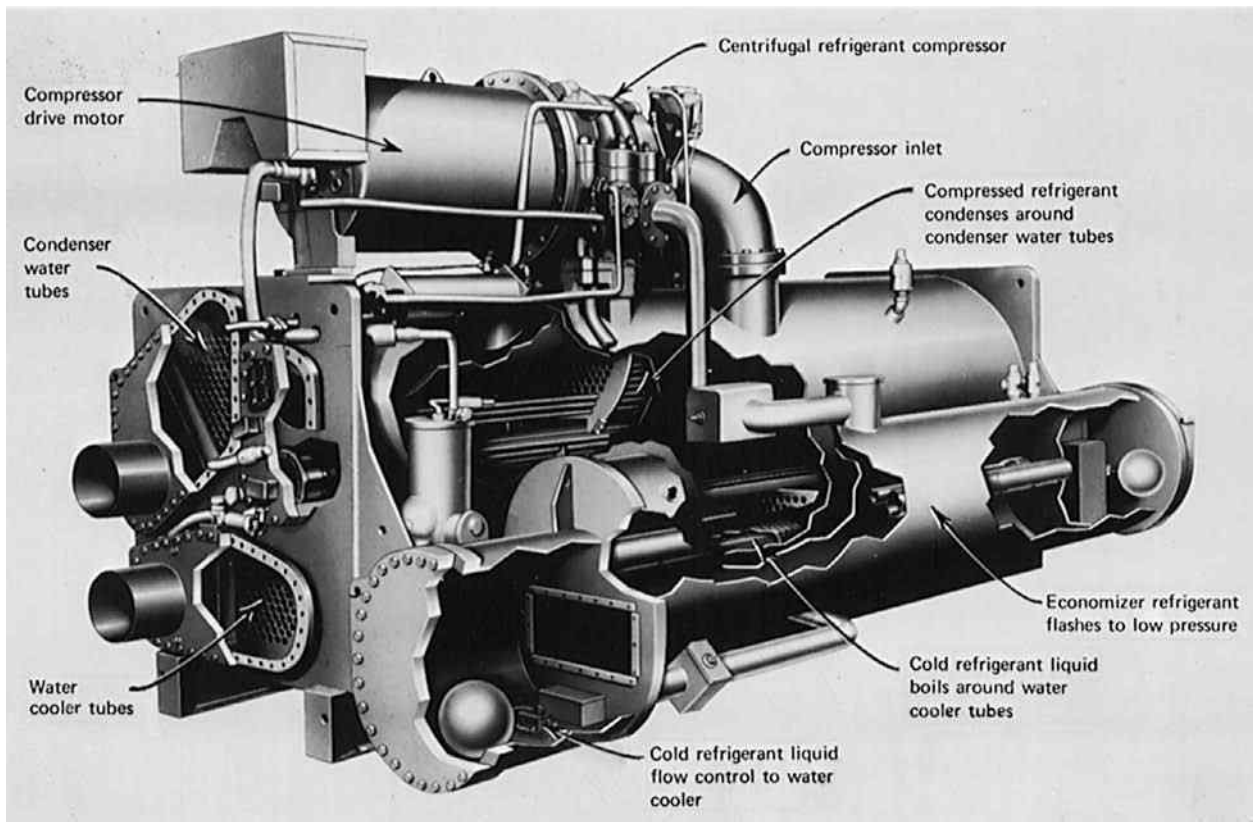


FIGURE 1.7 A refrigeration unit for an air-conditioning system. (Courtesy Carrier Air Conditioning Co.)

housing. This seal prevents leakage of the refrigerant. The condenser is also located at the back of the refrigerator and is arranged so that the air in the room flows past the condenser by natural convection. The expansion valve takes the form of a long capillary tube, and the evaporator is located around the outside of the freezing compartment inside the refrigerator.

Figure 1.7 shows a large centrifugal unit that is used to provide refrigeration for an air-conditioning unit. In this unit, water is cooled and then circulated to provide cooling where needed.

