Part V

Math Concepts: Wastewater Engineering

CHAPTER 16

Wastewater Calculations

> In the glory days of Empire Textiles, the solvents and dyes used on the fabrics were dumped directly into the river, staining the banks below the falls red and green and yellow, according to the day of the week and the size of the batch. The sloping banks contained rings, like those in a tree trunk, except these were in rainbow colors, they recorded not the years but the rise and fall of the river. Even now, fifty years later, only the hardiest weeds and scrub trees grew south of the pavement on Front Street, and when the brush was periodically cleared, surprising patches of fading chartreuse and magenta were revealed.
>
> **Richard Russo, *Empire Falls* (2001)**

16.1 INTRODUCTION

Standard wastewater treatment consists of a series of steps or unit processes tied together (see Figure 16.1) with the ultimate purpose of taking the raw sewage influent and turning it into an effluent that is often several times cleaner than the water in the outfalled water body. As we did for the water calculations presented in Chapter 15, we present math calculations related to wastewater at the operations level as well as the engineering level. Again, our purpose in using this format is consistent with our intention to provide a single, self-contained, ready reference source.

16.2 PRELIMINARY TREATMENT CALCULATIONS

The initial stage of treatment in the wastewater treatment process (following collection and influent pumping) is *preliminary treatment.* Process selection is normally based upon the expected characteristics of the influent flow. Raw influent entering the treatment plant may contain many kinds of materials (trash); preliminary treatment protects downstream plant equipment by removing these materials, which could cause clogs, jams, or excessive wear in plant machinery. In addition, the removal of various materials at the beginning of the treatment train saves valuable space within the treatment plant.

Two of the processes used in preliminary treatment include screening and grit removal. However, preliminary treatment may also include other processes, each designed to remove a specific type of material that could present a potential problem for downstream unit treatment processes. These processes exclude shredding, flow measurement, preaeration, chemical addition, and flow equalization. Except in extreme cases, plant design will not include all of these items. In this chapter, we focus on and describe typical calculations used in two of these processes: screening and grit removal.

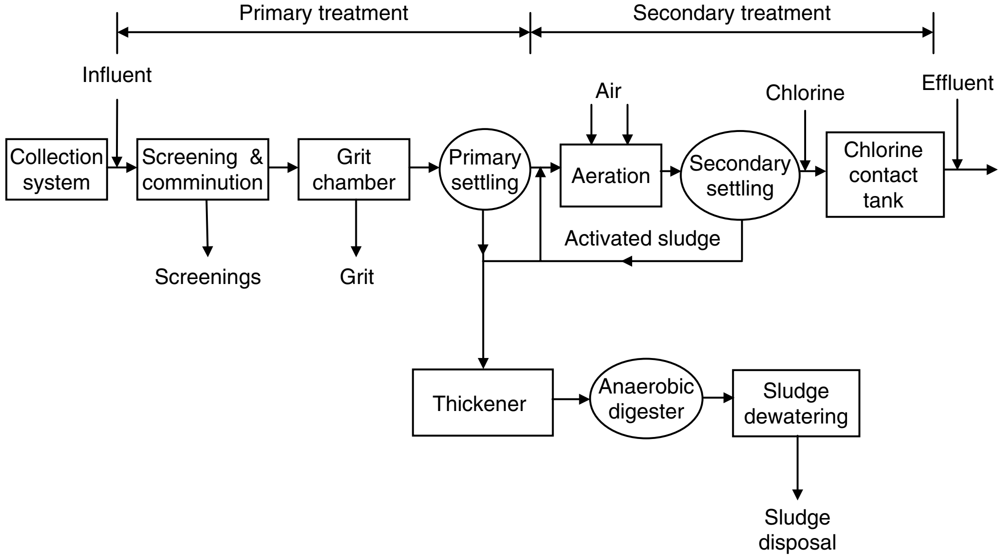

Figure 16.1 Schematic of an example wastewater treatment process providing primary and secondary treatment using activated sludge process. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1*,* Lancaster, PA: Technomic Publishing Company.)

16.2.1 Screening

Screening removes large solids (rags, cans, rocks, branches, leaves, and roots, for example) from the flow before the flow moves on to downstream processes.

16.2.2 Screenings Removal Calculations

Wastewater operators responsible for screenings disposal are typically required to keep a record of the amount of screenings removed from the flow (the plant engineer, obviously, is responsible for ensuring the accuracy of these records). To keep and maintain accurate screening records, the volume of screenings withdrawn must be determined. Two methods are commonly used to calculate the volume of screenings withdrawn:

$$\text{Screenings Removed, ft}^3\text{/day} = \frac{\text{Screenings, ft}^3}{\text{days}} \tag{16.1}$$

$$\text{Screenings Removed, ft}^3\text{/MG} = \frac{\text{Screenings, ft}^3}{\text{Flow, MG}} \tag{16.2}$$

Example 16.1

Problem:

A total of 65 gal of screenings is removed from the wastewater flow during a 24-h period. What is the screenings removal reported as cubic feet per day?

Solution:

First, convert gallon screenings to cubic feet:

$$\frac{65 \text{ gal}}{7.48 \text{ gal/ft}^3} = 8.7 \text{ ft}^3 \text{ screenings}$$

Next, calculate screenings removed as cubic feet per day:

$$\text{Screenings Removed, ft}^3\text{/day} = \frac{8.7 \text{ ft}^3}{1 \text{ day}} = 8.7 \text{ ft}^3\text{/day}$$

Example 16.2

Problem:

During 1 week, a total of 310 gal of screenings was removed from the wastewater screens. What is the average removal in cubic feet per day?

Solution:

First, gallon screenings must be converted to cubic feet screenings:

$$\frac{310 \text{ gal}}{7.48 \text{ gal/ft}^3} = 41.4 \text{ ft}^3 \text{ screenings}$$

Next, the screenings removal calculation is completed:

$$\text{Screenings Removed, ft}^3\text{/day} = \frac{41.4 \text{ ft}^3}{7 \text{ day}} = 5.9 \text{ ft}^3\text{/day}$$

16.2.3 Screenings Pit Capacity Calculations

Recall that detention time may be considered the time required to flow through a basin or tank, or the time required to fill a basin or tank at a given flow rate. In screenings pit capacity problems, the time required to fill a screenings pit is calculated. The equation used for these types of problems is:

$$\text{Screenings Pit Fill Time, days} = \frac{\text{Volume of Pit, ft}^3}{\text{Screenings Removed, ft}^3\text{/day}} \tag{16.3}$$

Example 16.3

Problem:

A screenings pit has a capacity of 500 ft^3. (The pit is actually larger than 500 ft^3 to accommodate soil for covering.) If an average of 3.4 ft^3 of screenings is removed daily from the wastewater flow, in how many days will the pit be full?

Solution:

$$\text{Screenings Pit Fill Time, days} = \frac{\text{Volume of Pit, ft}^3}{\text{Screenings Removed, ft}^3\text{/day}}$$

$$\frac{500\ \text{ft}^3}{3.4\ \text{ft}^3\text{/day}} = 147.1\ \text{days}$$

Example 16.4

Problem:

A plant has been averaging a screenings removal of 2 ft^3/MG. If the average daily flow is 1.8 MGD, how many days will it take to fill the pit with an available capacity of 125 ft^3?

Solution:

The filling rate must first be expressed as cubic feet per day:

$$\frac{(2\ \text{ft}^3)\ (1.8\ \text{MGD})}{\text{MG}} = 3.6\ \text{ft}^3\text{/day}$$

$$\text{Screenings Pit Fill Time, days} = \frac{125\ \text{ft}^3}{3.6\ \text{ft}^3\text{/day}}$$

$$= 34.7\ \text{days}$$

Example 16.5

Problem:

A screenings pit has a capacity of 12 yd^3 available for screenings. If the plant removes an average of 2.4 ft^3 of screenings per day, in how many days will the pit be filled?

Solution:

Because the filling rate is expressed as cubic feet per day, the volume must be expressed as cubic feet:

$$(12\ \text{yd}^3)\ (27\ \text{ft}^3\text{/yd}^3) = 324\ \text{ft}^3$$

Now calculate fill time:

$$\text{Screenings Pit Fill Time, days} = \frac{\text{Volume of Pit, ft}^3}{\text{Screenings Removed, ft}^3\text{/day}}$$

$$\frac{324\ \text{ft}^3}{2.4\ \text{ft}^3\text{/day}}$$

135 days

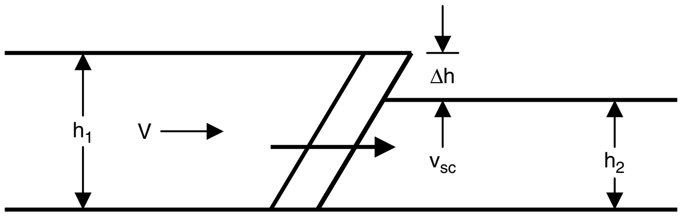

Figure 16.2 Water profile through a screen.

16.2.4 Headloss through Bar Screen

Headloss through a bar screen is determined by using Bernoulli's equation (see Figure 16.2):

$$h_1 + \frac{v^2}{2g} = h_2 + \frac{v_{sc}^2}{2g} + \text{Losses} \quad (16.4)$$

where
h_1 = upstream depth of flow
h_2 = downstream depth of flow
g = acceleration of gravity
v = upstream velocity
v_{sc} = velocity of flow through the screen

The losses can be incorporated into a coefficient.

$$\Delta h = h_1 - h_2 = \frac{1}{2gC_d^2}(v_{sc}^2 - v^2) \quad (16.5)$$

where C_d = discharge coefficient (typical value = 0.84), a value usually supplied by manufacturer or determined through experimentation.

16.2.5 Grit Removal

The purpose of grit removal is to remove inorganic solids (sand, gravel, clay, egg shells, coffee grounds, metal filings, seeds, and other similar materials) that could cause excessive mechanical wear. Several processes or devices are used for grit removal, all based on the fact that grit is heavier than the organic solids, which should be kept in suspension for treatment in unit processes that follow grit removal. Grit removal may be accomplished in grit chambers or by the centrifugal separation of biosolids. Processes use gravity/velocity, aeration, or centrifugal force to separate the solids from the wastewater.

16.2.6 Grit Removal Calculations

Wastewater systems typically average 1 to 15 ft^3 of grit per million gallons of flow (sanitary systems: 1 to 4 ft^3/MG; combined wastewater systems average from 4 to 15 ft^3/million gals of flow), with higher ranges during storm events. Generally, grit is disposed of in sanitary landfills. Because of this process, for planning purposes, operators must keep accurate records of grit removal. Most often, the data are reported as cubic feet of grit removed per million gallons of flow:

$$\text{Grit Removed, ft}^3/\text{MG} = \frac{\text{Grit Volume, ft}^3}{\text{Flow, MG}} \tag{16.6}$$

Over a given period, the average grit removal rate at a plant (at least a seasonal average) can be determined and used for planning purposes. Typically, grit removal is calculated as cubic yards because excavation is normally expressed in terms of cubic yards:

$$\text{Cubic Yards Grit} = \frac{\text{Total Grit, ft}^3}{27\ \text{ft}^3/\text{yd}^3} \tag{16.7}$$

Example 16.6

Problem:
A treatment plant removes 10 ft^3 of grit in 1 day. How many cubic feet of grit are removed per million gallons if the plant flow is 9 MGD?

Solution:

$$\text{Grit Removed, ft}^3/\text{MG} = \frac{\text{Grit Volume, ft}^3}{\text{Flow, MG}}$$

$$\frac{10\ \text{ft}^3}{9\ \text{MG}} = 1.1\text{ft}^3/\text{MG}$$

Example 16.7

Problem:
The total daily grit removed for a plant is 250 gal. If the plant flow is 12.2 MGD, how many cubic feet of grit are removed per million gallons of flow?

Solution:
First, convert gallon grit removed to cubic feet:

$$\frac{250\ \text{gal}}{7.48\ \text{gal/ft}^3} = 33\ \text{ft}^3$$

Next, complete the calculation of cubic feet per million gallons:

$$\text{Grit Removed, ft}^3/\text{MG} = \frac{\text{Grit Volume, ft}^3}{\text{Flow, MG}}$$

$$\frac{33\ \text{ft}^3}{12.2\ \text{MGD}} = 2.7\ \text{ft}^3/\text{MGD}$$

Example 16.8

Problem:

The monthly average grit removal is 2.5 ft^3/MG. If the monthly average flow is 2,500,000 gpd, how many cubic yards must be available for grit disposal if the disposal pit has a 90-day capacity?

Solution:

First, calculate the grit generated each day:

$$\frac{(2.5\ \text{ft}^3)}{\text{MGD}}(2.5\ \text{MGD}) = 6.25\ \text{ft}^3\ \text{each day}$$

The cubic feet of grit generated for 90 days would be

$$\frac{(6.25\ \text{ft}^3)}{\text{day}}(90\ \text{days}) = 562.5\ \text{ft}^3$$

Convert cubic feet to cubic yards of grit:

$$\frac{562.5\ \text{ft}^3}{27\ \text{ft}^3/\text{yd}^3} = 21\ \text{yd}^3$$

16.2.7 Grit Channel Velocity Calculation

The optimum velocity in sewers is approximately 2 ft/sec at peak flow because this velocity normally prevents solids from settling from the lines. However, when the flow reaches the grit channel, the velocity should decrease to about 1 ft/sec to permit heavy inorganic solids to settle. In the example calculations that follow, we describe how the velocity of the flow in a channel can be determined by the float and stopwatch method and by channel dimensions.

Example 16.9

Velocity by Float and Stopwatch

$$\text{Velocity, fps} = \frac{\text{Distance Traveled, ft}}{\text{Time Required, sec}} \tag{16.8}$$

Problem:

A float takes 30 sec to travel 37 ft in a grit channel. What is the velocity of the flow in the channel?

Solution:

$$\text{Velocity, fps} = \frac{37\ \text{ft}}{30\ \text{sec}} = 1.2\ \text{fps}$$

Example 16.10

Velocity by Flow and Channel Dimensions

This calculation can be used for a single channel or tank or for multiple channels or tanks with the same dimensions and equal flow. If the flow through each unit of the unit dimensions is unequal, the velocity for each channel or tank must be computed individually.

$$\text{Velocity, fps} = \frac{\text{Flow, MGD} \times 1.55 \text{ cfs/MGD}}{\text{\# Channels in Service} \times \text{Channel Width, ft} \times \text{Water Depth, ft}} \quad (16.9)$$

Problem:

The plant is currently using two grit channels. Each channel is 3 ft wide and has a water depth of 1.3 ft. What is the velocity when the influent flow rate is 4.0 MGD?

Solution:

$$\text{Velocity, fps} = \frac{4.0 \text{ MGD} \times 1.55 \text{ cfs/MGD}}{2 \text{ Channels} \times 3 \text{ ft} \times 1.3 \text{ ft}}$$

$$\text{Velocity, fps} = \frac{6.2 \text{ cfs}}{7.8 \text{ ft}^2} = 0.79 \text{ fps}$$

Key point: Because 0.79 is within the 0.7 to 1.4 level, the operator of this unit would not make any adjustments.

Key point: The channel dimensions must always be in feet. Convert inches to feet by dividing by 12 in. per foot.

16.2.7.1 Required Settling Time

This calculation can be used to determine the time required for a particle to travel from the surface of the liquid to the bottom at a given settling velocity. To compute the settling time, settling velocity in feet per second must be provided or determined by experiment in a laboratory.

$$\text{Settling Time, sec} = \frac{\text{Liquid Depth, ft}}{\text{Settling, Velocity, fps}} \quad (16.10)$$

Example 16.11

Problem:

The plant's grit channel is designed to remove sand, which has a settling velocity of 0.080 ft/sec. The channel is currently operating at a depth of 2.3 ft. How many seconds will it take for a sand particle to reach the channel bottom?

Solution:

$$\text{Settling Time, sec} = \frac{2.3 \text{ ft}}{0.080 \text{ fps}} = 28.8 \text{ sec}$$

16.2.7.2 Required Channel Length

This calculation can be used to determine the length of channel required to remove an object with a specified settling velocity.

$$\text{Required Channel Length} = \frac{\text{Channel Depth, ft} \times \text{Flow Velocity, fps}}{0.080 \text{ fps}} \tag{16.11}$$

Example 16.12

Problem:

The plant's grit channel is designed to remove sand, which has a settling velocity of 0.080 ft/sec. The channel is currently operating at a depth of 3 ft. The calculated velocity of flow through the channel is 0.85 ft/sec. The channel is 36 ft long; is it long enough to remove the desired sand particle size?

Solution:

$$\text{Required Channel Length} = \frac{3 \text{ ft} \times 0.85 \text{ fps}}{0.080 \text{ fps}} = 31.9 \text{ ft}$$

Yes, the channel is long enough to ensure that all the sand will be removed.

