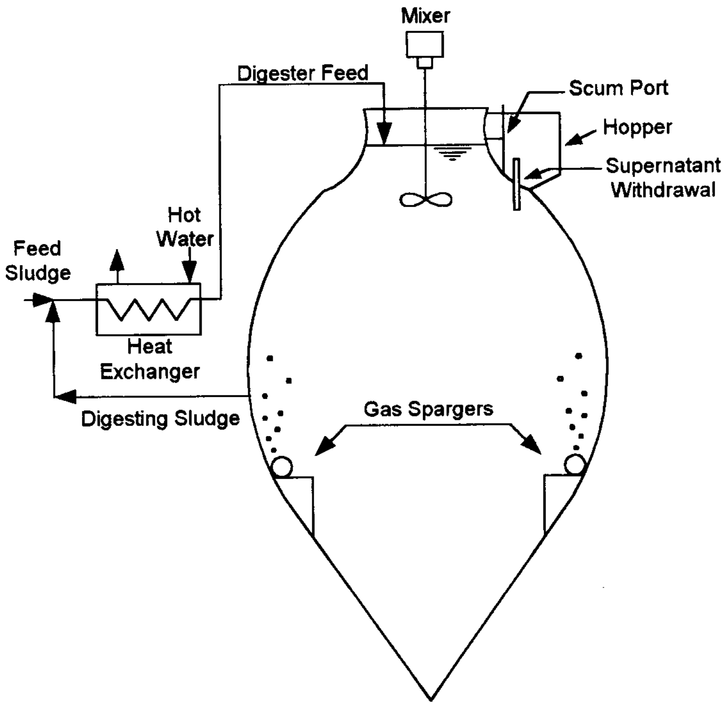

Figure 13.4 Egg shaped anaerobic digester.

that does accumulate. The waffle bottom digester is another configuration that facilitates grit and heavy solids removal.[72]

The purpose of anaerobic digestion is the stabilization of biodegradable particulate organic matter. Consequently, its performance can be quantified by the percent VS destruction. At an SRT of 15 to 20 days, 80 to 90% of the influent biodegradable particulate organic matter will be converted to methane gas.[58] This corresponds to destruction of about 60% of the VS contained in primary solids and 30 to 50% of the VS contained in waste activated sludges, as described further in Section 13.2.9.[21,46,58,72]

Many reference works and textbooks discuss two-stage anaerobic digestion, in which two digesters are operated in series.[46,52,72,75] Heating and mixing are provided in the first stage, where active digestion occurs, while quiescent conditions are provided in the second stage for liquid–solids separation. Supernatant from the second-stage is recycled to the liquid process train while thickened, settled solids are directed to further processing or ultimate disposal. Although of historical interest, use of the two-stage process has declined significantly in recent years for the following reasons:

- Experience indicates that while efficient liquid–solids separation will occur when treating primary solids or a mixture of primary solids and attached growth biomass, it can be quite poor when suspended growth biomass, either alone or mixed with primary solids, is digested. When suspended growth biomass is digested, the supernatant may be of poor quality, resulting biomass granules. Furthermore, the allowable organic loading rate is adversely impacted by the presence of suspended solids in the influent wastewater, special bioreactor configurations are required, and little process control is possible.

The design of AF systems is quite straightforward. Furthermore, they are not dependent on the development of a dense, settleable biomass because the media provides the primary mechanism for biomass retention. However, excessive accumulations of suspended solids can lead to plugging, which negatively impacts process performance; therefore, they are not suitable for wastewaters containing high concentrations of suspended solids. Little process control is possible, and the cost of the media and its associated supports can be relatively high.

Hybrid UASB/AF systems combine the advantages of their parent systems. However, they are still adversely impacted by the presence of suspended solids in the influent wastewater, and little process control is possible.

The performance of DSFF systems is not dependent on the development of settleable biomass and is less influenced by high concentrations of suspended solids in the influent wastewater. The suspended solids are not retained by the system, so their presence causes a poor-quality effluent unless it is treated in a downstream clarifier. As with the anaerobic filter, the cost for the media and its associated support system is relatively high, and little process control is possible.