1.4 THE THERMOELECTRIC REFRIGERATOR

We may well ask the same question about the vapor-compression refrigerator that we asked about the steam power plant: is it possible to accomplish our objective in a more direct manner? Is it possible, in the case of a refrigerator, to use the electrical energy (which goes to the electric motor that drives the compressor) to produce cooling in a more direct manner and thereby to avoid the cost of the compressor, condenser, evaporator, and all the related piping?

The thermoelectric refrigerator is such a device. This is shown schematically in Fig. 1.8*a*. The thermoelectric device, like the conventional thermocouple, uses two dissimilar materials. There are two junctions between these two materials in a thermoelectric refrigerator. One is located in the refrigerated space and the other in ambient surroundings. When a potential difference is applied, as indicated, the temperature of the junction located in the refrigerated space will decrease and the temperature of the other junction will increase. Under steady-state operating conditions, heat will be transferred from the refrigerated space to the cold junction. The other junction will be at a temperature above the ambient, and heat will be transferred from the junction to the surroundings.

A thermoelectric device can also be used to generate power by replacing the refrigerated space with a body that is at a temperature above the ambient. Such a system is shown in Fig. 1.8*b*.

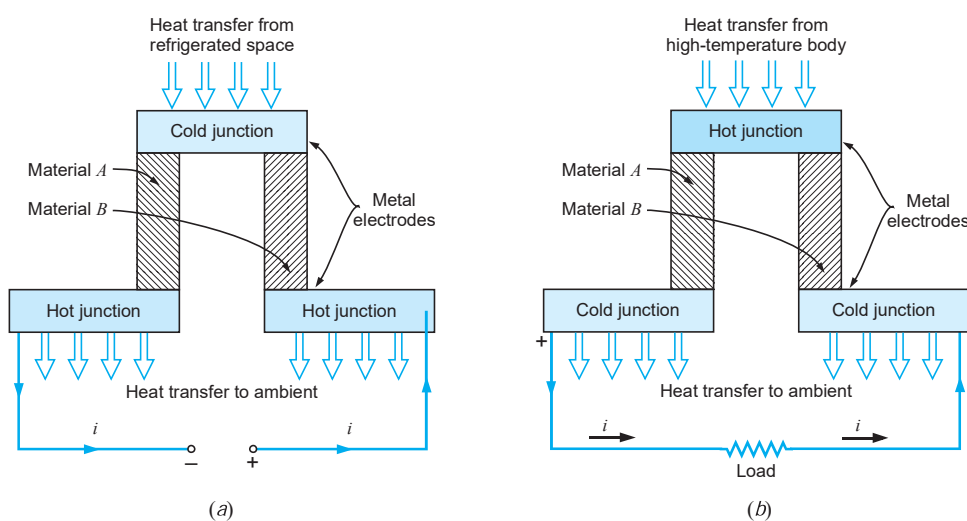


FIGURE 1.8 (a) A thermoelectric refrigerator. (b) A thermoelectric power generation device.

The thermoelectric refrigerator cannot yet compete economically with conventional vapor-compression units. However, in certain special applications, the thermoelectric refrigerator is already in use and, in view of research and development efforts underway in this field, it is quite possible that thermoelectric refrigerators will be much more extensively used in the future.

1.5 THE AIR SEPARATION PLANT

One process of great industrial significance is air separation. In an air separation plant, air is separated into its various components. The oxygen, nitrogen, argon, and rare gases so produced are used extensively in various industrial, research, space, and consumer-goods applications. The air separation plant can be considered an example from two major fields: chemical processing and cryogenics. *Cryogenics* is a term applied to technology, processes, and research at very low temperatures (in general, below about -125°C (-193°F)). In both chemical processing and cryogenics, thermodynamics is basic to an understanding of many phenomena and to the design and development of processes and equipment.

