Excerpt From
Viessman & Hammer "Water Supply & Poll. Control"

BIOLOGICAL SLUDGE DIGESTION

Biological digestion of sludge from wastewater treatment is widely practiced to stabilize the organic matter prior to ultimate disposal. Anaerobic digestion is used in plants employing primary clarification followed by either trickling-filter or activated-sludge secondary treatment. Aerobic digestion stabilizes waste-activated sludge from aeration plants without primary settling tanks. The fundamental differences between aerobic and anaerobic digestion are illustrated in Figures 12.2 and 12.3. The end product of aerobic digestion is cellular protoplasm, and growth is limited by depletion of the available carbon source. The end products of anaerobic metabolism are methane, unused organics, and a relatively small amount of cellular protoplasm. Growth is limited by a lack of hydrogen acceptors. Anaerobic digestion is basically a destructive process, although complete degradation of the organic matter under anaerobic conditions is not possible.

13.13 ANAEROBIC SLUDGE DIGESTION

Anaerobic digestion consists of two distinct stages that occur simultaneously in digesting sludge (Fig. 12.13). The first consists of hydrolysis of the high-molecular-weight organic compounds and conversion to organic acids by acid-forming bacteria [Eq. (12.9)]. The second stage is gasification of the organic acids to methane and carbon dioxide by the acid-splitting, methane-forming bacteria [Eq. (12.10)].

Methane bacteria are strict anaerobes and very sensitive to conditions of their environment. The optimum temperature and pH range for maximum growth rate are limited. Methane bacteria can be adversely affected by excess concentrations of oxidized compounds, volatile acids, soluble salts, and metal cations and also show a rather extreme substrate specificity. Each species is restricted to the use of only a few compounds, mainly alcohols and organic acids, whereas the normal energy sources, such as carbohydrates and amino acids, are not attacked. An enrichment culture developed on a feed of acetic or butyric acid cannot decompose propionic acid. The sensitivity exhibited by methane bacteria in the second stage of anaerobic digestion, coupled with the rugged nature of the acid-forming bacteria in the first stage, creates a biological system where the population dynamics are easily upset. Any shift in environment adverse to the population of methane bacteria causes a buildup of organic acids, which in turn further reduces the metabolism of acid-splitting methane formers.

Pending failure of the anaerobic digestion process is evidenced by a decrease in gas production, a lowering in the percentage of methane gas produced, an increase in the volatile acids concentration, and eventually a drop in pH when the accumulated volatile acids exceed the buffering capacity created by the ammonium bicarbonate in solution. Therefore, the operation of a digester can be monitored by any of the following methods: plotting the daily gas production per unit raw sludge fed, the percentage of carbon dioxide in the digestion gases, or the concentration of volatile acids in the digesting sludge. A reduction in gas production, an increase in carbon dioxide percentage, and a rise in volatile acids concentration all indicate reduced activity of the acid-splitting methane-forming bacteria. Digester failure may be caused by any of the following: a significant increase in organic loading, a sharp decrease in digesting sludge

TABLE 13.7 General Conditions for Sludge Digestion

Temperature	
Optimum	98°F (37°C)
General range of operation	85°–95°F (29°–35°C)
pH	
Optimum	7.0–7.1
General limits	6.7–7.4
Gas production	
Per pound of volatile solids added	8–12 ft^3 (230–340 l)
Per pound of volatile solids destroyed	16–18 ft^3 (450–510 l)
Gas composition	
Methane	65%–69%
Carbon dioxide	31%–35%
Hydrogen sulfide	Trace
Volatile acids concentration as acetic acid	
Normal operation	200–800 mg/l
Maximum	Approx. 2000 mg/l
Alkalinity concentrations as $CaCO_3$	
Normal operation	2000–3500 mg/l
Minimum solids retention times	
Single-stage digestion	25 d
High-rate digestion	15 d
Volatile solids reduction	
Single-stage digestion	50%–70%
High-rate digestion	50%

volume (i.e., when digested sludge is withdrawn), a sudden increase in operating temperature, or the accumulation of a toxic or inhibiting substance.

The Environmental Protection Agency specifies processing requirements for application of digested sludge as biosolids on agricultural land [1]. Anaerobic digestion reduces pathogens so that public health is not threatened, provided site restrictions minimize the potential for human and animal contact until after natural die-off reduces any remaining pathogens. The criteria for adequate digestion are a solids retention time (mean cell residence time) and temperature between 15 days at 35°C (95°F) and 60 days at 20°C (68°F). Stabilization for vector reduction is at least 38% reduction in volatile solids. Of the 10 toxic metals controlled, cadmium is of greatest concern since it is suspected of being taken up by plants to enter the human food chain.