Fluidized bed and expanded bed systems share many of the benefits and drawbacks of the other high-rate anaerobic processes, but they also possess some unique characteristics. The high specific surface areas of the carrier particles allow the development of exceptionally high biomass concentrations, thereby allowing small bioreactors to be used. The uniformly mixed conditions and turbulence provide an extremely uniform reaction environment with excellent mass transfer characteristics. As a consequence, the effluent quality achievable with FB/EB systems is generally superior to that from other high-rate anaerobic processes. Process performance is not dependent on the development of a settleable biomass, and process control is superior to that of the other high-rate processes. In contrast, power requirements can be high because of the high flow rates required to achieve the necessary upflow velocities. Fluidized bed and expanded bed bioreactors are not suitable for wastewaters containing high concentrations of suspended solids, require more process control, are more expensive, and are mechanically more complex than some of the other processes.

Although high organic removal rates can be achieved with all of the high-rate anaerobic processes, differences exist for soluble materials. The highest rates of soluble substrate removal are generally achieved in FB/EB systems because of their high biomass concentrations and excellent mass transfer characteristics. High soluble substrate removal rates can also be achieved in UASB and hybrid UASB/AF systems, particularly when a dense, readily settleable, granular sludge develops. This is because of the high biomass concentrations in the granular sludge bed and the mixing caused by the introduction of influent wastewater and the evolution of gas. Soluble substrate removal rates are lower in AF systems because of their lower biomass concentrations and poorer mixing conditions. Biomass concentrations are even lower in DSFF systems because the downward flow pattern results in reduced accumulation of suspended biomass. This causes lower soluble substrate removal rates. The lowest biomass concentrations occur in AC systems, causing the lowest soluble substrate removal rates. Although a settleable biomass is developed, mechanical mixing generally prevents the development of a dense, readily settleable granular sludge such as in UASB and hybrid UASB/AF systems.

13.1.7 Typical Applications

As discussed in Chapter 9, anaerobic processes are typically used to stabilize the organic matter present in wastewaters with biodegradable COD concentrations greater than about 1,000 mg/L. Although anaerobic systems have been applied to the treatment of more dilute wastewaters,[41,74] aerobic systems are often more economical for them.[23] Compared to aerobic systems, the advantages of anaerobic processes include less solids production, lower nutrient requirements, lower energy requirements, and the production of a potentially useful product (methane). On the other hand, the effluent quality from anaerobic processes is generally not as good as from aerobic processes, and aerobic polishing may be required to achieve effluent quality goals. Anaerobic processes can be more sensitive than aerobic processes to shock loads and toxic materials, although the anaerobic process technology developed in the past ten years has demonstrated significant resistance to them. Finally, anaerobic processes are capable of metabolizing some organic compounds not readily biodegraded in aerobic systems. Examples include chlorinated organics, which can be dechlorinated in anaerobic treatment systems even though they are not readily biodegraded in aerobic systems.[68]

Several factors affect the choice between anaerobic and aerobic treatment systems for wastewaters with biodegradable COD concentrations in the 1,000 to 4,000 mg/L range. One is wastewater temperature. Anaerobic processes perform best when operated at temperatures near the optimum for either mesophilic (30° to 40°C) or thermophilic (50° to 60°C) microorganisms. Deviations from these ranges can result in significant reductions in microbial activity and increases in the required SRT. In general, the impact of temperature on the required SRT is greater for anaerobic than for aerobic processes. This is offset somewhat because the methane produced in the anaerobic process can be used to heat the influent wastewater. Because the quantity of methane produced is a function of the concentration of biodegradable organic matter in the influent wastewater, the potential heat rise depends on the wastewater strength, as illustrated in Figure 13.17. Two cases are considered. One incorporates recovery of the heat in the bioreactor effluent and uses it to heat the influent wastewater while the other does not. Sufficient energy is available to achieve a significant temperature increase only for wastewaters with biodegradable COD concentrations greater than about 2,000 mg/L if heat recovery is practiced and around 7,000 mg/L if heat recovery is not practiced. Wastewater flow rate also affects the choice between aerobic and anaerobic systems for wastewaters containing 1,000 to 4,000 mg/L of biodegradable COD. The simplicity of aerobic systems generally favors their use for smaller wastewater flows, while the significant energy and solids production savings available favors the use of anaerobic systems for larger wastewater flows.[23]

Wastewater composition also affects the choice between anaerobic and aerobic systems. High-rate anaerobic treatment technology was developed for the treatment of SOM, and the presence of significant quantities of suspended solids adversely impacts its efficiency. As indicated in Figure 9.5, either acidogenesis or methanogenesis can be the rate limiting step in the anaerobic stabilization of SOM, with the nature of the organic matter determining which is slower. If the organic matter is