Air separation plants of many different designs have been developed. Consider Fig. 1.9, a simplified sketch of a type of plant that is frequently used. Air from the atmosphere is compressed to a pressure of 2 to 3 MPa (20 to 30 times normal atmospheric pressure). It is then purified, particularly to remove carbon dioxide (which would plug the flow passages as it solidifies when the air is cooled to its liquefaction temperature). The air is then compressed to a pressure of 15 to 20 MPa, cooled to the ambient temperature in the aftercooler, and dried to remove the water vapor (which would also plug the flow passages as it freezes).

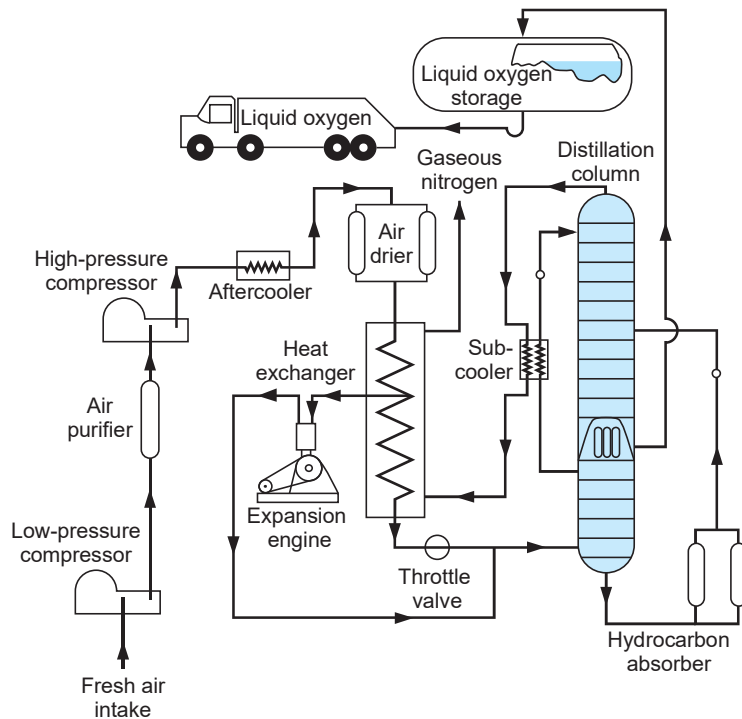


FIGURE 1.9 A simplified diagram of a liquid oxygen plant.

The basic refrigeration in the liquefaction process is provided by two different processes. In one process the air in the expansion engine expands. During this process the air does work and, as a result, the temperature of the air is reduced. In the other refrigeration process air passes through a throttle valve that is so designed and so located that there is a substantial drop in the pressure of the air and, associated with this, a substantial drop in the temperature of the air.

As shown in Fig. 1.9, the dry, high-pressure air enters a heat exchanger. As the air flows through the heat exchanger, its temperature drops. At some intermediate point in the heat exchanger, part of the air is bled off and flows through the expansion engine. The remaining air flows through the rest of the heat exchanger and through the throttle valve. The two streams join (both are at a pressure of 0.5 to 1 MPa) and enter the bottom of the distillation column, which is referred to as the *high-pressure column*. The function of the distillation column is to separate the air into its various components, principally oxygen and nitrogen. Two streams of different composition flow from the high-pressure column through throttle valves to the upper column (also called the *low-pressure column*). One of these streams is an oxygen-rich liquid that flows from the bottom of the lower column, and the other is a nitrogen-rich stream that flows through the subcooler. The separation is completed in the upper column. Liquid oxygen leaves from the bottom of the upper column, and gaseous nitrogen leaves from the top of the column. The nitrogen gas flows through the subcooler and the main heat exchanger. It is the transfer of heat to this cold nitrogen gas that causes the high-pressure air entering the heat exchanger to become cooler.

Not only is a thermodynamic analysis essential to the design of the system as a whole, but essentially every component of such a system, including the compressors, the expansion engine, the purifiers and driers, and the distillation column, operates according to the principles of thermodynamics. In this separation process we are also concerned with the thermodynamic properties of mixtures and the principles and procedures by which these mixtures can be separated. This is the type of problem encountered in petroleum refining and many other chemical processes. It should also be noted that cryogenics is particularly relevant to many aspects of the space program, and a thorough knowledge of thermodynamics is essential for creative and effective work in cryogenics.