16.2.7.3 Velocity of Scour

The Camp–Shields equation (Camp, 1942) is used to estimate the velocity of scour necessary to resuspend settled organics:

$$v_s = \sqrt{\frac{8kgd}{f}\,\frac{p_p - p}{p}} \tag{16.12}$$

where
v_s = velocity of scour
d = nominal diameter of the particle
k = empirically determined constant
f = Darcy–Weisbach friction factor

If the channel is rectangular and discharges over a rectangular weir, the discharge relation based on Bernoulli's equation is:

$$Q = C_d A\sqrt{2gH} = C_w H^{3/2} \tag{16.13}$$

where
w = width of the channel
A = cross-sectional area of the channel
C_d = discharge coefficient
C = equal to $C_d\sqrt{2g}$
H = depth of flow in the channel

The horizontal velocity, v_h, is related to the discharge rate and channel velocity by:

$$= \frac{Q}{A} = \frac{Q}{wH} = CH^{1/2} = C\left(\frac{Q}{C_w}\right)^{1/3} \tag{16.14}$$

16.3 PRIMARY TREATMENT CALCULATIONS

Primary treatment (primary sedimentation or clarification) should remove organic settleable and organic floatable solids. Poor solids removal during this step of treatment may cause organic overloading of the biological treatment processes following primary treatment. Normally, each primary clarification unit can be expected to remove 90 to 95% of settleable solids; 40 to 60% of the total suspended solids; and 25 to 35% of BOD.

16.3.1 Process Control Calculations

As with many other wastewater treatment plant unit processes, several process control calculations may be helpful in evaluating the performance of the primary treatment process. Process control calculations are used in the sedimentation process to determine:

- Percent removal
- Hydraulic detention time
- Surface loading rate (surface settling rate)
- Weir overflow rate (weir loading rate)
- Biosolids pumping
- Percent total solids (% ts)
- BOD and SS removed, pounds per day

In the following subsections, we take a closer look at a few of these process control calculations and example problems.

> *Key point*: The calculations presented in the following sections allow determination of values for each function performed. Again, keep in mind that an optimally operated primary clarifier should have values in an expected range. Recall that the expected range percentage removal for a primary clarifier is

- Settleable solids: 90 to 95%
- Suspended solids: 40 to 60%
- BOD: 25 to 35%

The expected range of hydraulic detention time for a primary clarifier is 1 to 3 h. The expected range of surface loading/settling rate for a primary clarifier is 600 to 1200 gpd/ft^2 (ballpark estimate). The expected range of weir overflow rate for a primary clarifier is 10,000 to 20,000 gpd/ft.

16.3.2 Surface Loading Rate (Surface Settling Rate/Surface Overflow Rate)

Surface loading rate is the number of gallons of wastewater passing over 1 ft^2 of tank per day. This can be used to compare actual conditions with design. Plant designs generally use a surface-loading rate of 300 to 1200 gpd/ft^2.

$$\text{Surface Loading Rate, gpd/ft}^2 = \frac{\text{gal/day}}{\text{Surface Tank Area, ft}^2} \tag{16.15}$$

Example 16.13

Problem:

The circular settling tank has a diameter of 120 ft. If the flow to the unit is 4.5 MGD, what is the surface loading rate in gallons per day per square foot?

Solution:

$$\text{Surface Loading Rate} = \frac{4.5\text{ MGD} \times 1{,}000{,}000\text{ gal/MGD}}{0.785 \times 120\text{ ft} \times 120\text{ ft}} = 398\text{ gpd/ft}^2$$

Example 16.14

Problem:

A circular clarifier has a diameter of 50 ft. If the primary effluent flow is 2,150,000 gpd, what is the surface overflow rate in gallons per day per square foot?

Solution:

Key point: Remember that area = (0.785) (50 ft) (50 ft)

$$\text{Surface Overflow Rate} = \frac{\text{Flow, gpd}}{\text{Area, ft}^2}$$

$$\frac{2{,}150{,}000}{(0.785)\ (50\text{ ft})\ (50\text{ ft})} = 1{,}096\text{ gpd/ft}^2$$

Example 16.15

Problem:

A sedimentation basin 90 ft by 20 ft receives a flow of 1.5 MGD. What is the surface overflow rate in gallons per day per square foot?

Solution:

$$\text{Surface Overflow Rate} = \frac{\text{Flow, gpd}}{\text{Area, ft}^2}$$

$$= \frac{1{,}500{,}000\text{ gpd}}{(90\text{ ft})\ (20\text{ ft})}$$

$$= 833\text{ gpd/ft}^2$$

16.3.3 Weir Overflow Rate (Weir Loading Rate)

A weir is a device used to measure wastewater flow. *Weir overflow rate (weir loading rate)* is the amount of water leaving the settling tank per linear foot of water. The result of this calculation can be compared with design. Normally, weir overflow rates of 10,000 to 20,000 gal/day/ft are used in the design of a settling tank.

$$\text{Weir Overflow Rate, gpd/ft} = \frac{\text{Flow, gal/day}}{\text{Weir Length, ft}} \tag{16.16}$$

Key point: In calculating weir circumference, use total feet of weir = (3.14) (weir diameter, feet).

Example 16.16

Problem:

The circular settling tank is 80 ft in diameter and has a weir along its circumference. The effluent flow rate is 2.75 MGD. What is the weir overflow rate in gallons per day per foot?

Solution:

$$\text{Weir Overflow Rate, gpd/ft} = \frac{2.75\text{ MGD} \times 1{,}000{,}000\text{ gal}}{3.14 \times 80\text{ ft}} = 10{,}947\text{ gal/day/ft}$$

Key point: Notice that 10,947 gal/day/ft is above the recommended minimum of 10,000.

Example 16.17

Problem:

A rectangular clarifier has a total of 70 ft of weir. What is the weir overflow rate in gallons per day per square foot when the flow is 1,055,000 gpd?

Solution:

$$\text{Weir Overflow Rate, gpd/ft} = \frac{\text{Flow, gal/day}}{\text{Weir Length, ft}}$$

$$= \frac{1{,}055{,}000\text{ gpd}}{70\text{ ft}} = 15{,}071\text{ gpd}$$

16.3.4 Primary Sedimentation Basins

Example 16.18

Problem:

Two rectangular settling tanks are each 8 m wide, 26 m long, and 2.5 m deep. Each is used alternatively to treat 1800 m^3 in a 12-h period. Compute the surface overflow (settling) rate, detention time, horizontal velocity, and outlet weir-loading rate using an H-shaped weir with three times width.

Solution:

Step 1. Determine the design flow Q:

$$Q = \frac{1800 \text{ m}^3}{12 \text{ h}} \times \frac{24 \text{ h}}{1 \text{ day}}$$

$$= 3600 \text{ m}^3/\text{day}$$

Step 2. Compute surface overflow rate v_o:

$$V_o = Q/A = 3600 \text{ m}^3/\text{day} \div (8 \text{ m} \times 26 \text{ m})$$

$$= 17.3 \text{ m}^3 \ (\text{m}^2 \cdot \text{day})$$

Step 3. Compute detention time *t*:

$$\text{Tank Volume V} = 8 \text{ m} \times 26 \text{ m} \times 2.5 \text{ m} \times 2$$

$$= 1040 \text{ m}_3$$

$$t = V/Q = 1040 \text{ m}^3/(3600 \text{ m}^3/\text{day})$$

$$= 0.289 \text{ day}$$

$$= 6.9 \text{ h}$$

Step 4. Compute horizontal velocity v_h:

$$V_h = \frac{3600 \text{ m}^3/\text{day}}{8 \text{ m} \times 2.5 \text{ m}}$$

$$= 180 \text{ m/day}$$

$$= 0.125 \text{ m/min}$$

$$= 0.410 \text{ ft/min}$$

Step 5. Compute outlet weir loading, *wl:*

$$\text{wl} = \frac{3600 \text{ m}^3/\text{day}}{8 \text{ m} \times 3 \text{ m}} = 150 \text{ m}^3/(\text{day} \cdot \text{m})$$

$$= 12{,}100 \text{ gal/(day)}$$

16.4 BIOSOLIDS PUMPING

Determination of biosolids pumping (the quantity of solids and volatile solids removed from the sedimentation tank) provides accurate information needed for process control of the sedimentation process.

$$\text{Solids Pumped} = \text{Pump Rt., gpm} \times \text{Pump Time, min/day} \times 8.34 \text{ lb/gal} \times \%\text{ Solid} \quad (16.17)$$

$$\text{Volatile Solids/lb/day} = \text{Pump Rt.} \times \text{Pump Time } 8.34 \times \%\text{ Solids} \times \%\text{ Vol. Matter} \quad (16.18)$$

Example 16.19

Problem:

The biosolids pump operates 30 min/h and delivers 25 gal/min of biosolids. Laboratory tests indicate that the biosolids are 5.3% solids and 68% volatile matter. Assuming a 24-h period, how many pounds of volatile matter are transferred from the settling tank to the digester?

Solution:

$$\text{Pump Time} = 30 \text{ min/hr}$$

$$\text{Pump Rate} = 25 \text{ gpm}$$

$$\%\text{ Solids} = 5.3\%$$

$$\%\text{ V.M.} = 68\%$$

$$\text{Volatile Solids, lb/day} = 25 \text{ gpm} \times (30 \text{ min/h} \times 24 \text{ h/day}) \times 8.34 \text{ lb/gal} \times 0.053 \times 0.68$$

$$= 5410 \text{ lb/day}$$

16.4.1 Percent Total Solids (% TS)

Problem:

A settling tank biosolids sample is tested for solids. The sample and dish weigh 73.79 g. The dish alone weighs 21.4 g. After drying, the dish with dry solids weighs 22.4 g. What is the percent total solids (% TS) of the sample?

Solution:

Sample + Dish	73.79 g
Dish alone	–21.40 g
	52.39 g

Dish + Dry Solids	22.4 g
Dish alone	–21.4 g
	1.0 g

$$\frac{1.0 \text{ g}}{52.39 \text{ g}} \times 100\% = 1.9\%$$

16.4.2 BOD and SS Removed, Pounds per Day

To calculate the pounds of BOD or suspended solids removed each day, we need to know the milligrams per liter of BOD or SS removed and the plant flow. Then, we can use the milligrams-per-liter to pounds-per-day equation:

$$\text{SS Removed} = \text{mg/L} \times \text{MGD} \times 8.34 \text{ lb/gal} \tag{16.19}$$

Example 16.20

Problem:
If 120 mg/L suspended solids are removed by a primary clarifier, how many pounds per day of suspended solids are removed when the flow is 6,250,000 gpd?

Solution:

$$\text{SS Removed} = 120 \text{ mg/L} \times 6.25 \text{ MGD} \times 8.34 \text{ lb/gal} = 6255 \text{ lb/day}$$

Example 16.21

Problem:
The flow to a secondary clarifier is 1.6 MGD. If the influent BOD concentration is 200 mg/L and the effluent BOD concentration is 70 mg/L, how many pounds of BOD are removed daily?

Solution:

$$\text{lb/day BOD removed} = 200 \text{ mg/L} - 70 \text{ mg/L} = 130 \text{ mg/L}$$

After calculating milligrams per liter of BOD removed, calculate pounds per day of BOD removed:

$$\text{BOD removed, lb/day} = (130 \text{ mg/L})\,(1.6 \text{ MGD})\,(8.34 \text{ lb/gal}) = 1735 \text{ lb/day}$$

16.5 TRICKLING FILTER CALCULATIONS

The trickling filter process (see Figure 16.3) is one of the oldest forms of dependable biological treatment for wastewater. By its very nature, the trickling filter has its advantages over other unit processes. It is a very economical and dependable process for treatment of wastewater prior to discharge and is capable of withstanding periodic shock loading; furthermore, process energy demands are low because aeration is a natural process.

As shown in Figure 16.4, trickling filter operation involves spraying wastewater over solid media such as rock, plastic, or redwood slats (or laths). As the wastewater trickles over the surface of the media, a growth of microorganisms (bacteria, protozoa, fungi, algae, helminths or worms, and larvae) develops. This growth is visible as a shiny slime similar to the slime found on rocks in a stream. As wastewater passes over this slime, the slime adsorbs the organic (food) matter. This organic matter is used for food by the microorganisms. At the same time, air moving through the open spaces in the filter transfers oxygen to the wastewater. This oxygen is then transferred to the slime to keep the outer layer aerobic. As the microorganisms use the food and oxygen, they produce

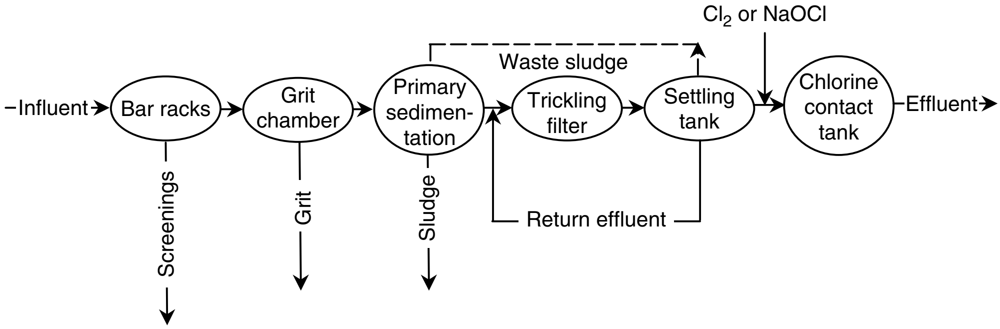

Figure 16.3 Simplified flow diagram of trickling filter used for wastewater treatment. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

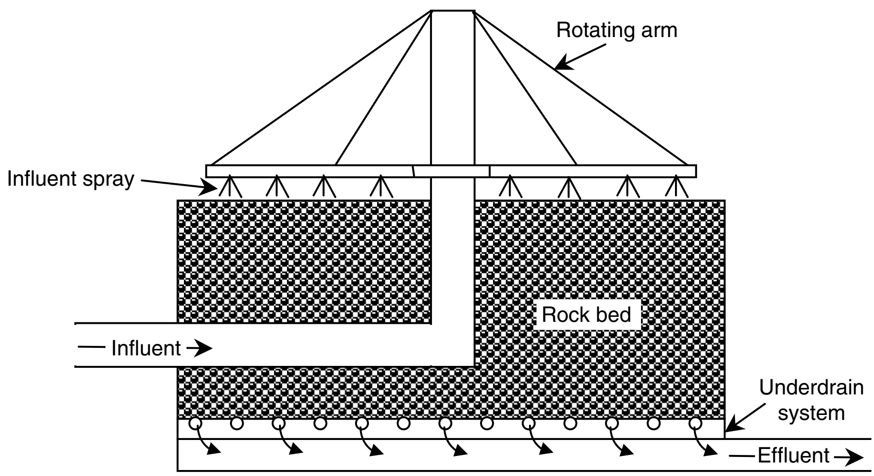

Figure 16.4 Schematic of cross-section of a trickling filter. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

more organisms, carbon dioxide, sulfates, nitrates, and other stable by-products; these materials are then discarded from the slime back into the wastewater flow and carried out of the filter.

16.5.1 Trickling Filter Process Calculations

Several calculations are useful in the operation of trickling filters; these include hydraulic loading, organic loading, and biochemical oxygen demand (BOD) and suspended solids (SS) removal. Each type of trickling filter is designed to operate with specific loading levels, which depend on the filter classification. To operate the filter properly, filter loading must be within the specified levels. The main three loading parameters for the trickling filter are hydraulic loading, organic loading, and recirculation ratio.

16.5.2 Hydraulic Loading

Calculating the hydraulic loading rate is important in accounting for the primary effluent as well as the recirculated trickling filter effluent. These are combined before they are applied to the filter surface. The hydraulic loading rate is calculated based on filter surface area. The normal hydraulic loading-rate ranges for standard- and high-rate trickling filters are:

$$\text{Standard Rate} = 25 - 100 \text{ gpd/ft}^2 \text{ or } 1 - 40 \text{ MGD/acre}$$

$$\text{High Rate} = 100 - 1000 \text{ gpd/ft}^2 \text{ or } 4 - 40 \text{ MGD/acre}$$

Key point: If the hydraulic loading rate for a particular trickling filter is too low, septic conditions begin to develop.

Example 16.22

Problem:

A trickling filter 80 ft in diameter is operated with a primary effluent of 0.588 MGD and a recirculated effluent flow rate of 0.660 MGD. Calculate the hydraulic loading rate on the filter in units of gallons per day per square foot.

Solution:

The primary effluent and recirculated trickling filter effluent are applied together across the surface of the filter; therefore, 0.588 MGD + 0.660 MGD = 1.248 MGD = 1,248,000 gpd.

$$\text{Circular surface area} = 0.785 \times (\text{diameter})^2$$

$$= 0.785 \times (80 \text{ ft})^2$$

$$= 5{,}024 \text{ ft}^2$$

$$\frac{1{,}248{,}000 \text{ gpd}}{5{,}024 \text{ ft}^2} = 248.4 \text{ gpd/ft}^2$$

Example 16.23

Problem:

A trickling filter 80 ft in diameter treats a primary effluent flow of 550,000 gpd. If the recirculated flow to the clarifier is 0.2 MGD, what is the hydraulic loading on the trickling filter?

Solution:

$$\text{Hydraulic loading rate} = \frac{\text{Total Flow, gpd}}{\text{Area, ft}^2}$$

$$\frac{750{,}000 \text{ gpd total flow}}{(0.785)\ (80 \text{ ft})(80 \text{ ft})}$$

$$= 149 \text{ gpd/ft}^2$$

Example 16.24

Problem:

A high-rate trickling filter receives a daily flow of 1.8 MGD. What is the dynamic loading rate in MGD per acre if the filter is 90 ft in diameter and 5 ft deep?