General conditions for mesophilic sludge digestion are given in Table 13.7.

13.14 SINGLE-STAGE FLOATING-COVER DIGESTERS

The cross section of a floating-cover digestion tank is shown in Figure 13.11. Raw sludge is pumped into the digester through pipes terminating either near the center of the tank or in the gas dome. Pumping sludge into the dome helps to break up the scum layer that forms on the surface.

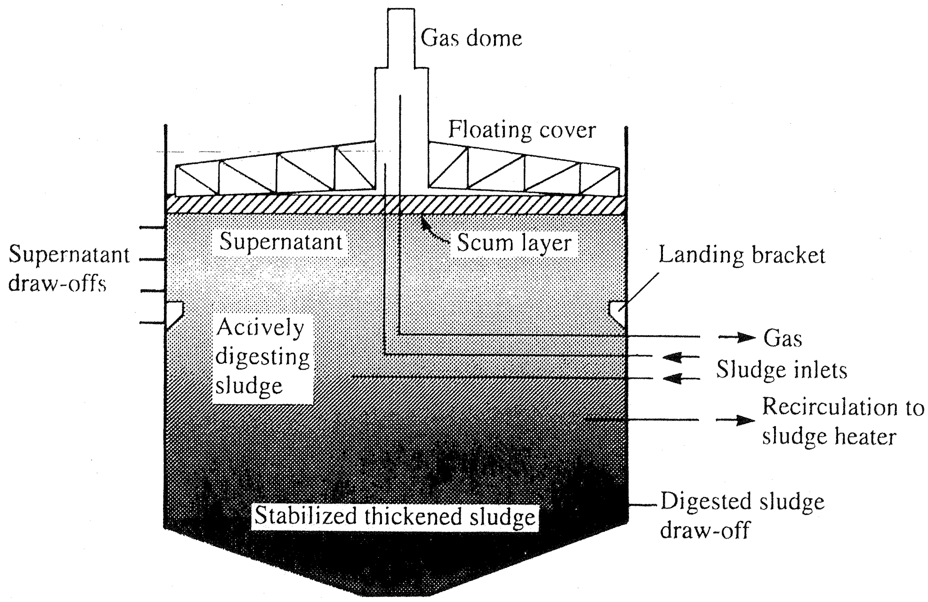


FIGURE 13.11 Cross-sectional diagram of a floating-cover anaerobic digester.

Digested sludge is withdrawn from the tank bottom. The contents are heated in the zone of digesting sludge by pumping them through an external heater and returning the heated slurry through the inlet lines. The tank contents stratify with a scum layer on top and digested thickened sludge on the bottom. The middle zones consist of a layer of supernatant (water of separation) underlain by the zone of actively digesting sludge. Supernatant is drawn from the digester through any one of a series of pipes extending out of the tank wall. Digestion gas from the gas dome is burned as fuel in the external heater or wasted to a gas burner.

The weight of the cover is supported by sludge, and the liquid forced up between the tank wall and the side of the cover provides a gas seal. Gas rises out of the digesting sludge, moves along the ceiling of the cover, and collects in the gas dome. The cover can float on the surface of the sludge between the landing brackets and the height of the overflow pipe. Rollers around the circumference of the cover keep it from binding against the tank wall.

Three functions of a single-stage floating-cover digester are (1) anaerobic digestion of the volatile solids, (2) gravity thickening, and (3) storage of the digested sludge. A floating-cover feature of the tank provides for a storage volume equal to approximately one-third that of the tank. The unmixed operation of the tank permits gravity thickening of sludge solids and withdrawal of the separated supernatant. Anaerobic digestion of the sludge solids is promoted by maintaining near optimum temperature and stirring the digesting sludge through the recirculation of heated sludge. However, the rate of biological activity is inhibited by the lack of mixing; on the other hand, good mixing would prevent supernatant formation. Therefore, in single-tank operation, the biological process is compromised to allow both digestion and thickening to occur in the same tank.