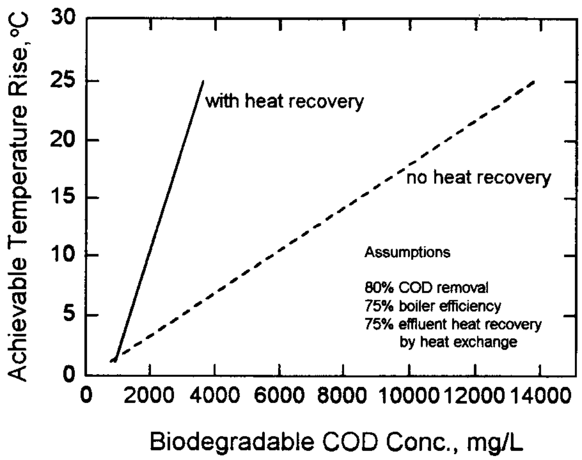

Figure 13.17 Relationship between wastewater strength and achievable temperature rise for anaerobic processes. (From E. R. Hall, Anaerobic treatment of wastewaters in suspended growth and fixed film processes. In *Design of Anaerobic Processes for the Treatment of Industrial and Municipal Wastes*. J. F. Malina, Jr. and F. G. Pohland, eds. Technomics Publishing, Lancaster, Pennsylvania, pp. 41–118, 1992. Copyright © Technomics Publishing Co., Inc.; reprinted with permission.)

predominantly simple carbohydrates and proteins, methanogenesis will be slower, but can still be accomplished at short SRTs. In fact, some of the high-rate anaerobic systems were developed for food processing wastes containing such constituents. On the other hand, wastes high in lipids require much longer SRTs for acidogenesis, which can increase the SRT required in an anaerobic system. Hydrolysis and fermentation are generally the rate limiting steps in the anaerobic stabilization of particulate organic matter, and longer SRTs are required for them as well. Furthermore, some of the suspended solids are likely to be nonbiodegradable, and will accumulate in the bioreactor, thereby reducing the specific activity of the anaerobic biomass. Both of these factors significantly affect the VOLs that can be applied to an anaerobic bioreactor and negatively impact its economics. The presence of inhibitory or toxic materials also results in significant increases in the required SRT, which negatively impacts the economics of anaerobic processes. Finally, as illustrated in Figure 9.2, differences also exist among anaerobic processes with respect to the waste strengths for which they are suited.

Anaerobic digestion is generally applied to the treatment of high-strength wastewaters, particularly those with high suspended solids concentrations. In fact, historically it has been one of the most widely used processes for stabilizing organic solids produced in wastewater treatment plants. As a consequence, several thousand operating facilities exist around the world. The uniform reaction conditions and long SRTs used provide the conditions necessary for hydrolysis and stabilization of these materials. Volumetric organic loadings approaching those in low-rate anaerobic systems are achieved in anaerobic digestion because of the high wastewater strengths applied. Anaerobic digesters are capital intensive, but have low operating costs. Consequently, they are generally found in larger wastewater treatment plants where the which an inhibitory response may be observed.[35,68,81] They may also be used to develop cultures capable of biodegrading a target compound.

The response of both aerobic and anaerobic processes to inhibitory organic chemicals is an area of continued research, and the reader is urged to consult the literature for on-going developments. This topic is discussed further in Chapter 22.

13.2.7 Nutrients

Like all other biochemical operations, nutrients are required by anaerobic processes because they are essential components of the biomass produced. However, biomass yields are much lower in anaerobic processes than in aerobic ones, and this results in reduced nutrient requirements.[23,62] While the nutrient requirements in Table 9.3 are appropriate for anaerobic processes, only about 4 to 10% of the COD removed is converted into biomass, and thus the nutrient quantities required will be much lower. Consequently, adequate nutrients will generally be available when complex wastes are being treated. However, nutrient addition may be required when carbon rich industrial wastes are being treated. Such wastewaters may be deficient in the macronutrients nitrogen and phosphorus. The concentrations of micronutrients such as iron, nickel, cobalt, sulfur, and calcium may also be limiting.[58,62,68] Nickel and cobalt are particularly important for growth of methanogens.