Solution:

$$(0.785)\,(90\text{ ft})\,(90\text{ ft}) = 6359\text{ ft}^2$$

$$\frac{6359\text{ ft}^2}{43{,}560\text{ ft}^2/\text{acre}} = 0.146\text{ acre}$$

$$\text{Hydraulic Loading Rate} = \frac{1.8\text{ MGD}}{0.146\text{ acre}} = 12.3\text{ MGD/acre}$$

Key point: When hydraulic loading rate is expressed as MGD per acre, this is still an expression of gallon flow over surface area of trickling filter.

16.5.3 Organic Loading Rate

Trickling filters are sometimes classified by the organic loading rate applied. This rate is expressed as a certain amount of BOD applied to a certain volume of media. In other words, the organic loading is defined as the pounds of BOD or chemical oxygen demand (COD) applied per day per 1000 ft^3 of media — a measure of the amount of food applied to the filter slime. To calculate the organic loading on the trickling filter, two things must be known: (1) the pounds of BOD or COD applied to the filter media per day; and (2) the volume of the filter media in 1000 ft^3-units. The BOD and COD contribution of the recirculated flow is not included in the organic loading.

Example 16.25

Problem:

A trickling filter 60 ft in diameter receives a primary effluent flow rate of 0.440 MGD. Calculate the organic loading rate in units of pounds of BOD applied per day per 1000 ft^3 of media volume. The primary effluent BOD concentration is 80 mg/L. The media depth is 9 ft.

Solution:

$$0.440\text{ MGD} \times 80\text{ mg/L} \times 8.34\text{ lb/gal} = 293.6\text{ lb of BOD applied/day}$$

$$\text{Surface Area} = 0.785 \times (60)^2 = 2826\text{ ft}^2$$

$$\text{Area} \times \text{Depth} \times \text{Volume}$$

$$2826\text{ ft}^2 \times 9\text{ ft} = 25{,}434\text{ (TF Volume)}$$

Key point: To determine the pounds of BOD per 1,000 ft³ in a volume of thousands of cubic feet, we must set up the equation as shown below.

$$\frac{293.6 \text{ lb BOD/day}}{25{,}434 \text{ ft}^3} \times \frac{1000}{1000}$$

Regrouping the numbers and the units together:

$$\frac{293.6 \text{ lb BOD/day} \times 1000}{25{,}434 \text{ ft}^3} \times \frac{\text{lb BOD/day}}{1000 \text{ ft}^3} = 11.5 \frac{\text{lb BOD/day}}{1000 \text{ ft}^3}$$

16.5.4 BOD and SS Removed

To calculate the pounds of BOD or suspended solids removed each day, we need to know the milligrams per liter of BOD and SS removed and the plant flow.

Example 16.26

Problem:

If 120 mg/L suspended solids are removed by a trickling filter, how many pounds per day suspended solids are removed when the flow is 4.0 MGD?

Solution:

$$(\text{mg/L})\ (\text{MGD flow}) \times 8.34 \text{ lb/gal}$$

$$(120 \text{ mg/L})\ (4.0 \text{ MGD}) \times (8.34 \text{ lb/gal}) = 4003 \text{ lb SS/day}$$

Example 16.27

Problem:

The 3,500,000-gpd influent flow to a trickling filter has a BOD content of 185 mg/L. If the trickling filter effluent has a BOD content of 66 mg/L, how many pounds of BOD are removed daily?

Solution:

$$(\text{mg/L})\ (\text{MGD flow})\ (8.34 \text{ lb/gal}) = \text{lb/day removed}$$

$$185 \text{ mg/L} - 66 \text{ mg/L} = 119 \text{ mg/L}$$

$$(119 \text{ mg/L})\ (3.5 \text{ MGD})\ (8.34 \text{ lb/gal}) = 3474 \text{ lb/day removed}$$

16.5.5 Recirculation Flow

Recirculation in trickling filters involves the return of filter effluent back to the head of the trickling filter. It can level flow variations and assist in solving operational problems, such as ponding, filter flies, and odors. The operator must check the rate of recirculation to ensure that it is within design specifications. Rates above design specifications indicate hydraulic overloading; rates under them indicate hydraulic underloading. The *trickling filter recirculation ratio* is the ratio of the recirculated trickling filter flow to the primary effluent flow.

The trickling filter recirculation ratio may range from 0.5:1 (0.5) to 5:1 (5). However, the ratio is often 1:1 or 2:1.

$$\text{Recirculation} = \frac{\text{Recirculated Flow, MGD}}{\text{Primary Effluent Flow, MGD}} \tag{16.20}$$

Example 16.28

Problem:

A treatment plant receives a flow of 3.2 MGD. If the trickling filter effluent is recirculated at the rate of 4.50 MGD, what is the recirculation ratio?

Solution:

$$\text{Recirculation Ratio} = \frac{\text{Recirculated Flow, MGD}}{\text{Primary Effluent Flow, MGD}}$$

$$\frac{4.5 \text{ MGD}}{3.2 \text{ MGD}}$$

$$= 1.4 \text{ Recirculation Ratio}$$

Example 16.29

Problem:

A trickling filter receives a primary effluent flow of 5 MGD. If the recirculated flow is 4.6 MGD, what is the recirculation ratio?

Solution:

$$\text{Recirculation Ratio} = \frac{\text{Recirculated Flow, MGD}}{\text{Primary Effluent Flow, MGD}}$$

$$\frac{4.6 \text{ MGD}}{5 \text{ MGD}}$$

$$= 0.92 \text{ Recirculation Ratio}$$

16.5.6 Trickling Filter Design

In trickling filter design, the parameters used are the hydraulic loading and BOD:

$$\text{Hydraulic Loading} = \frac{Q_o + R}{A} \tag{16.21}$$

where
Q_o = average wastewater flow rate, million gallons per day
R = recirculated flow = $Q_o \times$ circulation ratio
A = filter area, acres

$$\text{BOD loading} = \frac{8340\ (\text{BODs})(\text{Q}_\text{o})}{\text{V}} \tag{16.22}$$

where
BOD_s = settled BOD_5 from primary, milligrams per liter
Q_o = Average wastewater flow rate, million gallons per day
V = filter volume, cubic feet
8340 = conversion of units

16.6 ROTATING BIOLOGICAL CONTACTORS (RBCS)

In essence the rotating biological contactor (RBC) is a variation of the attached growth idea provided by the trickling filter (see Figure 16.5 and Figure 16.6). Still relying on microorganisms that grow on the surface of a medium, the RBC is instead a *fixed film* biological treatment device. The basic biological process, however, is similar to that occurring in trickling filters.

An RBC consists of a series of closely spaced (mounted side by side, circular, plastic [synthetic]) disks, typically about 11.5 ft in diameter. Attached to a rotating horizontal shaft, approximately 40% of each disk is submersed in a tank that contains the wastewater to be treated. As the RBC rotates, the attached biomass film (zoogleal slime) that grows on the surface of the disks moves into and out of the wastewater. While submerged in the wastewater, the microorganisms absorb organics; while they are rotated out of the wastewater, they are supplied with needed oxygen for aerobic decomposition. As the zoogleal slime re-enters the wastewater, excess solids and waste

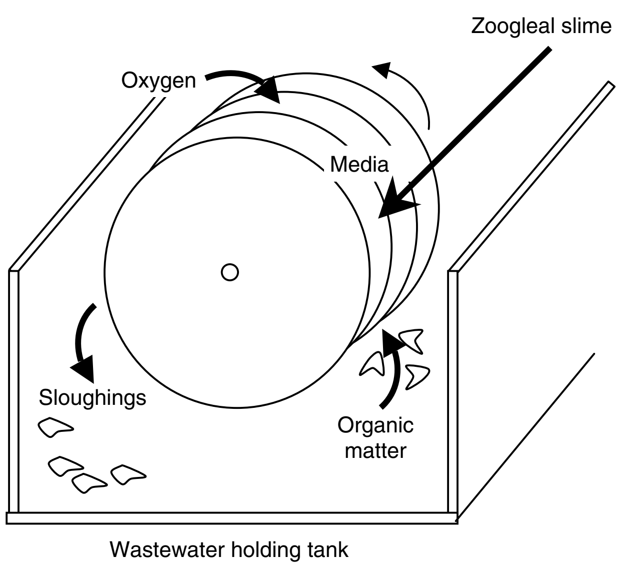

Figure 16.5 Rotating biological contactor (RBC) cross-section and treatment system. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

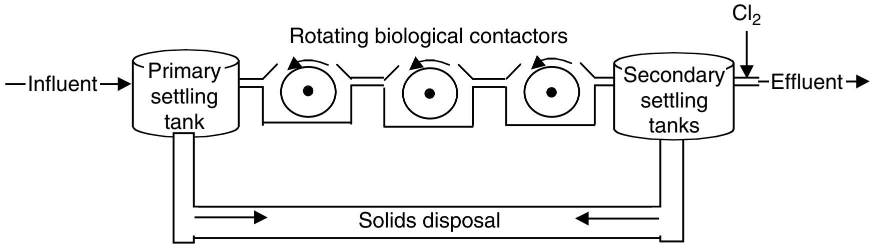

Figure 16.6 Rotating biological contactor (RBC) treatment system. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

products are stripped off the media as sloughings, which are transported with the wastewater flow to a settling tank for removal.

16.6.1 RBC Process Control Calculations

Several process control calculations are useful in the operation of an RBC. These include soluble BOD, total media area, organic loading rate, and hydraulic loading. Settling tank calculations and biosolids pumping calculations may be helpful for evaluation and control of the settling tank following the RBC.

16.6.2 Hydraulic Loading Rate

The manufacturer normally specifies the RBC media surface area, and the hydraulic loading rate is based on the media surface area, usually in square feet. Hydraulic loading is expressed in terms of gallons of flow per day per square foot of media. This calculation can be helpful in evaluating the current operating status of the RBC. Comparison with design specifications can determine if the unit is hydraulically over- or underloaded. Hydraulic loading on an RBC can range from 1 to 3 gpd/ft^2.

Example 16.30

Problem:

An RBC treats a primary effluent flow rate of 0.244 MGD. What is the hydraulic loading rate in gallons per day per square foot if the media surface area is 92,600 ft^2?

Solution:

$$\frac{244{,}000\text{ gpd}}{92{,}000\text{ ft}^2} = 2.65\text{ gpd/ft}^2$$

Example 16.31

Problem:

An RBC treats a flow of 3.5 MGD. The manufacturer's data indicate a media surface area of 750,000 ft^2. What is the hydraulic loading rate on the RBC?

Solution:

$$\text{Hydraulic Loading Rate} = \frac{\text{Flow, gpd}}{\text{Media Area, ft}^2}$$

$$= \frac{3{,}500{,}000\ \text{gpd}}{750{,}000\ \text{ft}^2} = 4.7\ \text{ft}^2$$

Example 16.32

Problem:

A rotating biological contactor treats a primary effluent flow of 1,350,000 gpd. The manufacturer's data indicate that the media surface area is 600,000 ft^2. What is the hydraulic loading rate on the filter?

Solution:

$$\text{Hydraulic Loading Rate} = \frac{\text{Flow, gpd}}{\text{Area, ft}^2}$$

$$= \frac{1{,}350{,}000\ \text{gpd}}{600{,}000\ \text{ft}^2} = 2.3\ \text{ft}^2$$

16.6.3 Soluble BOD

The soluble BOD concentration of the RBC influent can be determined experimentally in the laboratory, or it can be estimated using the suspended solids concentration and the "K" factor. This factor is used to approximate the BOD (particulate BOD) contributed by the suspended matter. The *K* factor must be provided or determined experimentally in the laboratory; for domestic wasters, it is normally in the range of 0.5 to 0.7.

$$\text{Soluble BOD}_5 = \text{Total BOD}_5 - (\text{K Factor} \times \text{Total Suspended Solids}) \tag{16.23}$$

Example 16.33

Problem:

The suspended solids concentration of a wastewater is 250 mg/L. If the amount of *K*-value at the plant is 0.6, what is the estimated particulate biochemical oxygen demand (BOD) concentration of the wastewater?

Solution:

Key point: The 0.6 *K*-value indicates that about 60% of the suspended solids are organic suspended solids (particulate BOD).

$$(250\ \text{mg/L})\,(0.6) = 150\ \text{mg/L Particulate BOD}$$

Example 16.34

Problem:

A rotating biological contactor receives a flow of 2.2 MGD with a BOD content of 170 mg/L and suspended solids (SS) concentration of 140 mg/L. If the *K*-value is 0.7, how many pounds of soluble BOD enter the RBC daily?

Solution:

$$\text{Total BOD} = \text{Particulate BOD} + \text{Soluble BOD}$$

$$170 \text{ mg/L} = (140 \text{ mg/L})(0.7) + \text{x mg/L}$$

$$170 \text{ mg/L} = 98 \text{ mg/L} + \text{x mg/L}$$

$$170 \text{ mg/L} - 98 \text{ mg/L} = \text{x}$$

$$\text{x} = 72 \text{ mg/L Soluble BOD}$$

Now, pounds per day of soluble BOD may be determined:

$$(\text{mg/L Soluble BOD})(\text{MGD Flow})(8.34 \text{ lb/gal}) = \text{lb/day}$$

$$(72 \text{ mg/L})(2.2 \text{ MGD})(8.34 \text{ lb/gal}) = 1321 \text{ lb/day Soluble BOD}$$

Example 16.35

Problem:

The wastewater entering a rotating biological contactor has a BOD content of 210 mg/L. The suspended solids content is 240 mg/L. If the *K*-value is 0.5, what is the estimated soluble BOD (milligrams per liter) of the wastewater?

Solution:

$$\text{Total BOD, mg/L} = \text{Particulate BOD, mg/L} + \text{Soluble BOD, mg/L}$$

$$\underset{\text{BOD}}{210 \text{ mg/L}} = \underset{\text{SS}}{(240 \text{ mg/L})}(0.5) + \underset{\text{Sol. BOD}}{\text{x mg/L}}$$

$$210 \text{ mg/L} = 120 \text{ mg/L} + \underset{\text{Sol. BOD}}{\text{x mg/L}}$$

$$210 - 120 = \text{x}$$

$$\text{Sol. BOD } 90 \text{ mg/L} = \text{x}$$

16.6.4 Organic Loading Rate

The organic loading rate can be expressed as total BOD loading in pounds per day per 1000 ft^2 of media. The actual values can then be compared with plant design specifications to determine the current operating condition of the system.

$$\text{Organic Loading Rate} = \frac{\text{Sol. BOD} \times \text{Flow, MGD} \times 8.34\text{ lb/gal}}{\text{Media Area, 1000 ft}^2} \tag{16.24}$$

Example 16.36

Problem:

A rotating biological contactor (RBC) has a media surface area of 500,000 ft^2 and receives a flow of 1,000,000 gpd. If the soluble BOD concentration of the primary effluent is 160 mg/L, what is the organic loading on the RBC in pounds per day per 1000 ft^2?

Solution:

$$\text{Organic Loading Rate} = \frac{\text{Sol. BOD, lb/day}}{\text{Media Area, 1000 ft}^2}$$

$$\frac{(160\text{ mg/L})(1.0\text{ MGD})\ (8.34\text{ lb/gal})}{500 \times 1000\text{ ft}^2}$$

$$\frac{2.7\text{ lb/day Sol. BOD}}{1000\text{ ft}^2}$$

Example 16.37

Problem:

The wastewater flow to an RBC is 3,000,000 gpd. The wastewater has a soluble BOD concentration of 120 mg/L. The RBC consists of six shafts (each 110,000 ft^2), with two shafts comprising the first stage of the system. What is the organic loading rate in pounds per day per 1000 ft^2 on the first stage of the system?

Solution:

$$\text{Organic Loading Rate} = \frac{\text{Sol. BOD, lb/day}}{\text{Media Area, 1000 ft}^2}$$

$$\frac{(120\text{ mg/L}) \times (3.0\text{ MGD})\ (8.34\text{ lb/gal})}{220 \qquad 1000\text{ ft}^2}$$

$$= 13.6\text{ lb Sol. BOD/day/1000 ft}^2$$

16.6.5 Total Media Area

Several process control calculations for the RBC use the total surface area of all the stages within the train. As was the case with the soluble BOD calculation, plant design information or information supplied by the unit manufacturer must provide the individual stage areas (or the total train area) because physical determination of this would be extremely difficult.

$$\text{Total Area} = \text{1st Stage Area} + \text{2nd Stage Area} + \ldots + \text{nth Stage Area} \tag{16.25}$$

16.6.6 Modeling RBC Performance

Although a number of semiempirical formulations have been used, the Schultz–Germain formula for trickling filters is recommended for modeling RBC performance (Spengel and Dzombok, 1992):

$$Se = Sie^{k(V/Q)0.5} \tag{16.26}$$

where
Se = total BOD of settled effluent, milligrams per liter
Si = total BOD of wastewater applied to filter, milligrams per liter
V = in square meters
Q = in square meters per second

16.6.7 RBC Performance Parameter

The control parameter for RBC performance is soluble BOD (SBOD):

$$\text{SBOD} = \text{TBOD} - \text{Suspended BOD} \tag{16.27}$$

$$\text{Suspended BOD} = \text{c (TSS)} \tag{16.28}$$

$$\text{SBOD} = \text{TBOD} - \text{c (TSS)} \tag{16.29}$$

where
c = a coefficient
= 0.5 to 0.7 for domestic wastewater
= 0.5 for raw domestic wastewater (TSS > TBOD)
= 0.6 for raw wastewater (TSS ≅ TBOD)
= 0.6 for primary effluents
= 0.5 for secondary effluents

Example 16.38

Problem:
Average TBOD is 152 mg/L and TSS is 132 mg/L. What is the influent SBOD concentration that can be used for the design of an RBC system? The RBC is used as the secondary treatment unit.