1.6 THE GAS TURBINE

The basic operation of a gas turbine is similar to that of a steam power plant, except that air is used instead of water. Fresh atmospheric air flows through a compressor that brings it to a high pressure. Energy is then added by spraying fuel into the air and igniting it so that the combustion generates a high-temperature flow. This high-temperature, high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing shaft work output in the process. The turbine shaft work is used to drive the compressor and other devices, such as an electric generator that may be coupled to the shaft. The energy that is not used for shaft work is released in the exhaust gases, so these gases have either a high temperature or a high velocity. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. An example of a large gas turbine for stationary power generation is shown in Fig. 1.10. The unit has 16 stages of compression and 4 stages in the turbine and is rated at 43 MW (43 000 kW). Notice that since the combustion of fuel uses the oxygen in the air, the exhaust gases cannot be recirculated, as the water is in a steam power plant.

A gas turbine is often the preferred power-generating device where a large amount of power is needed but only a small physical size is possible. Examples are jet engines,

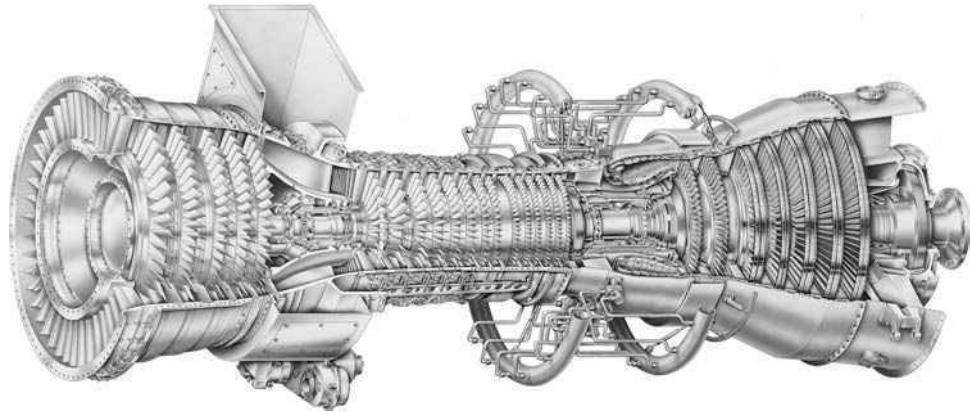


FIGURE 1.10 A 43 MW gas turbine. (Courtesy General Electric Corporation.)

turbofan jet engines, offshore oilrig power plants, ship engines, helicopter engines, smaller local power plants, or peak-load power generators in larger power plants. Since the gas turbine has relatively high exhaust temperatures, it can also be arranged so that the exhaust gases are used to heat water that runs in a steam power plant before it exhausts to the atmosphere.

In the examples mentioned previously, the jet engine and turboprop applications utilize part of the power to discharge the gases at high velocity. This is what generates the thrust of the engine that moves the airplane forward. The gas turbines in these applications are