In the operation of an unmixed digester, raw sludge is pumped to the digester from the bottom of the settling tanks once or twice a day. Supernatant is withdrawn daily and returned to the influent of the treatment plant. It is normally returned by gravity flow to the wet well during periods of low raw-wastewater flow, or, in the case of an activated-sludge plant, it may be pumped to the head end of the aeration basin. Because of the floating cover, supernatant does not have to be drawn off simultaneously with the pumping of raw sludge into the digester.

Digested sludge is stored in the tank and withdrawn periodically for disposal. Spreading of liquid sludge from smaller plants on grassland or cropland is common practice in agricultural regions. In larger plants, it is mechanically dewatered and used as a fertilizer and soil conditioner or hauled to land burial. In either case, weather often dictates the schedule for digested sludge disposal. In northern climates, the cover is lowered as close as possible to the corbels (landing brackets) in the fall of the year to provide maximum volume for winter sludge storage.

13.15 HIGH-RATE (COMPLETELY MIXED) DIGESTERS

The biological process of anaerobic digestion is significantly improved by complete mixing of the digesting sludge, either mechanically or by use of compressed digestion gases. Mechanical mixing is normally accomplished by an impeller suspended from the cover of the digester [Fig. 13.12(a)]. Three common methods of gas mixing are the injection of

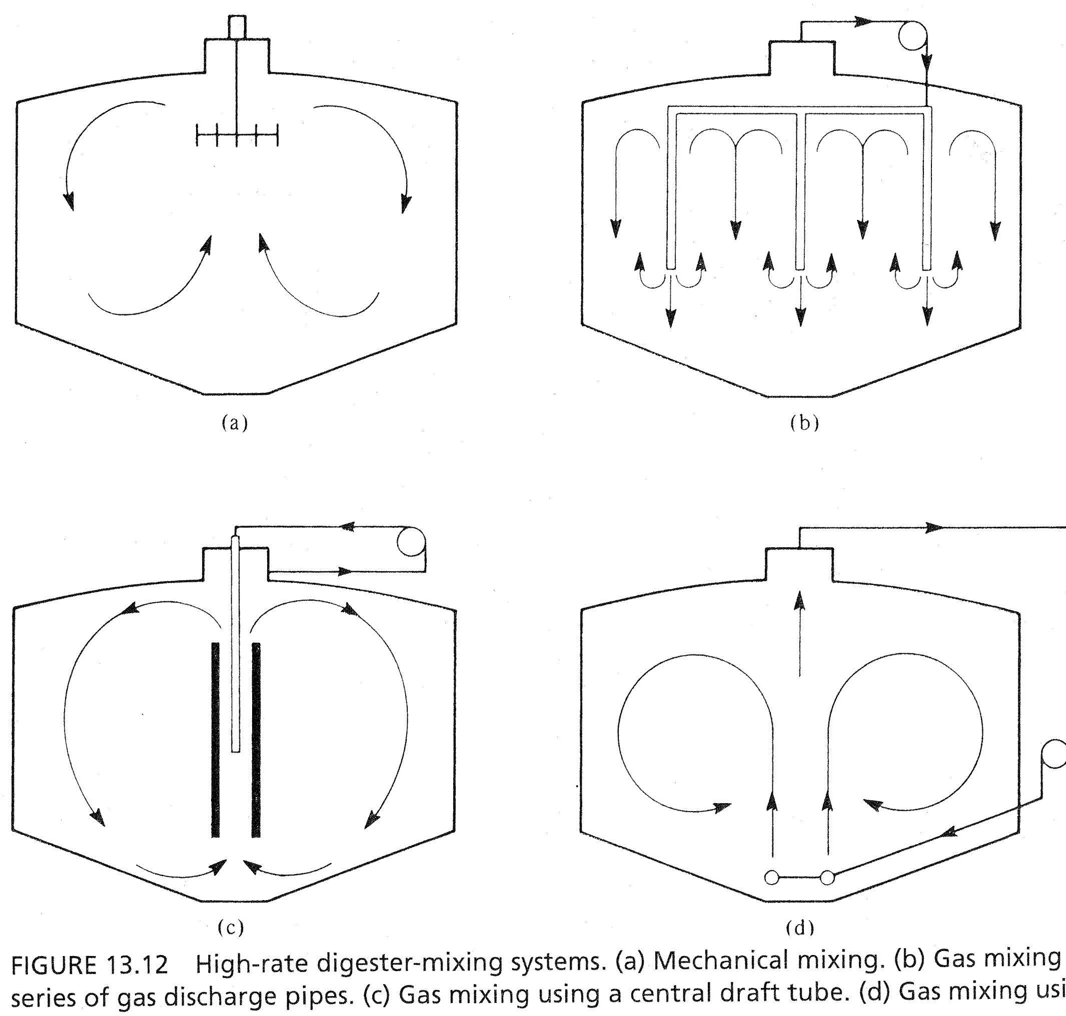
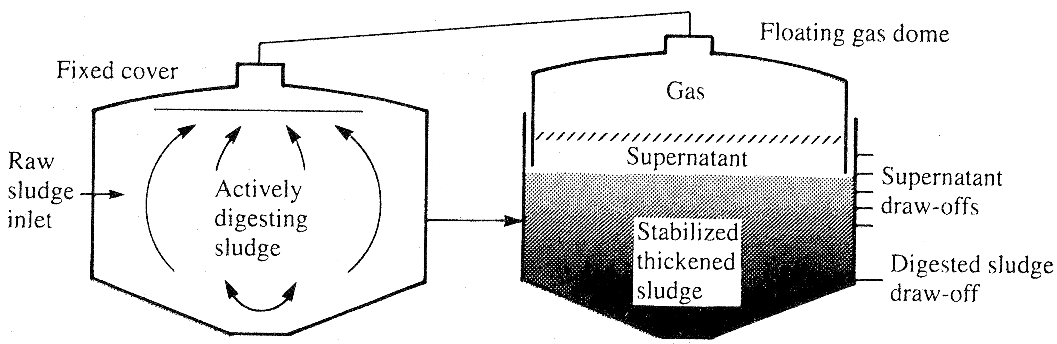