Solution:
For the primary effluent (RBC influent)

$$c = 0.6$$

Estimate SBOD concentration of RBC influent using Equation 16.29.

$$\text{SBOD} = \text{TBOD} - \text{c (TSS)}$$

$$= 152 \text{ mg/L} - 0.6 \text{ (132 mg/L)}$$

$$= 73 \text{ mg/L}$$

16.7 ACTIVATED BIOSOLIDS

The activated biosolids (sludge) process is a man-made process that mimics the natural self-purification process that takes place in streams. In essence, we can state that the activated biosolids treatment process is a "stream in a container."

In wastewater treatment, activated-biosolids processes are used for secondary treatment as well as complete aerobic treatment without primary sedimentation. *Activated biosolids* refers to biological treatment systems that use a suspended growth of organisms to remove BOD and suspended solids. The basic components of an activated biosolids sewage treatment system include an aeration tank and a secondary basin, settling basin, or clarifier. Primary effluent is mixed with settled solids recycled from the secondary clarifier and is then introduced into the aeration tank. Compressed air is injected continuously into the mixture through porous diffusers located at the bottom of the tank, usually along one side.

Wastewater is fed continuously into the aerated tank, where the microorganisms metabolize and biologically flocculate the organics. Microorganisms (activated biosolids) are settled from the aerated mixed liquor under quiescent conditions in the final clarifier and are returned to the aeration tank. Left uncontrolled, the number of organisms would eventually become too great; therefore, some must periodically be removed (waste). A portion of the concentrated solids from the bottom of the settling tank must be removed from the process (waste activated sludge, or WAS). Clear supernatant from the final settling tank is the plant effluent.

16.7.1 Activated Biosolids Process Control Calculations

As with other wastewater treatment unit processes, process control calculations are important tools used to control and optimize process operations. In this section, we review many of the most frequently used activated biosolids process calculations.

16.7.2 Moving Averages

When performing process control calculations, using a 7-day moving average is recommended. The moving average is a mathematical method to level the impact of any single test result. Determine the moving average by adding all of the test results collected during the preceding 7 days and dividing by the number of tests.

$$\text{Moving Average} = \frac{\text{Test 1} + \text{Test 2} + \text{Test 3} + \ldots \text{Test 6} + \text{Test 7}}{\text{\# of Tests Performed during the Seven Days}} \tag{16.30}$$

Example 16.39

Problem:

Calculate the 7-day moving average for days 7, 8, and 9:

Day	MLSS	Day	MLSS
1	3340	6	2780
2	2480	7	2476
3	2398	8	2756
4	2480	9	2655
5	2558	10	2396

Solution:

1. Moving Average, Day 7 =

$$\frac{3340 + 2480 + 2398 + 2480 + 2558 + 2780 + 2476}{7} = 2645$$

2. Moving Average, Day 8 =

$$\frac{2480 + 2398 + 2480 + 2558 + 2780 + 2476 + 2756}{7} = 2561$$

3. Moving Average, Day 9 =

$$\frac{2398 + 2480 + 2558 + 2780 + 2476 + 2756 + 2655}{7} = 2586$$

16.7.3 BOD or COD Loading

When calculating BOD, COD, or SS loading on an aeration process (or any other treatment process), loading on the process is usually calculated as pounds per day. The following equation is used:

$$\text{BOD, COD, or SS Loading, lb/day} = (\text{mg/L})\ (\text{MGD})\ (8.34\ \text{lb/gal}) \tag{16.31}$$

Example 16.40

Problem:

The BOD concentration of the wastewater entering an aerator is 210 mg/L. If the flow to the aerator is 1,550,000 gpd, what is the pounds-per-day BOD loading?

Solution:

$$\text{BOD lb/day} = (\text{mg/L})\ (\text{MGD})\ (8.34\ \text{lb/gal})$$

$$= (210\ \text{mg/L})\ (1.55\ \text{MGD})\ (8.34\ \text{lb/gal})$$

$$= 2715\ \text{lb/day}$$

Example 16.41

Problem:

The flow to an aeration tank is 2750 gpm. If the BOD concentration of the wastewater is 140 mg/L, how many pounds of BOD are applied to the aeration tank daily?

Solution:

First, convert the gallons-per-minute flow to gallons-per-day flow:

$$(2750 \text{ gpm})(1440 \text{ min/day}) = 3{,}960{,}000 \text{ gpd}$$

Then calculate pounds per day of BOD:

$$\text{BOD, lb/day} = (\text{BOD, mg/L})(\text{Flow, MGD})(8.34 \text{ lb/gal})$$

$$= (140, \text{mg/L})(3.96 \text{ MGD})(8.34 \text{ lb/day})$$

$$= 4624 \text{ lb/day}$$

16.7.4 Solids Inventory

In the activated biosolids process, controlling the amount of solids under aeration is important. The suspended solids in an aeration tank are called mixed liquor suspended solids (MLSS). To calculate the pounds of solids in the aeration tank, we need to know the milligrams per liter of MLSS concentration and the aeration tank volume. Then pounds of MLSS can be calculated as follows:

$$\text{lb MLSS} = (\text{MLSS, mg/L})(\text{MG})(8.34) \tag{16.32}$$

Example 16.42

Problem:

If the mixed liquor suspended solids concentration is 1200 mg/L and the aeration tank has a volume of 550,000 gal, how many pounds of suspended solids are in the aeration tank?

Solution:

$$\text{Lb} = (\text{mg/L})(\text{MG Volume})(8.34 \text{ lb/gal})$$

$$= (1200 \text{ mg/L})(0.550 \text{ MG})(8.34 \text{ lb/gal})$$

$$= 5504 \text{ lb MLSS}$$

16.7.5 Food-to-Microorganism Ratio (F/M Ratio)

The food-to-microorganism ratio (F/M ratio) is a process control method/calculation based upon maintaining a specified balance between available food materials (BOD or COD) in the aeration tank influent and the aeration tank mixed liquor volatile suspended solids (MLVSS) concentration.

The chemical oxygen demand (COD) test is sometimes used because the results are available in a relatively short period of time. To calculate the F/M ratio, the following information is required:

- Aeration tank influent flow rate, million gallons per day
- Aeration tank influent BOD or COD, milligrams per liter
- Aeration tank MLVSS, milligrams per liter
- Aeration tank volume, million gallons

$$\text{F/M Ratio} = \frac{\text{Primary Eff. COD/BOD mg/L} \times \text{Flow MGD} \times 8.34\ \text{lb/mg/L/MG}}{\text{MLVSS mg/L} \times \text{Aerator Vol., MG} \times 8.34\ \text{lb/mg/L/MG}} \quad (16.33)$$

Typical F/M ratio for an activated biosolids process is shown in the following table:

Process	Pounds BOD Pounds MLVSS	Pounds COD Pounds MLVS
Conventional	0.2–0.4	0.5–1.0
Contact stabilization	0.2–0.6	0.5–1.0
Extended aeration	0.05–0.15	0.2–0.5
Pure oxygen	0.25–1.0	0.5–2.0

Example 16.43

Problem:

The aeration tank influent BOD is 145 mg/L and the aeration tank influent flow rate is 1.6 MGD. What is the F/M ratio if the MLVSS is 2300 mg/L and the aeration tank volume is 1.8 MG?

Solution:

$$\text{F/M ratio} = \frac{145\ \text{mg/L} \times 1.6\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}}{2300\ \text{mg/L} \times 1.8\ \text{MG} \times 8.34\ \text{lb/mg/L/M}}$$

$$= 0.06\ \text{BOD/lb MLVSS}$$

Key point: If the MLVSS concentration is not available, it can be calculated if the percent of volatile matter (% VM) of the mixed liquor suspended solids (MLSS) is known:

$$\text{MLVSS} = \text{MLSS} \times \%\ \text{(decimal) Volatile Matter (VM)} \quad (16.34)$$

Key point: The "F" value in the F/M ratio for computing loading to an activated biosolids process can be BOD or COD. Remember that the reason for biosolids production in the activated biosolids process is to convert BOD to bacteria. One advantage of using COD over BOD for analysis of organic load is that COD is more accurate.

Example 16.44

Problem:

The aeration tank contains 2885 mg/L of MLSS. Lab tests indicate the MLSS is 66% volatile matter. What is the MLVSS concentration in the aeration tank?

Solution:

$$\text{MLVSS, mg/L} = 2885 \text{ mg/L} \times 0.66 = 1904 \text{ mg/L}$$

Required MLVSS Quantity (Pounds)

The pounds of MLVSS required in the aeration tank to achieve the optimum F/M ratio can be determined from the average influent food (BOD or COD) and the desired F/M ratio:

$$\text{MLVSS, lb} = \frac{\text{Primary Effluent BOD or COD} \times \text{Flow, MGD} \times 8.34}{\text{Desired F/M Ratio}} \tag{16.35}$$

The required pounds of MLVSS determined by this calculation can then be converted to a concentration value by:

$$\text{MLVSS, mg/L} = \frac{\text{Desired MLVSS, lb}}{[\text{Aeration Volume, MG} \times 8.34]} \tag{16.36}$$

Example 16.45

Problem:

The aeration tank influent flow is 4.0 MGD, and the influent COD is 145 mg/L. The aeration tank volume is 0.65 MG. The desired F/M ratio is 0.3 lb COD/lb MLVSS.

1. How many pounds of MLVSS must be maintained in the aeration tank to achieve the desired F/M ratio?
2. What is the required concentration of MLVSS in the aeration tank?

Solution:

$$\text{MLVSS} = \frac{145 \text{ mg/L} \times 4.0 \text{ MGD} \times 8.34 \text{ lb/gal}}{0.3 \text{ lb COD/lb MLVSS}} = 16{,}124 \text{ lb MLVSS}$$

$$\text{MLVSS, mg/L} = \frac{16{,}124 \text{ lb MLVSS}}{[0.65 \text{ MG} \times 8.34]} = 2974 \text{ mg/L MLVSS}$$

Calculating Waste Rates Using F/M Ratio

Maintaining the desired F/M ratio is accomplished by controlling the MLVSS level in the aeration tank. This may be accomplished by adjustment of return rates; however, the most practical method is by proper control of the waste rate.

$$\text{Waste Vol. Solids, lb/day} = \text{Actual MLVSS, lb} - \text{Desired MLVSS, lb} \tag{16.37}$$

If the desired MLVSS is greater than the actual MLVSS, wasting is stopped until the desired level is achieved.

Practical considerations demand that the required waste quantity be converted to a required volume to waste ratio per day. This is accomplished by converting the waste pounds to flow rate in million gallons per day or gallons per minute.

$$\text{Waste, MGD} = \frac{\text{Waste Volatile, lb/day}}{[\text{Waste Volatile Conc., mg/L} \times 8.34]} \tag{16.38}$$

$$\text{Waste, MGD} = \frac{\text{Waste, MGD} \times 1{,}000{,}000 \text{ gpd/MGD}}{1440 \text{ min/day}} \tag{16.39}$$

Key point: When F/M ratio is used for process control, the volatile content of the waste-activated sludge should be determined.

Example 16.46

Problem:

Given the following information, determine the required waste rate in gallons per minute to maintain an F/M ratio of 0.17-lb COD/lb MLVSS.

Primary effluent COD	140 mg/L
Primary effluent flow	2.2 MGD
MLVSS, mg/L	3549 mg/L
Aeration tank volume	0.75 MG
Waste volatile concentrations	4440 mg/L (volatile solids)

Solution:

$$\text{Actual MLVSS, lb} = 3{,}549 \text{ mg/L} \times 0.75 \text{ MG} \times 8.34 = 22{,}199 \text{ lb}$$

$$\text{Required MLVSS, lb} = \frac{140 \text{ mg/L} \times 2.2 \text{ MGD} \times 8.34}{0.17 \text{ lb COD/lb MLVSS}} = 15{,}110 \text{ lb MLVSS}$$

$$\text{Waste, lb/day} = 22{,}199 \text{ lb} - 15{,}110 \text{ lb} = 7089 \text{ lb}$$

$$\text{Waste, MGD} = \frac{7089 \text{ lb/day}}{4440 \text{ mg/L} \times 8.34} = 0.19 \text{ MGD}$$

$$\text{Waste, gpm} = \frac{0.19 \text{ MGD} \times 1{,}000{,}000 \text{ gpd/MGD}}{1440 \text{ min/day}} = 132 \text{ gpm}$$

16.7.6 Gould Biosolids Age

Biosolids age refers to the average number of days a particle of suspended solids remains under aeration; it is a part of the calculation used to maintain the proper amount of activated biosolids in the aeration tank. This calculation is sometimes referred to as Gould biosolids age, so that it is not confused with similar calculations such as solids retention time, or mean cell residence time.

When considering sludge age, in effect we are asking, "How many days of suspended solids are in the aeration tank?" For example, if 3000 lb SS enter the aeration tank daily and the tank contains 12,000 lb of suspended solids, when 4 days of solids are in the aeration tank, the tank has a sludge age of 4 days.

$$\text{Sludge Age, days} = \frac{\text{SS in Tank, lb}}{\text{SS Added, lb/day}} \tag{16.40}$$

Example 16.47

Problem:

A total of 2740 lb/day of suspended solids enters an aeration tank in the primary effluent flow. If the aeration tank has a total of 13,800 lb of mixed liquor suspended solids, what is the biosolids age in the aeration tank?

Solution:

$$\text{Sludge Age, day} = \frac{\text{MLSS, lb}}{\text{SS Added, lb/day}}$$

$$= \frac{13{,}800\ \text{lb}}{2740\ \text{lb/day}}$$

$$= 5.0\ \text{days}$$

16.7.7 Mean Cell Residence Time (MCRT)

Mean cell residence time (MCRT), sometimes called *sludge retention time,* is another process control calculation used for activated biosolids systems. MCRT represents the average length of time an activated biosolids particle remains in the activated biosolids system. It can also be defined as the length of time required at the current removal rate to remove all the solids in the system.

$$\text{Mean Cell Residence Time, day} =$$

$$\frac{[\text{MLSS mg/L} \times (\text{Aeration Vol.} + \text{Clarifier Vol.}) \times 8.34\ \text{lb/mg/L/MG}]}{[\text{WAS, mg/L} \times (\text{WAS flow} \times 8.34) + (\text{TSS out} \times \text{flow out} \times 8.34)]} \tag{16.41}$$

> *Key point*: MCRT can be calculated using only the aeration tank solids inventory. When comparing plant operational levels to reference materials, it is necessary to determine the calculation that reference manual uses to obtain its example values. Other methods are available to determine the clarifier solids concentrations. However, the simplest method assumes that the average suspended solids concentration is equal to the aeration tank's solids concentration.

Example 16.48

Problem:

Given the following data, what is the MCRT?

Aerator volume	1,000,000 gal
Final clarifier	600,000 gal
Flow	5.0 MGD
Waste rate	0.085 MGD
MLSS mg/L	2500 mg/L
Waste mg/L	6400 mg/L
Effluent TSS	14 mg/L

Solution:

$$\text{MRCT} = \frac{[2500\text{ mg/L} \times (1.0\text{ MG} + 0.60\text{ MG}) \times 8.34]}{[6400\text{ mg/L} \times (0.085\text{ MGD} \times 8.34) + (14\text{ mg/L} \times 5.0\text{ MGD} \times 8.34)]} = 6.5\text{ days}$$

Waste Quantities/Requirements

MCRT for process control requires determination of the optimum range for MCRT values. This is accomplished by comparison of the effluent quality with MCRT values. When the optimum MCRT is established, the quantity of solids to be removed (wasted) is determined by:

$$\text{Waste, lb/day} = \left(\frac{\text{MLSS} \times (\text{Aer., MG} + \text{Clarifier, MG}) \times 8.34}{\text{Desired MCRT}}\right) - [\text{TSS}_{\text{out}} \times \text{Flow} \times 8.34] \tag{16.42}$$

Example 16.49

$$\frac{3400\text{ mg/L} \times (1.4\text{ MG} + 0.50\text{ MG}) \times 8.34}{8.6\text{ days}} - [10\text{ mg/L} \times 5.0\text{ MGD} \times 8.34]$$

$$\text{Waste Quality, lb/day} = 5848\text{ lb}$$

Waste Rate in Million Gallons per Day

When the quantity of solids to be removed from the system is known, the desired waste rate in million gallons per day can be determined. The unit used to express the rate (million gallons per day; gallons per day; and gallons per minute) is a function of the volume of waste to be removed and the design of the equipment.

$$\text{Waste, MGD} = \frac{\text{Waste lb/day}}{\text{WAS Concentration, mg/L} \times 8.34} \tag{16.43}$$

$$\text{Waste, gpm} = \frac{\text{Waste MGD} \times 1{,}000{,}000\text{ gpd/MGD}}{1440\text{ min/day}} \tag{16.44}$$

Example 16.50

Problem:

Given the following data, determine the required waste rate to maintain an MCRT of 8.8 days:

MLSS, milligrams per liter	2500 mg/L
Aeration volume	1.20 MG
Clarifier volume	0.20 MG
Effluent TSS	11 mg/L
Effluent flow	5.0 MGD
Waste concentration	6000 mg/L

Solution:

$$\text{Waste, lb/day} = \frac{2500\text{ mg/L} \times (1.20 + 0.20) \times 8.34}{8.8\text{ days}} - [11\text{ mg/L} \times 5.0\text{ MGD} \times 8.34]$$

$$= 3317\text{ lb/day} - 459\text{ lb/day}$$

$$= 2858\text{ lb/day}$$

$$\text{Waste, lb/day} = \frac{2858\text{ lb/day}}{[6000\text{ mg/L} \times 8.34]} = 0.057\text{ MGD}$$

$$\text{Waste, gpm} = \frac{0.057\text{ MGD} \times 1{,}000{,}000\text{ gpd/MGD}}{1440\text{ min/day}} = 40\text{ gpm}$$

16.7.8 Estimating Return Rates from SBV_{60} (SSV_{60})

Many methods are available for estimating the proper return biosolids rate. A simple method described in the *Operation of Wastewater Treatment Plants, Field Study Programs* (1986), developed by the California State University, Sacramento, uses the 60-min percent-settled biosolids (sludge) volume. The percent SBV_{60} test results can provide an approximation of the appropriate return-activated biosolids rate. This calculation assumes that the SBV_{60} results are representative of the actual settling occurring in the clarifier. If this is true, the return rate in percent should be approximately equal to the SBV_{60}. To determine the approximate return rate in million gallons per day, the influent flow rate, current return rate, and SBV_{60} must be known. The results of this calculation can then be adjusted based upon sampling and visual observations to develop the optimum return biosolids rate.