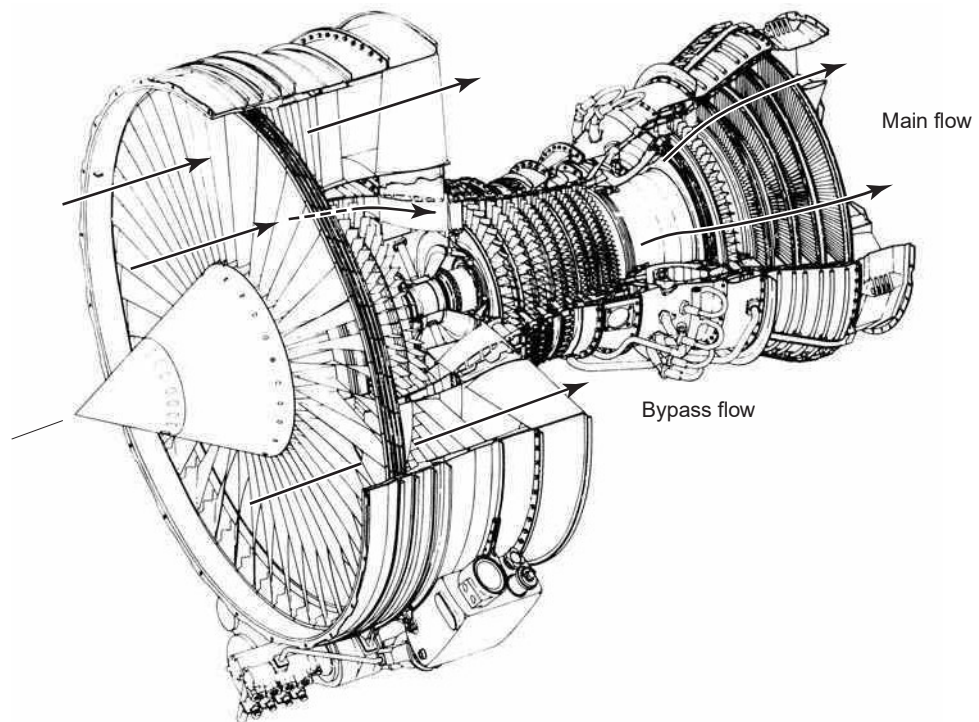


FIGURE 1.11 A turbofan jet engine. (Courtesy General Electric Aircraft Engines.)

therefore designed differently than those for the stationary power plant, where the energy is released as shaft work to an electric generator. An example of a turbofan jet engine used in a commercial airplane is shown in Fig. 1.11. The large front-end fan also blows air past the engine, providing cooling and giving additional thrust.

1.7 THE CHEMICAL ROCKET ENGINE

The advent of missiles and satellites brought to prominence the use of the rocket engine as a propulsion power plant. Chemical rocket engines may be classified as either liquid propellant or solid propellant, according to the fuel used.

Figure 1.12 shows a simplified schematic diagram of a liquid-propellant rocket. The oxidizer and fuel are pumped through the injector plate into the combustion chamber, where combustion takes place at high pressure. The high-pressure, high-temperature products of combustion expand as they flow through the nozzle, and as a result they leave the nozzle with a high velocity. The momentum change associated with this increase in velocity gives rise to the forward thrust on the vehicle.

The oxidizer and fuel must be pumped into the combustion chamber, and an auxiliary power plant is necessary to drive the pumps. In a large rocket this auxiliary power plant must be very reliable and have a relatively high power output, yet it must be light in weight. The oxidizer and fuel tanks occupy the largest part of the volume of a rocket, and the range and payload of a rocket are determined largely by the amount of oxidizer and fuel that can be carried. Many different fuels and oxidizers have been considered and tested, and much effort has gone into the development of fuels and oxidizers that will give a higher thrust per unit mass rate of flow of reactants. Liquid oxygen is frequently used as the oxidizer in liquid-propellant rockets, and liquid hydrogen is frequently used as the fuel.

