externally (see Fig. 14–24*d*). Mixing is promoted by the circulation of sludge. Mechanical pumping systems are suitable for digesters with fixed covers.

Egg-Shaped Tanks. The purpose of the egg-shaped design is to enhance mixing and to eliminate the need for cleaning. The digester sides form a steep cone at the bottom so that grit accumulation is minimized (see Fig. 14–25*a*). Other advantages cited for the egg-shaped design include better mixing, better control of the scum layer, and smaller land-area requirements. Steel construction is more common for egg-shaped tanks in the United States; reinforced concrete construction requires complex formwork and special construction techniques. The structures are relatively high as compared to other treatment plant structures (see Fig. 14–25*b*), and may require an elevator for access to the top of the structure. In recent designs in Boston, MA (see Fig. 14–19), and Baltimore, MD, the heights of the digesters were over 40 m (130 ft).

Egg-shaped digester mixing systems are similar to those for cylindrical tanks and consist of unconfined gas mixing, mechanical draft-tube mixing, or pumped recirculation mixing (see Fig. 14–26). Gas mixing is considered by some to be relatively ineffective in mixing the digester contents below the level of the injection nozzles. The mechanical draft tube and pumped recirculation mixing systems, however, are considered able to provide sufficient energy to mix even the sludge in the bottom cone of the digester. The mechanical draft-tube mixer, which can be operated in either an up- or

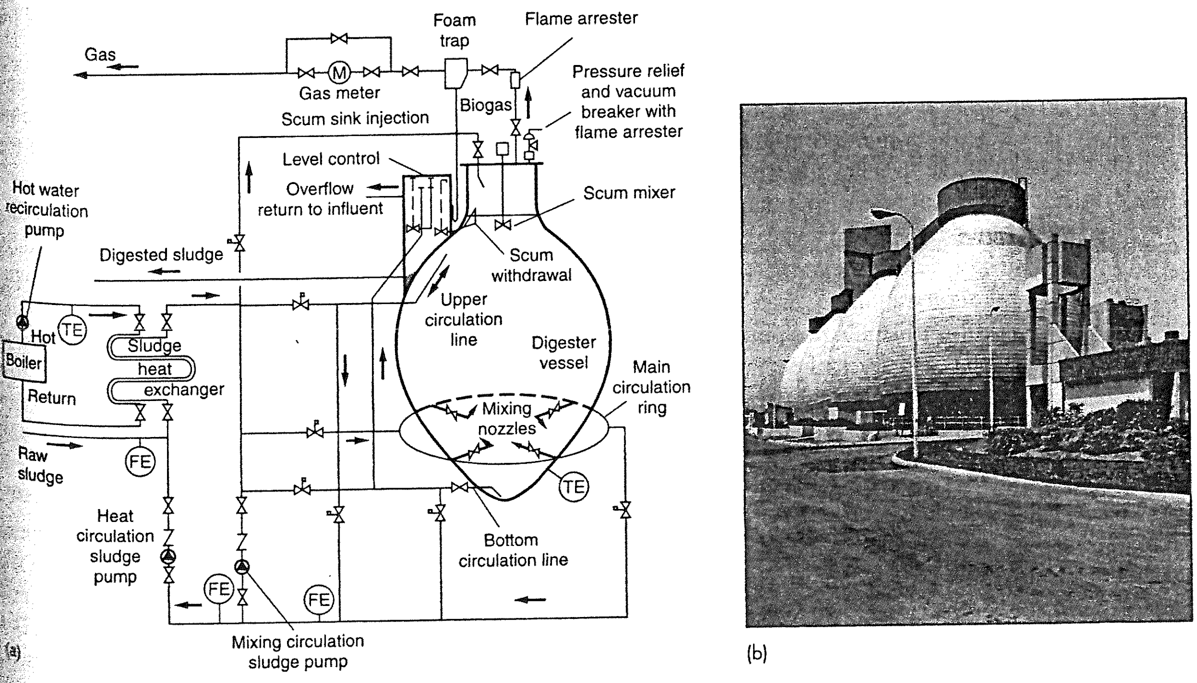

Figure 14-25

Egg-shaped anaerobic digester: (*a*) schematic diagram from Walker Process catalog, (*b*) pictorial view.