13.2.8 Mixing

As discussed in Section 13.1 and indicated in Table 13.1, an effective mixing system is critical to the successful operation of an anaerobic process. It provides intimate contact between the microorganisms and their substrates, reduces resistance to mass transfer, minimizes the buildup of inhibitory reaction intermediates, and stabilizes environmental conditions. Mixing is an integral part of the design of many high-rate systems. For example, introduction of the influent wastewater directly into the sludge bed in a UASB bioreactor promotes intimate contact between the wastewater and the granules. Likewise, fluidization in a FB/EB bioreactor promotes intense mixing, which allows high process loadings. Mixing is less efficient in other high-rate anaerobic processes, such as AF and DSFF systems, and this is one of the factors restricting their loading. Likewise, poorer mixing, along with less effective mechanisms for solids retention, result in lower allowable loadings for low-rate anaerobic processes.

Mechanical or gas mixing is an integral component of some anaerobic processes, such as anaerobic digestion and anaerobic contact. Several systems have been developed to mix these processes, and the reader is referred to design references for a detailed discussion.[46,72,75] The contents of such processes are viscous, thixotropic slurries, and mixing criteria applied to other processes are not generally applicable. The solids and wastewaters treated may contain rags and hair, which can wrap around and damage mixing equipment, and inorganic solids such as grit, which can accumulate and reduce the effective volume of the bioreactor if mixing is inadequate. Floating material can accumulate in a scum layer, which also reduces effective volume. Given these challenges, it is interesting that anaerobic digester volumetric power inputs are often lower than those used in aerobic suspended growth processes, such as activated sludge and aerated lagoons. Volumetric power inputs in anaerobic

0.7 standard m^3 of methane produced/kg of VS destroyed, as presented in Section 13.1.1. The process design for an anaerobic digester to stabilize the waste solids produced at a municipal wastewater treatment plant is illustrated in the following example.

Example 13.3.1.1

An anaerobic digestion system is to be designed to stabilize the solids produced by a municipal wastewater treatment plant. It must be capable of destroying pathogens, implying that the SRT must be at least 15 days at 35°C. The estimated masses of primary solids and waste activated sludge to be produced daily under various conditions are given in Table E13.1. After blending and thickening, the solids concentration entering the digestion system is expected to average 60 g/L (kg/m^3) and to range from 50 to 70 g/L. The volatile solids concentration is 75% of the total solids concentration. Design the system with multiple digesters, but assume that one will be taken out of service for cleaning only under average loading conditions.

a. What solids flow rates must be processed by the system?
The mass flow rates of dry solids under various conditions are given in Table E13.1. These may be converted to volumetric flow rates by assuming solids concentrations. It is likely that the thickener can maintain the average solids concentration under average and maximum month conditions, but that performance will deteriorate during the maximum solids production week. Consequently, the average solids concentration is used to calculate the average and maximum month volumetric flow rates but the minimum solids concentration is used to calculate the maximum week volumetric flow rate. The results are summarized in Table E13.2.

b. What SRT should be used in the design?
Because an excellent degree of solids stabilization is desired under average loading conditions, an SRT of 20 days is appropriate, based on Figure 13.23. This value should be attained even during the maximum solids production month, but it is unrealistic to maintain it during the maximum week. However, to ensure pathogen destruction under all conditions, an SRT of at least 15 days must be maintained even during the maximum week.

c. What effective total digester volume must be provided?
The required effective digester volume must be calculated in two steps. First the volume required for each flow rate must be calculated based on the assumption that all units are in service. Since the SRT is the same as the

Table E13.1 Solids Production Rates for Design of the Anaerobic Digester in Example 13.3.1.1

Type of solids	Mass of dry solids, kg/day		
	Average	Maximum month	Maximum week
Primary	18,000	22,500	27,000
WAS	16,000	20,000	24,000
Total	34,000	42,500	51,000

Table E13.2 Anticipated Volumetric Solids Flow Rates Under Various Conditions for Example 13.3.1.1

	Solids mass kg/day	Concentration kg/m^3	Flow rate m^3/day
Average	34,000	60	567
Maximum month	42,500	60	708
Maximum week	51,000	50	1,020

HRT, this is done by multiplying the volumetric flow rate by the SRT. The results are given in Table E13.3. If all units could be kept in service all of the time, then the maximum week would control the design and a total volume of 15,300 m^3 would be required. However, it must be possible to take a unit out of service for maintenance during average conditions, so this must also be considered. If two units were used, then one would have to have a volume of 11,340 m^3 under average conditions to maintain the 20 day SRT, making the total volume 22,680 m^3. This is larger than the volume required during the maximum month or maximum week since both units would be in service then, and would control. Similarly, if three units were used, two would have to have a total volume of 11,340 m^3 under average conditions, making the system volume 17,100 m^3. This, too, is larger than the volume required during the maximum month or maximum week, and would control. In this case, using three units reduces the total volume by 25%.