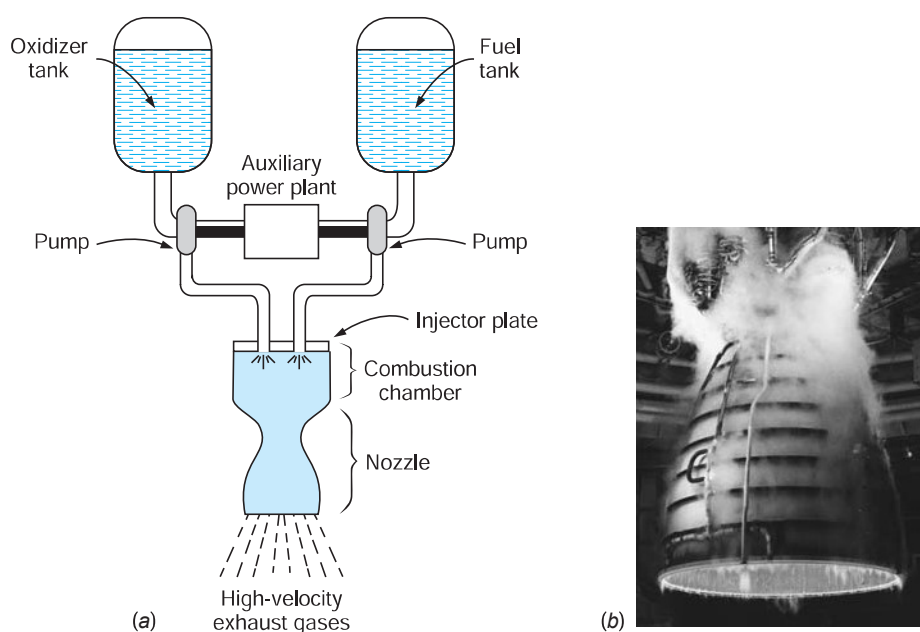


FIGURE 1.12
(a) Simplified schematic diagram of a liquid-propellant rocket engine. (b) Photo of the NASA space shuttle's main engine.

Much work has also been done on solid-propellant rockets. They have been successfully used for jet-assisted takeoffs of airplanes, military missiles, and space vehicles. They require much simpler basic equipment for operation and fewer logistic problems are involved in their use, but they are more difficult to control.

1.8 OTHER APPLICATIONS AND ENVIRONMENTAL ISSUES

There are many other applications in which thermodynamics is relevant. Many municipal landfill operations are now utilizing the heat produced by the decomposition of biomass waste to produce power, and they also capture the methane gas produced by these chemical reactions for use as a fuel. Geothermal sources of heat are also being utilized, as are solar- and windmill-produced electricity. Sources of fuel are being converted from one form to another, more usable or convenient form, such as in the gasification of coal or the conversion of biomass to liquid fuels. Hydroelectric plants have been in use for many years, as have other applications involving water power. Thermodynamics is also relevant to such processes as the curing of a poured concrete slab, which produces heat, the cooling of electronic equipment, various applications in cryogenics (cryosurgery, food fast-freezing), and many other applications. Several of the topics and applications mentioned in this paragraph will be examined in detail in later chapters of this book.

We must also be concerned with environmental issues related to these many devices and applications of thermodynamics. For example, the construction and operation of the steam power plant creates electricity, which is so deeply entrenched in our society that we take its ready availability for granted. In recent years, however, it has become increasingly apparent that we need to consider seriously the effects of such an operation on our environment. Combustion of hydrocarbon fuels releases carbon dioxide into the atmosphere, where its concentration is increasing. Carbon dioxide, as well as other gases, absorbs infrared radiation from the surface of the earth, holding it close to the planet and creating the greenhouse effect, which in turn causes global warming and critical climatic changes around the earth. Power plant combustion, particularly of coal, releases sulfur dioxide, which is absorbed in clouds and later falls as acid rain in many areas. Combustion processes in power plants, and in gasoline and diesel engines, also generate pollutants other than these two. Species such as carbon monoxide, nitric oxides, and partly burned fuels, together with particulates, all contribute to atmospheric pollution and are regulated by law for many applications. Catalytic converters on automobiles help to minimize the air pollution problem. Figure 1.1 indicates the fly ash and flue gas cleanup processes that are now incorporated in power plants to address these problems. Thermal pollution associated with power plant cooling water requirements was discussed in Section 1.1.

Refrigeration and air-conditioning systems, as well as other industrial processes, have used certain chlorofluorocarbon fluids that eventually find their way to the upper atmosphere and destroy the protective ozone layer. Many countries have already banned the production of some of these compounds, and the search for improved replacement fluids continues.

These are only some of the many environmental problems caused by our efforts to produce goods and effects intended to improve our way of life. During our study of thermodynamics, which is the science of the conversion of energy from one form to another, we must continue to reflect on these issues. We must consider how we can eliminate or at least minimize damaging effects, as well as use our natural resources, efficiently and responsibly.