5. Determine the effect of heat shutoff.

   a. Digester volume $= \pi\left(\frac{D^2}{4}\right)h_s + \pi\left(\frac{D^2}{12}\right)h_c$

   $$= \pi\left(\frac{18^2}{4}\right)(6) + \pi\left(\frac{18^2}{12}\right)(3) = 1526.8 + 254.5$$

   $$= 1781.3 \text{ m}^3$$

   b. Weight of sludge $= (1781.3 \text{ m}^3)(10^3 \text{ kg/m}^3)$

   $$= 1.78 \times 10^6 \text{ kg}$$

   c. Drop in temperature $= \dfrac{(60.7 \times 10^8 \text{ J/d})(1.0)}{(1.78 \times 10^6 \text{ kg})(4200 \text{ J/kg·°C})} = 0.81\text{°C/d}$

Heating Equipment. The contents of the digester can be heated by tube-in-tube, spiral-plate, or water-bath external heat exchangers. The tube-in-tube and spiral-heat exchangers are similar in design. A tube-in-tube exchanger consists of two concentric pipes, one containing the circulating sludge and the other containing hot water. Flow through the pipes is countercurrent. Spiral-plate heat exchangers (see Fig. 14–28*a* and *b*) are composed of two long strips of plate that are wrapped to form a pair of concentric passages. The flow regime is also countercurrent. Water temperatures are kept generally below 68°C (154°F) to prevent caking of the sludge. Heat-transfer coefficients for external heat exchangers range from 0.9 to 1.6 $\text{W/m}^2\text{·°C}$ (WEF 1998).

Operation of a water-bath heat exchanger involves circulation of the sludge through a heated water bath (see Fig. 14–28*c*). The heat transfer rate is increased by pumping hot water in and out of the bath. Recirculation pumps allow the sludge feed to be heated before introduction to the digester.

Boilers and cogeneration systems are used typically to supply heat to the circulating water in the heat exchangers. Boilers can be fueled by digester gas; however, natural gas or fuel oil may be used as auxiliary fuel for times when sufficient digester gas is not available, such as for digester startup. If a cogeneration system is provided that uses digester gas to fuel an internal-combustion engine for generating electricity or powering pumps or blowers, heat from the engine jacket water can be used in the heat exchanger.

Thermophilic Anaerobic Digestion

Thermophilic digestion occurs at temperatures between 50 and 57°C (120 and 135°F), conditions suitable for thermophilic bacteria. Because biochemical reaction rates increase with temperature, doubling with every 10°C (18°F) rise in temperature until a limiting temperature is reached, thermophilic digestion is much faster than mesophilic digestion. Advantages cited for thermophilic digestion include increased solids destruction capability, improved dewatering, and increased bacterial destruction. Disadvantages of thermophilic digestion are higher energy requirements for heating, poorer-quality supernatant containing larger quantities of dissolved solids, odors, and less