FIGURE 13.12 High-rate digester-mixing systems. (a) Mechanical mixing. (b) Gas mixing using a series of gas discharge pipes. (c) Gas mixing using a central draft tube. (d) Gas mixing using diffusers mounted on the tank bottom.

compressed gas through a series of small-diameter pipes hanging from the cover into the digesting sludge [Fig. 13.12(b)]; the use of a draft tube in the center of the tank, with compressed gas injected into the tube to lift recirculating sludge from the bottom and spill it out on top [Fig. 13.12(c)]; and supplying compressed gas to a number of diffusers mounted in the center at the bottom of the tank [Fig. 13.12(d)].

A completely mixed digester may be either a fixed- or a floating-cover tank. Digesting sludge is displaced when raw sludge is pumped into a fixed-cover digester. By use of a floating cover, tank volume is available for the storage of digesting sludge, and withdrawals do not have to coincide with the introduction of raw sludge.

The homogeneous nature of the digesting sludge in a high-rate digester does not permit formation of supernatant. Therefore, thickening cannot be performed in a completely mixed digester. High-rate digestion systems normally consist of two tanks operated in series (Fig. 13.13). The first stage is a completely mixed, heated, floating-, or fixed-cover digester fed as continuously as possible, whose function is anaerobic digestion of the volatile solids. The second stage may be heated or unheated, and it accomplishes gravity thickening and storage of the digested sludge. Two-stage systems may consist of two similar floating-cover tanks with provisions for mixing in one tank.



(a)

(b)

FIGURE 13.13 Sketch of a two-stage anaerobic digestion system. (a) The first stage is a completely mixed high-rate digester with a fixed cover. The second stage is a thickening and storage tank covered with a dome for collecting and storing gas. (b) Photograph of two-stage digesters. *Source*: Lincoln, NE.

13.16 VOLATILE SOLIDS LOADINGS AND DIGESTER CAPACITY

Typical ranges of loadings and detention times employed in the design and operation of heated anaerobic digestion tanks treating domestic waste sludge are listed in Table 13.8. Values given for volatile solids loading and digester capacity for conventional, single-stage digesters are based on the total sludge volume available in the tank (i.e., the volume with the floating cover fully raised). Figures given for high-rate digestion apply only to the volume needed for the first-stage tank. There are no established design standards for the tank capacity required in second-stage thickening and supernatant separation.

The loading applied to a digester is expressed in terms of pounds of volatile solids applied per day per cubic foot of digester capacity. Detention time is the volume of the tank divided by the daily raw-sludge pumpage. Digester capacity in Table 13.8 is given in terms of cubic feet of tank volume provided per design population equivalent of the treatment plant.