> *Key point*: The percent SBV_{60} must be converted to a decimal percent and total flow rate (wastewater flow and current return rate in million gallons per day must be used).

$$\text{Est. Return Rate, MGD} = (\text{Influent Flow, MGD} + \text{Current Return Flow, MGD}) \times \%SBV_{60} \tag{16.45}$$

$$\text{RAS Rate, GPM} = \frac{\text{Return, Biosolids Rate, gpd}}{1440\text{ min/day}} \tag{16.46}$$

Assume:

- Percent SBV_{60} is representative.
- Return rate in percent equals $\%SBV_{60}$.
- Actual return rate is normally set slightly higher to ensure organisms are returned to the aeration tank as quickly as possible. The rate of return must be adequately controlled to prevent the following:
  - Aeration and settling hydraulic overloads
  - Low MLSS levels in the aerator
  - Organic overloading of aeration
  - Septic return-activated biosolids
  - Solids loss due to excessive biosolids blanket depth

Example 16.51

Problem:

The influent flow rate is 5.0 MGD and the current return-activated sludge flow rate is 1.8 MGD. The SBV_{60} is 37%. Based upon this information, what should be the return biosolids rate in million gallons per day?

Solution:

$$\text{Return, MGD} = (5.0\text{ MGD} + 1.8\text{ MGD}) \times 0.37 = 2.5\text{ MGD}$$

16.7.9 Biosolids (Sludge) Volume Index (BVI)

Biosolids volume index (BVI) is a measure (an indicator) of the settling quality (a quality indicator) of the activated biosolids. As the BVI increases, the biosolids settle more slowly, do not compact as well, and are likely to result in an increase in effluent suspended solids. As the BVI decreases, the biosolids become denser, settling is more rapid, and the biosolids age. BVI is the volume in milliliters occupied by 1 g of activated biosolids. For the settled biosolids volume (milliliters per liter) and the MLSS calculation, milligrams per liter are required. The proper BVI range for any plant must be determined by comparing BVI values with plant effluent quality.

$$\text{Biosolids (Sludge) Volume Index (SBI)} = \frac{\text{SBV, mL/L} \times 1000}{\text{MLSS, mg/L}} \tag{16.47}$$

Example 16.52

Problem:

The SBV_{30} is 250 mL/L and the MLSS is 2425 mg/L. What is the SBI?

Solution:

$$\text{Biosolids Volume Index (BVI)} = \frac{350\text{ mL/L} \times 1000}{2425\text{ mg/L}} = 144$$

BI equals 144. What does this mean? What it means is that the system is operating normally with good settling and low effluent turbidity. How do we know this? We know this because we compare the 144 result with the following parameters to obtain the expected condition (the result).

BVI	Expected condition (indicates)
Less than 100	Old biosolids — possible pin floc Effluent turbidity increasing
100–250	Normal operation — good settling Low effluent turbidity
Greater than 250	Bulking biosolids — poor settling High effluent turbidity

16.7.10 Mass Balance: Settling Tank Suspended Solids

Solids are produced whenever biological processes are used to remove organic matter from wastewater. Mass balance for anaerobic biological process must take into account the solids removed by physical settling processes and the solids produced by biological conversion of soluble organic matter to insoluble suspended matter organisms. Research has shown that the amount of solids produced per pound of BOD removed can be predicted, based upon the type of process used. Although the exact amount of solids produced can vary from plant to plant, research has developed a series of *K*-factors used to estimate the solids production for plants using a particular treatment process. These average factors provide a simple method to evaluate the effectiveness of a facility's process control program. The mass balance also provides an excellent mechanism to evaluate the validity of process control and effluent monitoring data generated.

16.7.11 Mass Balance Calculation

$$\text{BOD in, lb} = \text{BOD, mg/L} \times \text{Flow, MGD} \times 8.34 \qquad (16.48)$$

$$\text{BOD out, lb} = \text{BOD, mg/L} \times \text{Flow, MGD} \times 8.34$$

$$\text{Solids Produced, lb/day} = [\text{BOD in, lb} - \text{BOD out, lb}] \times \text{K}$$

$$\text{TSS out, lb/day} = \text{TSS out, mg/L} \times \text{Flow, MGD} \times 8.34$$

$$\text{Waste, lb/day} = \text{Waste, mg/L} \times \text{Flow, MGD} \times 8.34$$

$$\text{Solids Removed, lb/day} = \text{TSS out, lb/day} + \text{Waste, lb/day}$$

$$\text{\% Mass Balance} = \frac{(\text{Solids Produced} - \text{Solids Removed}) \times 100}{\text{Solids Produced}}$$

16.7.12 Biosolids Waste Based Upon Mass Balance

$$\text{Waste Rate, MGD} = \frac{\text{Solids Produced, lb/day}}{(\text{Waste Concentration} \times 8.34)} \qquad (16.49)$$

Example 16.53

Problem:

Given the following data, determine the mass balance of the biological process and the appropriate waste rate to maintain current operating conditions.

Process	**Extended aeration (no primary)**	
Influent	Flow	1.1 MGD
	BOD	220 mg/L
	TSS	240 mg/L
Effluent	Flow	1.5 MGD
	BOD	18 mg/L
	TSS	22 mg/L
Waste	Flow	24,000 gpd
	TSS	8710 mg/L

Solution:

$$\text{BOD in} = 220 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 2018 \text{ lb/day}$$

$$\text{BOD out} = 18 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 165 \text{ lb/day}$$

$$\text{BOD Removed} = 2018 \text{ lb/day} - 165 \text{ lb/day} = 1853 \text{ lb/day}$$

$$\text{Solids Produced} = 1853 \text{ lb/day} \times 0.65 \text{ lb/lb BOD} = 1204 \text{ lb solids/day}$$

$$\text{Solids Out, lb/day} = 22 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 = 202 \text{ lb/day}$$

$$\text{Sludge Out, lb/day} = 8710 \text{ mg/L} \times 0.024 \text{ MGD} \times 8.34 = 1743 \text{ lb/day}$$

$$\text{Solids Removed, lb/day} = (202 \text{ lb/day} + 1743 \text{ lb/day}) = 1945 \text{ lb/day}$$

$$\text{Mass Balance} = \frac{(1204 \text{ lb Solids/day} - 1945 \text{ lb/day}) \times 100}{1204 \text{ lb/day}} = 62\%$$

The mass balance indicates:

- The sampling points, collection methods, and/or laboratory testing procedures are producing nonrepresentative results.
- The process is removing significantly more solids than is required. Additional testing should be performed to isolate the specific cause of the imbalance.

To assist in the evaluation, the waste rate based upon the mass balance information can be calculated.

$$\text{Waste, GPD} = \frac{\text{Solids Produced, lb/day}}{(\text{Waste TSS, mg/L} \times 8.34)} \tag{16.50}$$

$$\text{Waste, GPD} = \frac{1204 \text{ lb/day} \times 1{,}000{,}000}{8710 \text{ mg/L} \times 8.34} = 16{,}575 \text{ gpd}$$

16.7.13 Aeration Tank Design Parameters

The two design parameters of aeration tanks are food-to-microorganism (F/M) ratio and aeration period (similar to detention time). F/M ratio (BOD loading) is expressed as pounds of BOD per day per pound of MLSS:

$$\frac{F}{M} = \frac{133{,}690\,(\text{BOD})\,Q_o}{(\text{MLSS})\,V\!\!\!-} \tag{16.51}$$

where
BOD = settled BOD from primary tank, milligrams per liter
Q_o = average daily wastewater flow, million gallons per day
MLSS = mixed liquor suspended solids, milligrams per liter
$V\!\!\!-$ = volume of tank, square feet
133,690 = conversion of units

Example 16.54

Problem:
Using the following given data, design a conventional aeration tank.

MGD = 1 million gallons per day
BOD from primary clarifier = 110 mg/L
MLSS = 2000 mg/L
Design F/M = 0.5/day
Design aeration period, t = 6 h

Solution:

$$0.50 = \frac{133{,}690\,(110)\,(1)}{(2000)\,V\!\!\!-}$$

$$V\!\!\!- = 14{,}706 \text{ ft}^3$$

Aeration tank volume, $V\!\!\!- = Qt$

$$= (1 \times 106 \text{ gal/day})\,(6 \text{ h})\,[1/7.48 \text{ ft}^3/\text{gal}][1 \text{ day}/24 \text{ h}]$$

$$= 33{,}422 \text{ ft}^3$$

Assume a depth of 10 ft and a length of twice the width:

$$A = \frac{33{,}422}{10} = 3342 \text{ ft}^2$$

$$(2w)(w) = 3342$$

$$w = 41 \text{ ft}$$

$$l = 82 \text{ ft}$$

16.7.14 Lawrence and McCarty Design Model

Over the years, numerous design criteria using empirical and rational parameters based on biological kinetic equations have been developed for suspended-growth systems. In practice, the basic Lawrence and McCarty (1970) model is widely used in the industry. We list the Lawrence and McCarty design equations used for sizing suspended-growth systems next.

16.7.14.1 Complete Mix with Recycle

For a complete mix system, the mean hydraulic retention time (HRT) θ for the aeration basin is:

$$\theta = V/Q \tag{16.52}$$

where
θ = hydraulic retention time, days
V = volume of aeration tank, cubic meters
Q = influent wastewater flow, cubic meters per day

The mean cell residence time θ_c (or biosolids age or BRT; i.e., for sludge, SRT) is expressed as:

$$\theta_c = \frac{X}{(\Delta X/\Delta t)} \tag{16.53}$$

$$\theta_c = \frac{VX}{(Q_{wa}X + Q_cX_c)} = \frac{\text{total mass SS in reactor}}{\text{SS wasting rate}} \tag{16.54}$$

where
θ_c = mean cell residence time based on solids in the tank, days
X = concentration of MLVSS maintained in the tank, milligrams per liter
$\Delta X/\Delta t$ = growth of biological sludge over time period Δt, milligrams per (liter days)
Q_{wa} = flow of waste sludge removed from the aeration tank, cubic meters per day
Q_c = flow of treated effluent, cubic meters per day
X_c = microorganism concentration (VSS in effluent, milligrams per liter)

The mean cell residence time for system-drawn sludge from the return line would be:

$$Q_c = \frac{VX}{(Q_{wr}X_r + Q_cX_c)} \tag{16.55}$$

where
Q_{wr} = flow of waste sludge from return sludge line, cubic meters per day
X_r = microorganism concentration in return sludge line, milligrams per liter

Microorganism mass balance. The mass balance for the microorganisms in the entire activated biosolids system is expressed as (Metcalf and Eddy, 1991):

$$V\frac{dX}{dt} = QX_o + V(r_g') - (Q_{wa}X + Q_cX_c) \tag{16.56}$$

where
V = volume of aeration tank, cubic meters
dX/dt = rate of change of microorganisms concentration (VSS), milligrams per (liter · cubic meter · day)
Q = flow, cubic meters per day
X_o = microorganisms concentration (VSS) in influent, milligrams per liter
X = microorganisms concentration in tank, milligrams per liter
r_g' = net rate of microorganism growth (VSS), milligrams per (liter · day)

The net rate of bacterial growth is expressed as

$$r_g' = Yr_{su} - K_dX \tag{16.57}$$

where
Y = maximum yield coefficient over finite period of log growth, milligrams per milligram
r_{su} = substrate utilization rate, milligrams per cubic meter
k_d = endogenous decay coefficient, per day

Assuming the cell concentration in the influent is zero and steady-state conditions, Equation 16.58 can be used.

$$\frac{Q_{wa}X + Q_eX_e}{VX} = -Y^r\frac{su}{X} - K_d \tag{16.58}$$

The net specific growth rate can be determined using:

$$\frac{1}{\theta_c} = -Y\frac{r_{su}}{X} - k_d \tag{16.59}$$

The term r_{su} can be computed from:

$$r_{su} = \frac{Q}{V}(S_o - S) = \frac{S_o - S}{\theta} \tag{16.60}$$

where
$S_o - S$ = mass concentration of substrate utilized, milligrams per liter
S_o = substrate concentration in influent, milligrams per liter
S = substrate concentration in effluent, milligrams per liter
θ = hydraulic retention time

16.7.15 Effluent Microorganism and Substrate Concentrations

The mass concentration of microorganisms *X* in the aeration basin can be computed from the following equation:

$$X = \frac{\theta_c Y(S_o - S)}{\theta(1 + k_d\theta_c)} = \frac{\mu_m(S_o - S)}{k(1 + k_d\theta_c)} \tag{16.61}$$

Aeration basin volume can be computed from the following equation:

$$V = \frac{\theta_c QY(S_o - S)}{X(1 + k_d\theta_c)} \tag{16.62}$$

The substrate concentration in effluent *S* can be determined by the following equation:

$$S = \frac{K_s(1 + \theta_c k_d)}{\theta_c(Yk - k_d) - 1} \tag{16.63}$$

where
S = effluent substrate (soluble BOD) concentration, milligrams per liter
K_s = half-velocity constant, substrate concentration at one half the maximum growth rate, milligrams per liter
k = maximum rate of substrate utilization per unit mass of microorganism per day

Other parameters have been mentioned in previous equations.

Observed yield in the system can be determined by using the following equation:

$$Y_{obs} = \frac{Y}{1 + Q_{ct}} \tag{16.64}$$

where
Y_{obs} = observed yield in the system with recycle, milligrams per milligram
Q_{ct} = mean of all residence times based on solids in the aeration tank and in the secondary clarifier, days

Other terms have been defined previously.

16.7.15.1 Process Design and Control Relationships

The specific substrate utilization rate (closely related to the F/M ratio widely used in practice) can be computed by:

$$U = \frac{r_{su}}{X} \tag{16.65}$$

$$U = \frac{Q(S_o - S)}{VX} = \frac{S_o - S}{\theta X} \tag{16.66}$$

The net specific growth rate can be computed by:

$$\frac{1}{\theta_c} = YU - k_d \tag{16.67}$$

The flow rate of waste sludge from the sludge return line will be approximately:

$$Q_{wt} = \frac{VX}{\theta_c X_r} \tag{16.68}$$

where X_r = the concentration (in milligrams per liter) of sludge in the sludge return line.

16.7.15.2 Sludge Production

The amount of sludge generated per day can be calculated by:

$$P_x = Y_{obs} Q(S_o - S)(8.34) \tag{16.69}$$

where
P_x = net waste-activated sludge (VSS), kilograms per day or pounds per day
Y_{obs} = observed yield, gallons per gallon or pounds per pound
Q = influent wastewater flow, cubic meters per day or million gallons per day
S_o = influent soluble BOD concentration, milligrams per liter
S = effluent soluble BOD concentration, milligrams per liter
8.34 = conversion factor, (pounds per million gallons):(milligrams per liter)

16.7.15.3 Oxygen Requirements

The theoretical oxygen requirement to remove the carbonaceous organic matter in wastewater for an activated-biosolids process is expressed by Metcalf and Eddy (1991) in SI units and British system:

$$\text{Mass of } O_2/\text{day} = \text{total mass of BOD}_u \text{ used} - 1.42 \text{ (mass of organisms wasted, } p_x)$$

$$\text{kg } O_2/\text{day} = \frac{Q(S_o - S)}{(1000 \text{ g/kg}) f} - 1.42 P_x \tag{16.70}$$

$$\text{kg } O_2/\text{day} = \frac{Q(S_o - S)}{(1000 \text{ g/kg})}\left(\frac{1}{f} - 1.42\, Y_{obs}\right) \tag{16.71}$$

$$\text{lb } O_2/\text{day} = Q(S_o - S) \times 8.34\left(\frac{1}{f} - 1.42\, Y_{obs}\right) \tag{16.72}$$

where

BOD_u = ultimate BOD

P_x = net waste activated sludge (VSS), kilograms per day or pounds per day

Q = influent flow, cubic meters per day or million gallons per day

S_o = influent soluble BOD concentration, milligrams per liter

S = effluent soluble BOD concentration, milligrams per liter

f = conversion factor for converting BOD to BOD_u

Y_{obs} = observed yield, gallons per gallon or pounds per pound

8.34 = conversion factor, pounds per million gallons: (mg/L)

16.8 OXIDATION DITCH DETENTION TIME

Oxidation ditch systems may be used when the treatment of wastewater is amendable to aerobic biological treatment and the plant design capacities generally do not exceed 1.0 MGD. The oxidation ditch is a form of aeration basin in which the wastewater is mixed with returned biosolids; it is essentially a modification of a completely mixed activated biosolids system used to treat wastewater from small communities. An oxidation ditch system can be classified as an extended aeration process and is considered a low loading rate system. This type of treatment facility can remove 90% or more of influent BOD. Oxygen requirements generally depend on the maximum diurnal organic loading, degree of treatment, and suspended solids concentration to be maintained in the aerated channel MLSS. Detention time is the length of time for required wastewater at a given flow rate to pass through a tank. This time is not normally calculated for aeration basins, but it is calculated for oxidation ditches.