Some savings in digester volume could be achieved by allowing the SRT to decrease to 15 days during the period when one unit was out of service for maintenance. This would have only a minimal impact on performance, as seen by Figure 13.23, and would still ensure pathogen destruction. If this were done, the total effective volume for a two unit system under average conditions would be 17,010 m^3. This is larger than the volumes required for the maximum month and maximum week, which would remain unchanged from the values in Table E13.3, and thus would control. However, for a three unit system, the total effective volume under average conditions would be 12,760 m^3. This is smaller than the volume required for the maximum month and maximum week, so the maximum week would control. Thus, a three unit system would have to have a total volume of 15,300 m^3. Consequently, in this case, using three units only reduces the total volume by 10%.

The choice between these possible designs would have to be made on the basis of economics. However, given the small sacrifice in performance associated with short-term operation at a 15 day SRT, a reasonable decision would be to allow the SRT to drop to 15 days when one unit is out of service for maintenance and to use two units, with a total volume of 17,010 m^3.

d. What volatile solids destruction efficiency and methane production rate would be achieved under the three loading conditions with all units in service?

The volatile solids destruction efficiencies for the primary solids and waste activated sludge must be estimated separately and then combined to obtain the overall digester performance. From Figure 13.23, the COD destruction efficiency for primary solids, which equals the volatile solids destruction

18. Total ammonia (the sum of the free plus ionized ammonia species) concentrations of 50 to 200 mg/L as N stimulate microbial growth in anaerobic processes. However, free ammonia (NH_3) can be inhibitory if it reaches concentrations of about 100 mg/L as N. The fraction of total ammonia present as free ammonia increases with increasing temperature and pH.
19. Three strategies are available for reducing ammonia toxicity, including: (1) reducing the temperature, (2) reducing the pH, and (3) reducing the total ammonia concentration. The pH can be reduced by the addition of hydrochloric acid.
20. Dissolved sulfide is toxic to anaerobic processes at a concentration of about 100 mg/L (200 mg/L with acclimation). Sulfide is formed by the destruction of sulfur-containing organic matter and by the reduction of sulfate. The possibility of sulfide inhibition must be considered for wastewaters with COD/$SO_4^=$ ratios less than about 7.5. Sulfide reacts with heavy metals, forming insoluble precipitates that are not inhibitory. The reduction of sulfate requires electrons from biodegradable organic matter, thereby decreasing the number available for methane production. Sulfide production also decreases the degree of waste stabilization because soluble sulfide exerts an oxygen demand.
21. Dissolved heavy metals can be quite toxic to anaerobic processes. However, the presence of dissolved sulfides minimizes their effect since the sulfide precipitates of heavy metals are quite insoluble.
22. Evidence concerning inhibition by volatile acids is mixed. Andrews and coworkers have suggested that it is the nonionized form of the VFAs that is actually inhibitory, with concentrations on the order of 30 to 60 mg/L having an effect.[2,3,4] At neutral pH relatively high total VFA concentrations are required to cause nonionized concentrations in that range.
23. A wide variety of organic compounds can inhibit anaerobic processes. However, biomass can become acclimated to many of these compounds and cultures can acquire the ability to biodegrade many of them.
24. Because the net process yield is low in anaerobic systems, nutrient limitations are seldom encountered when treating complex wastewaters, but they may occur when treating certain high-strength industrial wastewaters. Nutrients of concern include the macronutrients nitrogen and phosphorus, and the micronutrients iron, nickel, cobalt, sulfur, and calcium.
25. Several approaches are used to mix anaerobic processes, including effluent recirculation, gas recirculation, and mechanical mixing. Mixing in anaerobic digesters is particularly challenging because of the thixotropic nature of the solids processed.
26. The nature of the organic matter fed to an anaerobic process can dramatically affect its performance. For example, the biodegradable portion of the particulate organic matter in primary solids is typically about 70%, while the biodegradable portion of the particulate organic matter in waste activated sludge typically ranges from 30 to 50%, depending on the SRT of the activated sludge system from which it came.
27. Anaerobic digesters are typically designed with SRTs on the order of 15 to 20 days at 35°C to achieve good stabilization of biodegradable organic

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