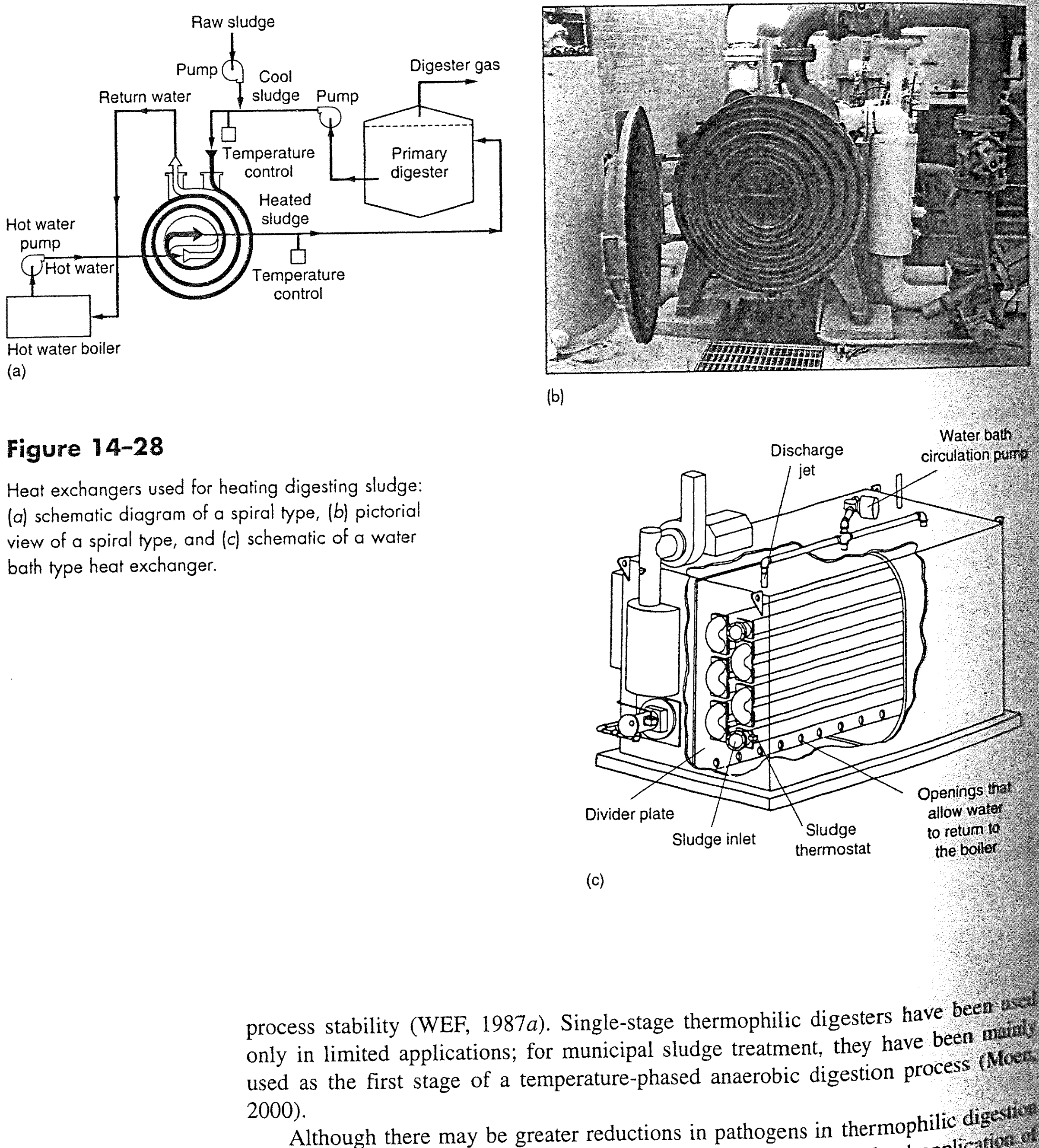

Figure 14-28

Heat exchangers used for heating digesting sludge: (*a*) schematic diagram of a spiral type, (*b*) pictorial view of a spiral type, and (*c*) schematic of a water bath type heat exchanger.

process stability (WEF, 1987*a*). Single-stage thermophilic digesters have been used only in limited applications; for municipal sludge treatment, they have been mainly used as the first stage of a temperature-phased anaerobic digestion process (Moen, 2000).

Although there may be greater reductions in pathogens in thermophilic digestion than in mesophilic digestion, U.S. federal regulations controlling land application of biosolids do not classify thermophilic digestion as a process to significantly reduce pathogens (PSRP). Both mesophilic and thermophilic digestion are classified as processes to further reduce pathogens (PFRP). Therefore, single-stage thermophilic digestion has significant limitations, as cited above.