> *Key point*: When calculating detention time, the time and volume units used in the equation must be consistent.

$$\text{Detention Time, h} = \frac{\text{Vol. of Oxidation Ditch, gal}}{\text{Flow Rate, gph}} \tag{16.73}$$

Example 16.55

Problem:

An oxidation ditch has a volume of 160,000 gal. If the flow to the oxidation ditch is 185,000 gpd, what is the detention time in hours?

Solution:

Because detention time is desired in hours, the flow must be expressed as gallons per hour:

$$\frac{185{,}000 \text{ gpd}}{24 \text{ h/day}} = 7708 \text{ gph}$$

Now calculate detention time:

$$\text{Detention Time, h} = \frac{\text{Vol. of Oxidation Ditch, gal}}{\text{Flow Rate, gph}}$$

$$\frac{160{,}000 \text{ gallons}}{7708 \text{ gph}}$$

$$= 20.8 \text{ h}$$

16.9 TREATMENT PONDS

The primary goals of wastewater treatment ponds focus on simplicity and flexibility of operation, protection of the water environment, and protection of public health. Ponds are relatively easy to build and manage; they accommodate large fluctuations in flow and can also provide treatment that approaches conventional systems (producing a highly purified effluent) at much lower cost. The cost (the economics) drives many managers to decide on the pond option of treatment.

The actual degree of treatment provided in a pond depends on the types and numbers of ponds used. Ponds can be used as the sole type of treatment, or they can be used in conjunction with other forms of wastewater treatment — that is, other treatment processes followed by a pond or a pond followed by other treatment processes. They can be classified according to their location in the system, by the type of wastes they receive, and by the main biological process occurring in the pond. First, we look at the types of ponds according to their location and the type of wastes they receive: raw sewage stabilization ponds, oxidation ponds, and polishing ponds.

16.9.1 Treatment Pond Parameters

Before we discuss the process control calculations mentioned earlier, we first describe the calculations for determining the area, volume, and flow rate parameters crucial in making treatment pond calculations.

Determining pond area in inches:

$$\text{Area, acres} = \frac{\text{Area, ft}^2}{43{,}560 \text{ ft}^2\text{/acre}} \tag{16.74}$$

Determining pond volume in acre-feet:

$$\text{Volume, acre-feet} = \frac{\text{Volume, ft}^3}{43{,}560 \text{ ft}^2\text{/acre-foot}} \tag{16.75}$$

Determining flow rate in acre-feet per day:

$$\text{Flow, acre-feet/day} = \text{flow, MGD} \times 3069 \text{ acre-feet/MG} \tag{16.76}$$

> *Key point*: "Acre-feet" (acre-ft) is a unit that can cause confusion, especially for those not familiar with pond or lagoon operations. One acre-foot is the volume of a box with a 1-acre top and 1 ft of depth; however, the top does not need to be an even number of acres in size to use the acre-feet unit of measurement.

Determining flow rate in acre-inches per day:

$$\text{Flow, acre-inches/day} = \text{flow, MGD} \times 36.8 \text{ acre-inches/MG} \tag{16.77}$$

16.9.2 Treatment Pond Process Control Calculations

Although there are no recommended process control calculations for treatment ponds, several calculations may be helpful in evaluating process performance or identifying causes of poor performance. These include hydraulic detention time; BOD loading; organic loading rate; BOD removal efficiency; population loading; and hydraulic loading rate. In this section, we provide a few calculations that might be helpful in evaluating pond performance and identifying causes of poor performance, along with other helpful calculations.

16.9.2.1 Hydraulic Detention Time, Days

$$\text{Hydraulic detention time, days} = \frac{\text{Pond volume, acre-ft}}{\text{Influent flow, acre-ft/day}} \tag{16.78}$$

Key point: Normally, hydraulic detention time ranges from 30 to 120 days for stabilization ponds.

Example 16.56

Problem:
A stabilization pond has a volume of 54.5 acre-ft. What is the detention time in days when the flow is 0.35 MGD?

Solution:

$$\text{Flow, acre-ft/day} = 0.35\text{ MGD} \times 3.069\text{ acre-ft/MG}$$

$$= 1.07\text{ acre-ft/day}$$

$$\text{DT day} = \frac{54.5\text{ acre/ft}}{1.07\text{ acre-ft/day}} = 51$$

16.9.2.2 BOD Loading

When calculating BOD loading on a wastewater treatment pond, use the following equation:

$$\text{Lb/day} = (\text{BOD, mg/L})\ (\text{flow, MGD})\ (8.34\text{lb/gal}) \tag{16.79}$$

Example 16.57

Problem:
Calculate the BOD loading (pounds per day) on a pond if the influent flow is 0.3 MGD with a BOD of 200 mg/L.

Solution:

$$\text{Lb/day} = (\text{BOD, mg/L})\ (\text{flow, MGD})\ (8.34\text{lb/gal})$$

$$= (200\text{ mg/L})\ (0.3\text{ MGD})\ (8.34\text{ lb/gal})$$

$$= 500\text{ lb/day BOD}$$

16.9.2.3 Organic Loading Rate

Organic loading can be expressed as pounds of BOD per acre per day (most common), pounds of BOD per acre-foot per day, or number of people per acre per day.

$$\text{Organic Loading, lb BOD/acre/day} = \frac{\text{BOD, mg/L Influ. Flow, MGD} \times 8.34}{\text{Pond area, acre}} \tag{16.80}$$

Key point: Normal range is 10 to 50 lb BOD per day per acre.

Example 16.58

Problem:

A wastewater treatment pond has an average width of 370 ft and an average length of 730 ft. The influent flow rate to the pond is 0.10 MGD with a BOD concentration of 165 mg/L. What is the organic loading rate to the pound in pounds per day per acre (lb/day/acre)?

Solution:

$$730 \text{ ft} \times 370 \text{ ft} \times \frac{1 \text{ acre}}{43{,}560 \text{ ft}^2} = 6.2 \text{ acre}$$

$$0.10 \text{ MGD} \times 165 \text{ mg/L} \times 8.34 \text{ lb/gal} = 138 \text{ lb/day}$$

$$\frac{138 \text{ lb/day}}{6.2 \text{ acre}} = 22.3 \text{ lb/day/acre}$$

16.9.2.4 BOD Removal Efficiency

The efficiency of any treatment process is its effectiveness in removing various constituents from the water or wastewater. BOD removal efficiency is therefore a measure of the effectiveness of the wastewater treatment pond in removing BOD from the wastewater.

$$\text{\% BOD Removed} = \frac{\text{BOD Removed, mg/L}}{\text{BOD Total, mg/L}} \times 100$$

Example 16.59

Problem:

The BOD entering a waste treatment pond is 194 mg/L. If the BOD in the pond effluent is 45mg/L, what is BOD removal efficiency of the pond?

Solution:

$$\text{\% BOD Removed} = \frac{\text{BOD Removed, mg/L}}{\text{BOD Total, mg/L}} \times 100$$

$$= \frac{149 \text{ mg/L}}{194 \text{ mg/L}} \times 100 = 77\%$$

16.9.2.5 Population Loading

$$\text{Pop. loading, people/acre/day} = \frac{\text{BOD, mg/L Infl.flow, MGD} \times 8.34}{\text{Pond area, acre}} \tag{16.81}$$

16.9.2.6 Hydraulic Loading, Inches/Day (Overflow Rate)

$$\text{Hydraulic Loading, in./day} = \frac{\text{Influent flow, acre-in./day}}{\text{Pond area, acre}} \tag{16.82}$$

16.9.3 Aerated Ponds

According to Metcalf and Eddy (1991), depending on the hydraulic retention time, the effluent from an aerated pond will contain from one third to one half the concentration of the influent BOD in the form of cell tissue. These solids must be removed by settling before the effluent is discharged. The mathematical relationship for BOD removal in a complete-mix-activated pond is derived from the following equation:

$$QS_o - QS - kSV = 0 \tag{16.83}$$

Rearranged:

$$\frac{S}{S_o} = \frac{1}{1 + k(VIQ)} = \frac{\text{effluent BOD}}{\text{influent BOD}} \tag{16.84}$$

$$= \frac{1}{1 + k\theta} \tag{16.85}$$

where
S = effluent BOD concentration, milligrams per liter
S_o = influent BOD concentration, milligrams per liter
k = overall first-order BOD removal rate, per day = 0.25 to 1.0, based on *e*
Q = wastewater flow, cubic meters per day or million gallons per day
θ = total hydraulic retention time, days

The resulting temperature in the aerated pond from the influent wastewater temperature, air temperature, surface area, and flow can be computed using the following equation (Mancini and Barnhart, 1968):

$$T_I - T_w = \frac{(T_w - T_a)fA}{Q} \tag{16.86}$$

where
T_I = influent wastewater temperature, degrees Celsius or Fahrenheit
T_w = lagoon water temperature, degrees Celsius or Fahrenheit
T_a = ambient air temperature, degrees Celsius or Fahrenheit

f = proportionality factor = 12×10^{-6} (British system) or 0.5 (for SI units)
A = surface area of lagoon, square meters or square feet
Q = wastewater flow, cubic meters per day or million gallons per day

Using Equation 16.86 rearranged, the pond water temperature is:

$$T_w = \frac{AfT_a + QT_1}{Af + Q} \tag{16.87}$$

16.10 CHEMICAL DOSAGE CALCULATIONS

Note: In Chapter 15 we discussed calculations used in the chlorination processes for treating potable water. Crossover of similar information occurs in this chapter.

16.10.1 Chemical Dosing

Chemicals are used extensively in wastewater treatment (and water treatment) operations. Plant operators add chemicals to various unit processes for slime-growth control; corrosion control; odor control; grease removal; BOD reduction; pH control; biosolids-bulking control; ammonia oxidation; bacterial reduction; and for other reasons.

To apply any chemical dose correctly, making certain dosage calculations is essential. Some of the most frequently used calculations in wastewater/water mathematics are calculations to determine dosage or loading. The general types of milligrams per liter to pounds per day or pound calculations are for chemical dosage; BOD; COD; SS loading/removal; pounds of solids under aeration; and WAS pumping rate. These calculations are usually made using Equation 16.88 or Equation 16.89:

$$\text{(Chemical, mg/L) (MGD flow) (8.34 lb/gal)} = \text{lb/day} \tag{16.88}$$

$$\text{(Chemical, mg/L) (MG volume) (8.34 lb/gal)} = \text{lb} \tag{16.89}$$

Key point: If milligrams per liter concentration represents a concentration in a flow, then million gallons per day flow is used as the second factor. However, if the concentration pertains to a tank or pipeline volume, then million gallons volume is used as the second factor.
Key point: Typically, especially in the past, the expression *parts per million* (ppm) was used as an expression of concentration, because 1 mg/L = 1 ppm. However, current practice is to use milligrams per liter as the preferred expression of concentration.

16.10.2 Chemical Feed Rate

In chemical dosing, a measured amount of chemical is added to the wastewater (or water). The amount of chemical required depends on the type of chemical used, the reason for dosing, and the flow rate being treated. The two expressions most often used to describe the amount of chemical added or required are (1) milligrams per liter (mg/L); and (2) pounds per day (lb/day).

A milligram per liter is a measure of concentration. For example, consider Figure 16.1 and in which it is apparent that the milligrams per liter concentration expresses a ratio of the milligram chemical in each liter of water. As shown, if a concentration of 5 mg/L is desired, then a total of 15 mg chemical would be required to treat 3 L:

$$\frac{5 \text{ mg} \times 3}{\text{L} \times 3} = \frac{15 \text{ mg}}{3 \text{ L}}$$

The amount of chemical required therefore depends on two factors:

- Desired concentration (milligrams per liter)
- Amount of wastewater to be treated (normally expressed as million gallons per day)

To convert from milligrams per liter to pounds per day, use Equation 16.88.

Example 16.60

Problem:

Determine the chlorinator setting (pounds per day) needed to treat a flow of 5 MGD with a chemical dose of 3 mg/L.

Solution:

$$\text{Chemical, lb/day} = \text{Chemical, mg/L} \times \text{Flow, MGD} \times 8.34 \text{ lb/gal}$$

$$= 3 \text{ mg/L} \times 5 \text{ MGD} \times 8.34 \text{ lb/gal} = 125 \text{ lb/day}$$

Example 16.61

Problem:

The desired dosage for a dry polymer is 10 mg/L. If the flow to be treated is 2,100,000 gpd, how many pounds per day of polymer are required?

Solution:

$$\text{Polymer, lb/day} = \text{Polymer, mg/L} \times \text{Flow, MGD} \times 8.34 \text{ lb/day}$$

$$= 10 \text{ mg/L Polymer} \times (2.10 \text{ MGD})(8.34 \text{ lb/day}) = 175 \text{ lb/day Polymer}$$

Key point: To calculate chemical dose for tanks or pipelines, a modified equation must be used. Instead of million gallons per day flow, million gallons volume is used:

$$\text{Lb Chemical} = \text{Chemical, mg/L} \times \text{Tank Volume, MG} \times 8.34 \text{ lb/gal} \quad (16.90)$$

Example 16.62

Problem:

To neutralize a sour digester, 1 lb of lime is added for every pound of volatile acids in the digester biosolids. If the digester contains 300,000 gal of biosolids with a volatile acid (VA) level of 2200 mg/L, how many pounds of lime should be added?

Solution:

Because the volatile acid concentration is 2200 mg/L, the lime concentration should also be 2200 mg/L:

$$\text{Lb Lime Required} = \text{Lime, mg/L} \times \text{Digester Volume, MG} \times 8.34 \text{ lb/gal}$$

$$= (2200 \text{ mg/L})\ (0.30 \text{ MG})\ 8.34 \text{ lb/gal}$$

$$= 5504 \text{ lb Lime}$$

16.10.3 Chlorine Dose, Demand, and Residual

Chlorine is a powerful oxidizer commonly used in wastewater and water treatment for disinfection; in wastewater treatment for odor control and bulking control; and in other applications. When chlorine is added to a unit process, obviously, we want to ensure that a measured amount is added.

Chlorine dose depends on two considerations—the chlorine demand and the desired chlorine residual:

$$\text{Chlorine Dose} = \text{Chlorine Demand} + \text{Chlorine Residual} \tag{16.91}$$

16.10.3.1 Chlorine Dose

In describing the amount of chemical added or required, we use Equation 16.92:

$$\text{lb/day} = \text{Chemical, mg/L} \times \text{MGD} \times 8.34 \text{ lb/day} \tag{16.92}$$

Example 16.63

Problem:

Determine the chlorinator setting (pounds per day) needed to treat a flow of 8 MGD with a chlorine dose of 6 mg/L.

Solution:

$$(\text{mg/L})(\text{MGD})(8.34) = \text{lb/day}$$

$$(6 \text{ mg/L})\ (8 \text{ MGD})\ (8.34 \text{ lb/gal} = \text{lb/day}$$

$$= 400 \text{ lb/day}$$

16.10.3.2 Chlorine Demand

Chlorine demand is the amount of chlorine used in reacting with various components of the water — harmful organisms and other organic and inorganic substances, for example. When the chlorine demand has been satisfied, these reactions cease.

Example 16.64

Problem:

The chlorine dosage for a secondary effluent is 6 mg/L. If the chlorine residual after 30 min of contact time is 0.5 mg/L, what is the chlorine demand expressed in milligrams per liter?

Solution:

$$\text{Chlorine Dose} = \text{Chlorine Demand} + \text{Chlorine Residual}$$

$$6 \text{ mg/L} = x \text{ mg/L} + 0.5 \text{ mg/L}$$

$$6 \text{ mg/L} - 0.5 \text{ mg/L} = x \text{ mg/L}$$

$$x = 5.5 \text{ mg/L Chlorine Demand}$$

16.10.3.3 Chlorine Residual

Chlorine residual is the amount of chlorine remaining after the demand has been satisfied.

Example 16.65

Problem:
What should the chlorinator setting be (pounds per day) to treat a flow of 3.9 MGD if the chlorine demand is 8 mg/L and a chlorine residual of 2 mg/L is desired?