The *Recommended Standards of the Great Lakes–Upper Mississippi River Board of State Public Health & Environmental Managers* [6] recommends a maximum of 0.08 lb/ft^3/day of VS (1.3 kg/m$^3 \cdot$ d) for high-rate digestion and a maximum of 0.04 lb (0.6 kg) of VS loading for single-stage operation. These loadings assume that the raw sludge is derived from domestic wastewater, the digestion temperature is in the range of 85°–95°F (29°–35°C), volatile solids reduction is 40%–50%, and the digested sludge is removed frequently from the digester.

The capacity required for a single-stage floating-cover digester can be determined by the formula

$$V = \frac{V_1 + V_2}{2} \times T_1 + V_2 \times T_2 \tag{13.11}$$

where

V = total digester capacity, ft^3 (m^3)

V_1 = volume of average daily raw-sludge feed, ft^3/day (m^3/d)

TABLE 13.8 Loadings and Detention Times for Heated Anaerobic Digesters

	Conventional Single-Stage (Unmixed)	First-Stage High-Rate (Completely Mixed)
Loading (lb/ft^3/day of VS)[a]	0.02–0.05	0.1–0.2
Detention time (days)	30–90	15
Capacity of digester (ft^3/population equivalent)[b]		
Primary only	2–1	0.4–0.6
Primary and secondary	4–6	0.7–1.5
Volatile solids reduction (%)	50–70	50

[a]1.0 lb/ft^3/day = 16.0 kg/m$^3 \cdot$ d
[b]1.0 ft^3 = 0.0283 m^3

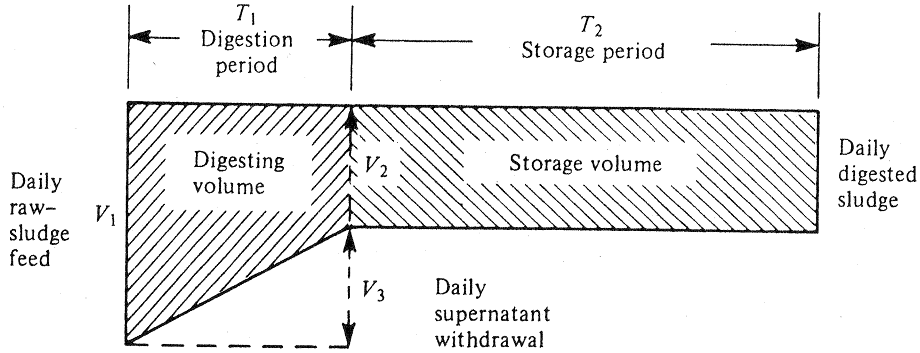


FIGURE 13.14 Pictorial presentation of Eq. (13.11).

V_2 = volume of daily digested sludge accumulation in tank, ft^3/day (m^3/d)

T_1 = period required for digestion, days [approximately 25 days at a temperature of 85°–95°F (29°–35°C)]

T_2 = period of digested sludge storage, days (normally 30–120 days)

Figure 13.14 is a pictorial representation of Eq. (13.11).

Predicting daily volumes of raw sludge produced and the digested sludge accumulated as required in Eq. (13.11) is often difficult. Therefore, the capacity of conventional digesters frequently is based on empirical values relating digester capacity to the equivalent population design of the plant (Table 13.8). Values of 5 and 6 ft^3/capita (0.14 and 0.17 m^3/capita) are frequently used for high-rate trickling-filter plants and activated-sludge plants, respectively.

The minimum detention time for satisfactory high-rate digestion at 95°F (35°C) is approximately 15 days. In general, this limiting period depends on the minimum time required to digest the grease component of raw sludge. Also, too little detention time results in depletion of the methane-bacteria populations, since they are washed out of the digester. The maximum volatile solids loadings, at a 15-day detention time, vary from 0.1 to 0.2 lb/ft^3/day (1.6–3.2 kg/$m^3 \cdot$ d) for adequate volatile solids destruction and gas production. For larger treatment plants with uniform loading conditions, design values of a 15-day minimum detention time and maximum 0.15 lb/ft^3/day of VS loading appear to be satisfactory. Digesters for small treatment plants with wider variations in daily sludge production should be planned using more conservative loading rates.