Solution:
First calculate the chlorine dosage in milligrams per liter:

$$\text{Chlorine Dose} = \text{Chlorine Demand} + \text{Chlorine Residual}$$

$$= 8 \text{ mg/L} + 2 \text{ mg/L}$$

$$= 10 \text{ mg/L}$$

Then calculate the chlorine dosage (feed rate) in pounds per day:

$$\text{(Chlorine, mg/L) (MGD flow) (8.34 lb/gal)} = \text{lb/day Chlorine}$$

$$\text{(10 mg/L) (3.9 MGD) (8.34 lb/gal)} = \text{325 lb/day Chlorine}$$

16.10.4 Hypochlorite Dosage

Hypochlorite is less hazardous than chlorine; therefore, it is often used as a substitute chemical for elemental chlorine. Hypochlorite is similar to strong bleach and comes in two forms: dry calcium hypochlorite (often referred to as HTH) and liquid sodium hypochlorite. Calcium hypochlorite contains about 65% available chlorine; sodium hypochlorite contains about 12 to 15% available chlorine (in industrial strengths).

> *Key point*: Because neither type of hypochlorite is 100% pure chlorine, more pounds per day must be fed into the system to obtain the same amount of chlorine for disinfection — an important economical consideration for facilities considering substituting hypochlorite for chlorine. Some

studies indicate that such a switch can increase overall operating expenses by up to three times the cost of using elemental chlorine.

To determine the pounds per day of hypochlorite needed requires a two-step calculation:

Step 1.

$$\text{mg/L (MGD) (8.34)} = \text{lb/day}$$

Step 2.

$$\frac{\text{Chorine, lb/day}}{\frac{\text{\% available}}{100}} = \text{Hypochlorite, lb/day} \tag{16.93}$$

Example 16.66

Problem:

A total chlorine dosage of 10 mg/L is required to treat a particular wastewater. If the flow is 1.4 MGD and the hypochlorite has 65% available chlorine, how many pounds per day of hypochlorite are required?

Solution:

Step 1. Calculate the pounds per day of chlorine required using the milligrams-to-liter to pounds-per-day equation:

$$\text{mg/L (MGD) (8.34)} = \text{lb/day}$$

$$\text{(10 mg/L) (1.4 MGD) (8.34 lb/gal)} = \text{117 lb/day}$$

Step 2. Calculate the pounds per day of hypochlorite required. Because only 65% of the hypochlorite is chlorine, more than 117 lb/day will be required:

$$\frac{\text{117 lb/day Chlorine}}{\frac{\text{65 \% available}}{100}} = \text{180 lb/day Hypochlorite}$$

Example 16.67

Problem:

A wastewater flow of 840,000 gpd requires a chlorine dose of 20 mg/L. If sodium hypochlorite (15% available chlorine) is used, how many pounds per day of sodium hypochlorite are required? How many gallons per day of sodium hypochlorite is this?

Solution:

Step 1. Calculate the pounds per day of chlorine required:

$$\text{mg/L (MGD) (8.34)} = \text{lb/day}$$

$$\text{(20 mg/L)(0.84 MGD) (8.34 lb/gal)} = \text{140 lb/day Chlorine}$$

Step 2. Calculate the pounds per day of sodium hypochlorite:

$$\frac{\text{140 lb/day Chlorine}}{\dfrac{\text{15 \% available}}{100}} = \text{933 lb/day Hypochlorite}$$

Step 3. Calculate the gallons per day of sodium hypochlorite:

$$= \frac{\text{933 lb/day}}{\text{8.34 lb/gal}} = \text{112 gal/day Sodium Hypochlorite}$$

Example 16.68

Problem:

How many pounds of chlorine gas are necessary to treat 5,000,000 gal of wastewater at a dosage of 2 mg/L?

Solution:

Step 1. Calculate the pounds of chlorine required.

$$\text{V, } 10^6 \text{ gal} = \text{Chlorine Concentration (mg/L)} \times 8.34 = \text{lb Chlorine}$$

Step 2. Substitute

$$5 \times 10^6 \text{ gal} \times 2 \text{ mg/L} \times 8.34 = 83 \text{ lb Chlorine}$$

16.10.5 Chemical Solutions

A *water solution* is a homogeneous liquid consisting of the solvent (the substance that dissolves another substance) and the solute (the substance that dissolves in the solvent). Water is the solvent (see Figure 16.7). The solute (whatever it may be) will dissolve up to a certain point. This is called its *solubility* — that is, the solubility of the solute in the particular solvent (water) at a particular temperature and pressure.

Remember that, in chemical solutions, the substance being dissolved is called the *solute*, and the liquid present in the greatest amount in a solution (and that does the dissolving) is called the *solvent*. We should also be familiar with another term: *concentration* — the amount of solute dissolved in a given amount of solvent. Concentration is measured as:

$$\text{\% Strength} = \frac{\text{Wt. of solute}}{\text{Wt. of solution}} \times 100 = \frac{\text{Wt. of solute}}{\text{Wt. of solute + solvent}} \times 100$$

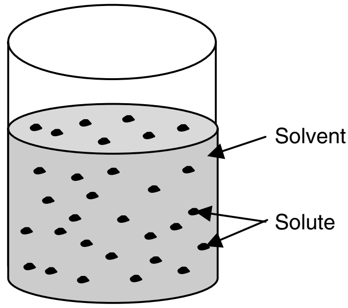

Figure 16.7 Solution with two components: solvent and solute. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1*,* Lancaster, PA: Technomic Publishing Company.)

Example 16.69

Problem:

If 30 lb of chemical is added to 400 lb of water, what is the percent strength (by weight) of the solution?

Solution:

$$\%\ \text{Strength} = \frac{30\ \text{lb Solute}}{400\ \text{lb Solution}} \times 100 = \frac{30\ \text{lb Solute}}{30\ \text{lb Solute} + 400\ \text{lb Water}} \times 100$$

$$= \frac{30\ \text{lb Solute}}{430\ \text{lb Solute/Water}} \times 100$$

$$\%\ \text{Strength} = 7.0\%$$

A complete understanding of the dimensional units involved is important to making accurate computations of chemical strength. For example, it is necessay to understand exactly what *milligrams per liter* signifies;

$$\text{Milligrams per Liter (mg/L)} = \frac{\text{Milligrams of Solute}}{\text{Liters of Solution}} \tag{16.94}$$

Another important dimensional unit commonly used when dealing with chemical solutions is *parts per million* (ppm);

$$\text{Parts per Million (ppm)} = \frac{\text{Parts of Solute}}{\text{Million Parts of Solution}} \tag{16.95}$$

Key point: "Parts" is usually a weight measurement.

For example:

$$8 \text{ ppm} = \frac{8 \text{ lb solids}}{1{,}000{,}000 \text{ lb solution}}$$

$$8 \text{ ppm} = \frac{8 \text{ mg solids}}{1{,}000{,}000 \text{ mg solution}}$$

16.10.6 Mixing Solutions of Different Strengths

When different percent strength solutions are mixed, we use the following equations, depending upon the complexity of the problem:

$$\% \text{ Strength of mixture} = \frac{\text{Chemical in Mixture, lbs}}{\text{Solution Mixture, lbs}} \times 100 \tag{16.96}$$

$$\% \text{ Strength of mixture} = \frac{\text{lbs Chemical (Sol. 1)} + \text{lbs Chem (Sol. 2)}}{\text{lbs Sol. 1} + \text{lbs Sol. 2}} \times 100 \tag{16.97}$$

$$\% \text{ Strength of Mixture} = \frac{(\text{Sol. 1, lb})\dfrac{(\% \text{ Strength Sol. 1})}{100} + (\text{Sol. 2})\dfrac{(\% \text{ Strength Sol. 2})}{100}}{\text{lbs Sol. 1} + \text{lbs Sol. 2}} \tag{16.98}$$

Example 16.70

Problem:

If 25 lb of a 10% strength solution are mixed with 40 lb of a 1% strength solution, what is the percent strength of the solution mixture?

Solution:

$$\% \text{ Strength of Mixture} = \frac{(\text{Sol. 1, lb})\dfrac{(\% \text{ Strength Sol. 1})}{100} + (\text{Sol. 2})\dfrac{(\% \text{ Strength Sol. 2})}{100}}{\text{lb Sol. 1} + \text{lb Sol. 2}} \times 100$$

$$= \frac{(25 \text{ lb})(0.1) + (40 \text{ lb})(0.01)}{25 \text{ lb} + 40 \text{ lb}} \times 100$$

$$= \frac{2.5 \text{ lb} + 0.4 \text{ lb}}{65 \text{ lb}} \times 100$$

$$= 4.5\%$$

Key point: Percent strength should be expressed in terms of pounds of chemical per pound of solution. For example, when solutions are expressed in terms of gallons, the gallons should be expressed as pounds before continuing with the percent strength calculations.

16.10.7 Solution Mixtures Target Percent Strength

When two different percent strength solutions are mixed to obtain a desired quantity of solution and a target percent strength, we use Equation 16.98 and fill in the given information. Then, we find for the unknown, *x*.

Example 16.71

Problem:

What weights of a 3% solution and a 6% solution must be mixed to make 800 lb of a 4% solution?

Solution:

$$\%\ \text{Strength of Mixture} = \frac{(\text{Sol. 1, lb})\dfrac{(\%\ \text{Strength Sol. 1})}{100} + (\text{Sol. 2})\dfrac{(\%\ \text{Strength Sol. 2})}{100}}{\text{lb Sol. 1} + \text{lb Sol. 2}} \times 100$$

$$4 = \frac{(\text{x lb})(0.03) + (800 - \text{x lb})(0.06)}{800\ \text{lb}} \times 100$$

$$\frac{(4)}{100} = (800) = 0.03\text{x} + 48 - 0.06\text{x}$$

$$34 = -0.03\text{x}\ 48$$

$$0.03\text{x} = 14$$

$$\text{x} = 467\ \text{lb of 3\% Solution}$$

$$\text{Then } 800 - 467 = 333\ \text{lb of 6\% Solution}$$

16.10.8 Solution Chemical Feeder Setting, GPD

Calculating GPD feeder setting depends on how the solution concentration is expressed: pounds per gallon or percent. If the solution strength is expressed as pounds per gallon, use the following equation:

$$\text{Solution, gpd} = \frac{(\text{Chemical, mg/L})\ (\text{Flow, MGD})\ (8.34\ \text{lb/gal})}{\text{lb Chemical Solution}} \tag{16.99}$$

In water/wastewater operations, a standard, trial-and-error method known as *jar testing* is conducted to determine optimum chemical dosage. This method of testing has been the accepted bench testing procedure for many years. After jar testing results are analyzed to determine the best chemical dosage, the following example problems demonstrate how the actual calculations are made.

Example 16.72

Problem:

Jar tests indicate that the best liquid alum dose for a water is 8 mg/L. The flow to be treated is 1.85 MGD. Determine the gallons per day setting for the liquid alum chemical feeder if the liquid alum contains 5.30 lb of alum per gallon of solution.

Solution:

First, calculate the pounds per day of dry alum required, using the milligrams-per-liter to pounds-per-day equation:

$$\text{lb/day} = (\text{Dose, mg/L})\ (\text{Flow, MGD})\ (8.34\ \text{lb/gal})$$

$$= (8\ \text{mg/L})\ (1.85\ \text{MGD})\ (8.34\ \text{lb/gal})$$

$$= 123\ \text{lb/day dry alum}$$

Then, calculate gallons per day of solution required.

$$\text{Alum Solution, gpd} = \frac{123\ \text{lb/day Alum}}{5.30\ \text{lb Alum/gal solution}}$$

$$\text{Feeder Setting} = 23\ \text{gpd Alum Solution}$$

If the solution strength is expressed as a percent, we use the following equation:

$$(\text{Chem., mg/L})\ (\text{Flow Treated, MGD})\ (8.34\ \text{lb/gal}) = (\text{Sol., mg/L})\ (\text{Sol. Flow, MGD})\ (8.34\ \text{lb/gal}) \tag{16.100}$$

Example 16.73

Problem:

The flow to a plant is 3.40 MGD. Jar testing indicates that the optimum alum dose is 10 mg/L. What should the gallons per day setting be for the solution feeder if the alum solution is a 52% solution?

Solution:

A solution concentration of 52% is equivalent to 520,000 mg/L:

$$\text{Desired Dose, lb/day} = \text{Actual Dose, lb/day}$$

$$(\text{Chem., mg/L})\ (\text{Flow Treated, MGD})\ (8.34\ \text{lb/gal}) = (\text{Sol., mg/L})\ (\text{Sol. Flow, MGD})\ (8.34\ \text{lb/gal})$$

$$(10\ \text{mg/L})\ (3.40\ \text{MGD})\ (8.34\ \text{lb/gal}) = (520{,}000\ \text{mg/L})\ (x\ \text{MGD})\ (8.34\ \text{lb/gal})$$

$$x = \frac{(10)(3.40)(8.34)}{(520{,}000)(8.34)}$$

$$x = 0.0000653 \text{ MGD}$$

This can be expressed as gallons per day of flow:

$$0.0000653 \text{ MGD} = 65.3 \text{ gpd flow}$$

16.10.9 Chemical Feed Pump — Percent Stroke Setting

Chemical feed pumps are generally positive displacement pumps (also called "piston" pumps). This type of pump displaces, or pushes out, a volume of chemical equal to the volume of the piston. The length of the piston, called the stroke, can be lengthened or shortened to increase or decrease the amount of chemical delivered by the pump. In calculating percent stroke setting, use the following equation:

$$\text{\% Stroke Setting} = \frac{\text{Required Feed, gpd}}{\text{Maximum Feed, gpd}} \qquad (16.101)$$

Example 16.74

Problem:

The required chemical pumping rate has been calculated at 8 gpm. If the maximum pumping rate is 90 gpm, what should the percent stroke setting be?

Solution:

The percent stroke setting is based on the ratio of the gallons per minute required to the total possible gallons per minute:

$$\text{\% Stroke Setting} = \frac{\text{Required Feed, gpd}}{\text{Maximum Feed, gpd}} \times 100$$

$$= \frac{8 \text{ gpm}}{90 \text{ gpm}} \times 100$$

$$= 8.9\%$$

16.10.10 Chemical Solution Feeder Setting, Milliliters per Minute

Some chemical solution feeders dispense chemical as milliliters per minute (mL/min). To calculate the milliliters per minute of solution required, use the following equation:

$$\text{Solution, mL/min} = \frac{(\text{gpd})(3785 \text{ mL/gal})}{1440 \text{ min/day}} \qquad (16.102)$$

Example 16.75

Problem:

The desired solution feed rate was calculated at 7 gpd. What is this feed rate expressed as milliliters per minute?

Solution:

Because the gallons-per-day flow has already been determined, the milliliters per minute flow rate can be calculated directly:

$$\text{Feed Rate mL/min} = \frac{\text{(gpd) (3785 mL/gal)}}{\text{1440 min/day}}$$

$$= \frac{\text{(7 gpd) (3785 mL/gal)}}{\text{1440 min/day}}$$

$$= \text{18 mL/min Feed Rate}$$

16.10.11 Chemical Feed Calibration

Routinely, to ensure accuracy, we need to compare the actual chemical feed rate with the feed rate indicated by the instrumentation. To accomplish this, we use calibration calculations.

To calculate the actual chemical feed rate for a dry chemical feed, place a container under the feeder, weigh the container when it is empty, and then weigh it again after a specified length of time, such as 30 min. Actual chemical feed rate can then be determined as:

$$\text{Chemical Feed Rate, lb/min} = \frac{\text{Chemical Applied, lb}}{\text{Length of Application, min}} \tag{16.103}$$

Example 16.76

Problem:

Calculate the actual chemical feed rate, pounds per day, if a container is placed under a chemical feeder and a total of 2.2 lb is collected during a 30-min period.

Solution:

First, calculate the pounds per minute feed rate:

$$\text{Chemical Feed Rate, lb/min} = \frac{\text{Chemical Applied, lb}}{\text{Length of Application, min}}$$

$$= \frac{\text{2.2 lb}}{\text{30 min}}$$

$$= \text{0.07 lb/min Feed Rate}$$

Then, calculate the pounds per day feed rate:

$$\text{Chemical Feed Rate, lb/day} = (0.07 \text{ lb/min})\ (1440 \text{ min/day})$$

$$= 101 \text{ lb/day Feed Rate}$$

Example 16.77

Problem:

A chemical feeder must be calibrated. The container to be used to collect the chemical is weighed (0.35 lb) and placed under the chemical feeder. After 30 min, the weight of the container and chemical is measured at 2.2 lb. Based on this test, what is the actual chemical feed rate, in pounds per day?