The capacities required for a high-rate digestion system can be determined by the following equations:

$$V_I = V_1 \times T \tag{13.12}$$

where

V_I = digester capacity required for first-stage high-rate, ft^3 (m^3)

V_1 = volume of average daily raw sludge feed, ft^3/day (m^3/d)

T = period required for digestion, days

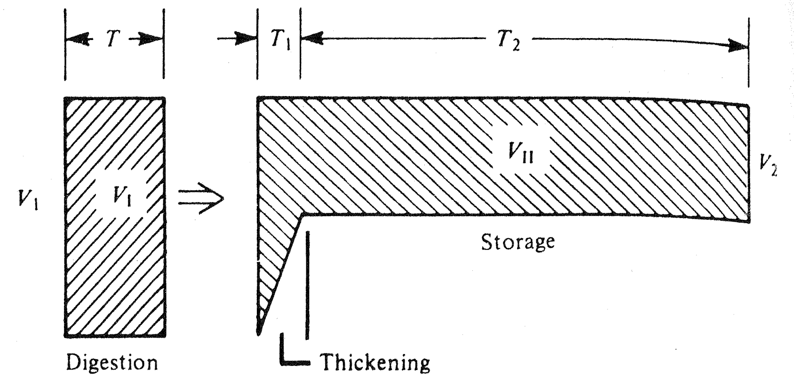


FIGURE 13.15 Diagrams for Eqs. (13.12) and (13.13).

and

$$V_{II} = \frac{V_1 + V_2}{2} \times T_1 + V_2 \times T_2 \tag{13.13}$$

where

V_{II} = digester capacity required for second-stage digested sludge thickening and storage, ft^3 (m^3)

V_1 = volume of digested sludge feed = volume of average daily raw sludge, ft^3/day (m^3/d)

V_2 = volume of daily digested sludge accumulation in tank, ft^3/day (m^3/d)

T_1 = period required for thickening, days

T_2 = period of digested sludge storage, days

Figure 13.15 explains Eqs. (13.12) and (13.13).

Example 13.11

A high-rate trickling-filter plant treats a domestic wastewater flow of 0.48 mgd. Characteristics of the wastewater are identical to those in Table 12.1. Determine the digester capacities required for a single-stage floating-cover digestion system. Digested sludge is to be dried on sand beds, and the longest anticipated storage period required is 90 days.

Solution:

Equivalent population = 4000 at 0.24 lb per capita

Assume the following:

water content in raw sludge = 96%

volatile solids in raw sludge solids = 70%

water content of digested sludge = 94%

volatile solids reduction = 50%

The volume of raw sludge, from Eq. (13.3), is

$$V = \frac{4000 \times 0.24}{[(100 - 96)/100]62.4} = 385 \text{ ft}^3/\text{day}$$

The volume of digested sludge is

$$V = \frac{0.30(4000 \times 0.24) + 0.70 \times 0.50(4000 \times 0.24)}{[(100 - 94)/100]62.4} = 167 \text{ ft}^3/\text{day}$$

Substituting into Eq. (13.11) yields

$$V = [(385 + 167)/2]25 + 167 \times 90 = 21{,}900 \text{ ft}^3$$

Check the volatile solids loading:

$$\frac{0.70 \times 4000 \times 0.24}{21{,}900} = 0.031 \text{ lb/ft}^3\text{/day of VS}$$

Verify the digester capacity per capita:

$$\frac{21{,}900}{4000} = 5.5 \text{ ft}^3\text{/population equivalent}$$

(This value is in the range of the empirical design figure of 4–6 ft^3/population equivalent given in Section 13.16.)

Example 13.12

A high-rate digester operating at a minimum temperature of 30°C with a volume of 2800 m^3 is fed 180,000 l/d of raw sludge with 7400 kg of solids that are 70% volatile. Calculate the concentration of solids in the raw sludge, in the digested sludge assuming 50% volatile solids destruction, volatile solids loading, and detention time. Compare the loading and detention times to those given in Table 13.8.

Solution:

$$\text{Raw sludge solids} = \frac{7400 \times 100}{180{,}000} = 4.1\%$$

$$\text{Digested sludge solids} = \frac{(0.30 \times 7400 + 0.50 \times 0.70 \times 7400)100}{180{,}000} = 2.7\%$$

$$\text{Volatile solids loading} = \frac{0.70 \times 7400}{2800} = 1.85 \text{ kg/m}^3 \cdot \text{d}$$

$$\text{Detention time} = \frac{2800}{180} = 15.6 \text{ days}$$

Values in Table 13.8 are 1.6–3.2 $kg/m^3 \cdot d$ and 15 d.