Solution:

First, calculate the pounds per minute feed rate:

> *Key point*: The chemical applied is the weight of the container and chemical minus the weight of the empty container.

$$\text{Chemical Feed Rate, lb/min} = \frac{\text{Chemical Applied, lb}}{\text{Length of Application, min}}$$

$$= \frac{2.2 \text{ lb} - 0.35 \text{ lb}}{30 \text{ min}}$$

$$= \frac{1.85 \text{ lb}}{30 \text{ min}}$$

$$= 0.062 \text{ lb/min Feed Rate}$$

Then calculate the pounds per day feed rate:

$$(0.062 \text{ lb/min})\ (1440 \text{ min/day}) = 89 \text{ lb/day Feed Rate}$$

When the chemical feeder is for a solution, the calibration calculation is slightly more difficult than that for a dry chemical feeder. As with other calibration calculations, the actual chemical feed rate is determined and then compared with the feed rate indicated by the instrumentation. Use these calculations for solution feeder calibration:

$$\text{Flow Rate, gpd} = \frac{(\text{mL/min})\ (1440 \text{ min/day})}{3785 \text{ mL/gal}} = \text{gpd} \tag{16.104}$$

Then, calculate chemical dosage, pounds per day:

$$\text{Chemical, lb/day} = (\text{Chemical, mg/L})\ (\text{Flow, MGD})\ (8.34 \text{ lb/day}) \tag{16.105}$$

Example 16.78

Problem:

A calibration test is conducted for a solution chemical feeder. During 5 min, the solution feeder delivers a total of 700 mL. The polymer solution is a 1.3% solution. What is the pounds-per-day feed rate? (Assume the polymer solution weighs 8.34 lb/gal.)

Solution:

The milliliters-per-minute flow rate is calculated as:

$$\frac{700\text{ mL}}{5\text{ min}} = 140\text{ mL/min}$$

Then convert milliliters-per-minute flow rate to gallons-per-day flow rate:

$$\frac{(140\text{ mL/min})\,(1440\text{ min/day})}{3785\text{ mL/gal}} = 53\text{ gpd flow rate}$$

and calculate pounds-per-day fee rate:

$$\text{Chemical, lb/day} = (\text{Chemical, mg/L})\,(\text{Flow, MGD})\,(8.34\text{ lb/day})$$

$$(13{,}000\text{ mg/L})\,(0.000053\text{ MGD})\,(8.34\text{ lb/day}) = 5.7\text{ lb/day polymer}$$

Actual pumping rates can be determined by calculating the volume pumped during a specified time frame. For example, if 120 gal are pumped during a 15-min test, the average pumping rate during the test is 8 gpm. The gallons pumped can be determined by measuring the drop in tank level during the timed test:

$$\text{Flow, gpm} = \frac{\text{Volume Pumped, gal}}{\text{Duration of Test, min}} \tag{16.106}$$

Then the actual flow rate (gallons per minute) is calculated using

$$\text{Flow, gpm} = \frac{(0.785)\,(D^2)\,(\text{Drop in Level, ft})\,(7.48\text{ gal/ft}^3)}{\text{Duration of Test, min}} \tag{16.107}$$

Example 16.79

Problem:

A pumping rate calibration test is conducted for a 5-min period. The liquid level in the 4-ft diameter solution tank is measured before and after the test. If the level drops 0.4 ft during the 5-min test, what is the pumping rate in gallons per minute?

Solution:

$$\text{Flow, gpm} = \frac{(0.785)\,(D^2)\,(\text{Drop in Level, ft})\,(7.48\ \text{gal/ft}^3)}{\text{Duration of Test, min}}$$

$$= \frac{(0.785)\,(D^2)\,(4\ \text{ft})\,(4\ \text{ft})\,(0.4\ \text{ft})\,(7.48\ \text{gal/ft}^3)}{5\ \text{min}}$$

$$\text{Pumping Rate} = 7.5\ \text{gpm}$$

16.10.12 Average Use Calculations

During a typical shift, operators log in or record several parameter readings. The data collected are important in monitoring plant operation — in providing information on how to best optimize plant or unit process operation. One of the important parameters monitored each shift or each day is the actual use of chemicals. From the recorded chemical use data, expected chemical use can be forecast. These data are also important for inventory control; determination can be made when additional chemical supplies will be required.

In determining average chemical use, we first must determine the average daily chemical use:

$$\text{Average Use, lb/day} = \frac{\text{Total Chemical Used, lb}}{\text{Number of Days}} \tag{16.108}$$

or

$$\text{Average Use, gpd} = \frac{\text{Total Chemical Used, gal}}{\text{Number of Days}} \tag{16.109}$$

Then calculate day's supply in inventory:

$$\text{Days Supply in Inventory} = \frac{\text{Total Chemical in Inventory, lb}}{\text{Average Use, lb/day}} \tag{16.110}$$

or

$$\text{Days Supply in Inventory} = \frac{\text{Total Chemical in Inventory, gal}}{\text{Average Use, gpd}} \tag{16.111}$$

Example 16.80

Problem:

The chemical amount used for each day during a week is given in the following table. Based on these data, what was the average pounds-per-day chemical use during the week?

Day	Amount (lb/day)
Monday	92
Tuesday	94
Wednesday	92
Thursday	88
Friday	96
Saturday	92
Sunday	88

Solution:

$$\text{Average Use, lb/day} = \frac{\text{Total Chemical Used, lb}}{\text{Number of Days}}$$

$$= \frac{642 \text{ lb}}{7 \text{ days}}$$

$$\text{Average Use} = 91.7 \text{ lb/day}$$

Example 16.81

Problem:

The average chemical use at a plant is 83 lb/day. If the chemical inventory in stock is 2600 lb, how many days' supply is this?

Solution:

$$\text{Days Supply in Inventory} = \frac{\text{Total Chemical in Inventory, lb}}{\text{Average Use, lb/day}}$$

$$= \frac{2600 \text{ lb in Inventory}}{83 \text{ lb/day Average Use}}$$

$$= 31.3 \text{ days supply}$$

16.11 BIOSOLIDS PRODUCTION AND PUMPING CALCULATIONS

16.11.1 Process Residuals

The wastewater unit treatment processes remove solids and biochemical oxygen demand from the waste stream before the liquid effluent is discharged to its receiving waters. What remains to be disposed is a mixture of solids and wastes called *process residuals* — more commonly referred to as biosolids (or sludge).

Key point: Sludge is the commonly accepted name for wastewater residual solids. However, if wastewater sludge is used for beneficial reuse (as a soil amendment or fertilizer), it is commonly called biosolids. We choose to refer to process residuals as biosolids in this text.

The most costly and complex aspect of wastewater treatment can be the collection, processing, and disposal of biosolids because the quantity of biosolids produced may be as high as 2% of the original volume of wastewater, depending somewhat on the treatment process used. Biosolids can be as much as 97% water content and the costs of disposal are related to the volume of biosolids processed; thus, one of the primary purposes or goals of biosolids treatment (along with stabilizing it so that it is no longer objectionable or environmentally damaging) is to separate as much of the water from the solids as possible.

16.11.2 Primary and Secondary Solids Production Calculations

We point out that when making calculations pertaining to solids and biosolids, the term "solids" refers to *dry solids* and the term "biosolids" refers to the *solids and water*. The solids produced during primary treatment depend on the solids that settle in or are removed by the primary clarifier. In making primary clarifier solids production calculations, we use the milligrams-per-liter to pounds-per-day equation:

$$\text{Susp. Solids (SS) Removed, lb/day} = \text{(SS Removed, mg/L) (Flow, MGD) (8.34 lb/gal)} \tag{16.112}$$

16.11.3 Primary Clarifier Solids Production Calculations

Example 16.82

Problem:

A primary clarifier receives a flow of 1.80 MGD with suspended solids concentrations of 340 mg/L. If the clarifier effluent has a suspended solids concentration of 180 mg/L, how many pounds of solids are generated daily?

Solution:

$$\text{Susp. Solids (SS) Removed, lb/day} = \text{(SS Removed, mg/L) (Flow, MGD) (8.34 lb/gal)}$$

$$= \text{(160 mg/L) (1.80 MGD) (8.34 lb/gal)}$$

$$\text{Solids} = \text{2402 lb/day}$$

Example 16.83

Problem:

The suspended solids content of the primary influent is 350 mg/L and the primary influent is 202 mg/L. How many pounds of solids are produced during a day on which the flow is 4,150,000 gpd?

Solution:

$$\text{SS, lb/day Removed} = \text{(SS Removed, mg/L) (Flow, MGD) (8.34 lb/gal)}$$

$$= \text{(148 mg/L) (4.15 MGD) (8.34 lb/gal)}$$

$$\text{Solids Removed} = \text{5122 lb/day}$$

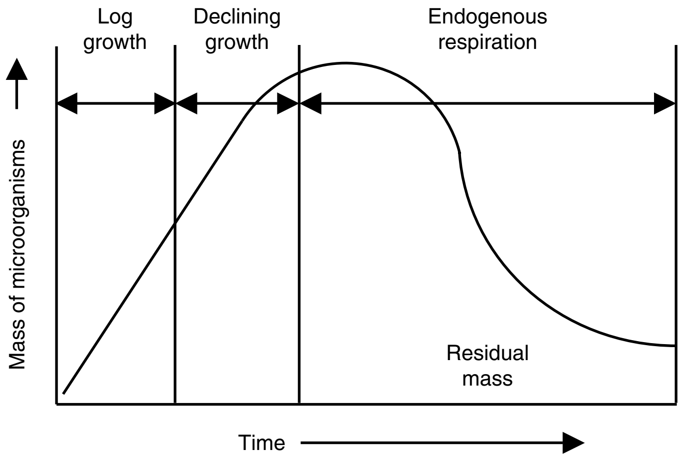

Figure 16.8 Bacteria growth curve. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

16.11.4 Secondary Clarifier Solids Production Calculation

Solids produced during secondary treatment depend on many factors, including the amount of organic matter removed by the system and the growth rate of bacteria (see Figure 16.8). Because precise calculations of biosolids production are complex, we provide a rough estimate method of solids production that uses an estimated growth rate (unknown) value: the BOD-removed, pounds-per-day equation:

$$\text{BOD Removed, lb/day} = (\text{BOD Removed, mg/L})\ (\text{Flow, MGD})\ (8.34\ \text{lb/day}) \quad (16.113)$$

Example 16.84

Problem:

The 1.5-MGD influent to the secondary system has a BOD concentration of 174 mg/L. The secondary effluent contains 22 mg/L BOD. If the bacteria growth rate (unknown *x*-value) for this plant is 0.40 lb SS per pound of BOD removed, how many pounds of dry biosolids solids are produced each day by the secondary system?

Solution:

$$\text{BOD Removed, lb/day} = (\text{BOD, mg/L})\ (\text{Flow, MGD})\ (8.34\ \text{lb/day})$$

$$= (152\ \text{mg/L})\ (1.5\ \text{MGD})\ 8.34\ \text{lb/gal}$$

$$= 1902\ \text{lb/day}$$

Then use the unknown *x*-value to determine pounds per day of solids produced.

$$\frac{0.44 \text{ lb SS Produced}}{1 \text{ lb BOD Removed}} = \frac{x \text{ lb SS Produced}}{1902 \text{ lb/day BOD Removed}}$$

$$= \frac{(0.44)\,(1902)}{1} = x$$

$$837 \text{ lb/day Solids Produced} = x$$

Key point: Typically, for every pound of food consumed (BOD removed) by the bacteria, between 0.3 and 0.7 lb of new bacteria cells are produced; these are solids that must be removed from the system.

16.11.5 Percent Solids

Biosolids are composed of water and solids. The vast majority of biosolids are water — usually in the range of 93 to 97%. To determine the solids content of biosolids, a sample is dried overnight in an oven at 103 to 105°F. The solids that remain after drying represent the total solids content of the biosolids. Solids content may be expressed as a percent or as milligrams per liter. Either of two equations is used to calculate percent solids:

$$\% \text{ Solids} = \frac{\text{Total Solids, g (grams)}}{\text{Biosolids Sample, g}} \times 100 \tag{16.114}$$

$$\% \text{ Solids} = \frac{\text{Solids, lb/day}}{\text{Biosolids, lb/day}} \times 100 \tag{16.115}$$

Example 16.85

Problem:

The total weight of a biosolids sample (sample only, not the dish) is 22 g. If the weight of the solids after drying is 0.77 g, what is the percent total solids of the biosolids?

Solution:

$$\% \text{ Solids} = \frac{\text{Total Solids, g}}{\text{Biosolids Sample, g}} \times 100$$

$$= \frac{0.77 \text{ g}}{22 \text{ g}} \times 100$$

$$= 3.5\%$$

16.11.6 Biosolids Pumping

While on shift, wastewater operators are often required to make various process control calculations. One important calculation (covered in this subsection) involves biosolids pumping.

16.11.7 Estimating Daily Biosolids Production

The calculation for estimation of the required biosolids-pumping rate provides a method to establish an initial pumping rate or to evaluate the adequacy of the current withdrawal rate:

$$\text{Est. pump rate} = \frac{(\text{Influ. TSS Conc.} - \text{Effluent TSS Conc.}) \times \text{Flow} \times 8.34}{\%\ \text{Solids in Sludge} \times 8.34 \times 1440\ \text{min/day}} \qquad (16.116)$$

Example 16.86

Problem:

The biosolids withdrawn from the primary settling tank contain 1.4% solids. The unit influent contains 285 mg/L TSS, and the effluent contains 140 mg/L TSS. If the influent flow rate is 5.55 MGD, what is the estimated biosolids withdrawal rate in gallons per minute (assuming the pump operates continuously)?

Solution:

$$\text{Biosolids Rate, gpm} = \frac{(285\ \text{mg/L} - 140\ \text{mg/L} \times 5.55 \times 8.34}{0.014 \times 8.34 \times 1440\ \text{min/day}} = 40\ \text{gpm}$$

16.11.8 Biosolids Production (Pounds per Million Gallons)

A common method of expressing biosolids production is in pounds of biosolids per million gallons of wastewater treated:

$$\text{Biosolids, lb/MG} = \frac{\text{Total Biosolids Production, lb}}{\text{Total Wastewater Flow, MG}} \qquad (16.117)$$

Example 16.87

Problem:

Records show that a plant has produced 85,000 gal of biosolids during the past 30 days. The average daily flow for this period was 1.2 MGD. What was the plant's biosolids production in pounds per million gallons?

Solution:

$$\text{Biosolids, lb/MG} = \frac{85{,}000\ \text{gal} \times 8.34\ \text{lb/gal}}{1.2\ \text{MGD} \times 30\ \text{days}} = 19{,}692\ \text{lb/MG}$$

16.11.9 Biosolids Production (Wet Tons per Year)

Biosolids production can also be expressed in terms of the amount of biosolids (water and solids) produced per year. This is normally expressed in wet tons per year:

$$\text{Biosolids, wet tons/yr} \; \frac{\text{Biosolids Prod., lb/MG} \times \text{Ave. Daily Flow, MGD} \times 365\ \text{day/yr}}{2000\ \text{lb/ton}} = 40\ \text{gpm} \qquad (16.118)$$

Example 16.88

Problem:

A plant is currently producing biosolids at the rate of 16,500 lb/MG. The current average daily wastewater flow rate is 1.5 MGD. What is the total amount of biosolids produced per year in wet tons per year?

Solution:

$$\text{Biosolids, Wet Tons/yr} = \frac{16{,}500 \text{ lb/MG} \times 1.5 \text{ MGD} \times 365 \text{ days/yr}}{2000 \text{ lb/ton}}$$

$$= 4517 \text{ Wet Tons/yr}$$

16.11.10 Biosolids Pumping Time

The biosolids pumping time is the total time the pump operates during a 24-h period, expressed in minutes.

$$\text{Pump Operating Time} = \text{Time/Cycle, min} \times \text{Frequency, cycles/day} \qquad (16.119)$$

Note: The following information is used for Example 16.89 through Example 16.94:

Frequency	24 times per day
Pump rate	120 gpm
Solids	3.70%
Volatile matter	66%

Example 16.89

Problem:

What is the pump operating time?

Solution:

$$\text{Pump Operating Time} = 15 \text{ min/h} \times 24 \text{ (cycles)/day} = 360 \text{ min/day}$$

Biosolids pumped per day in gallons:

$$\text{Biosolids, gpd} = \text{Operating Time, min/day} \times \text{Pump Rate, gpm} \qquad (16.120)$$

Example 16.90

Problem:

What is the amount of biosolids pumped per day in gallons?

Solution:

$$\text{Biosolids, gpd} = 360 \text{ min/day} \times 120 \text{ gpm} = 43{,}200 \text{ gpd}$$

Biosolids pumped per day in pounds:

$$\text{Sludge, lb/day} = \text{Gallons of Biosolids Pumped} \times 8.34 \text{ lb/gal} \tag{16.121}$$

Example 16.91

Problem:
What is the amount of biosolids pumped per day in pounds?

Solution:

$$\text{Biosolids, lb/day} = 43{,}200 \text{ gal/day} \times 8.34 \text{ lb/gal} = 360{,}300 \text{ lb/day}$$

Biosolids pumped per day in pounds:

$$\text{Solids Pumped, lb/day} = \text{Biosolids Pumped, lb/day} \times \% \text{ Solids}$$

Example 16.92

Problem:
What are the solids pumped per day?

Solution:

$$\text{Solids Pumped lb/day} = 360{,}300 \text{ lb/day} \times 0.0370 = 13{,}331 \text{ lb/day}$$

Volatile matter pumped per day in pounds:

$$\text{Vol. Matter (lb/day)} = \text{Solids Pumped, lb/day} \times \% \text{ Volatile Matter} \tag{16.122}$$

Example 16.93

Problem:
What is the volatile matter in pounds per day?

Solution:

$$\text{Volatile Matter, lb/day} = 13{,}331 \text{ lb/day} \times 0.66 = 8798 \text{ lb/day}$$

Pounds of solids/pounds of volatile solids per day:

If we wish to calculate the pounds of solids or the pounds of volatile solids removed per day, the individual equations demonstrated earlier can be combined into single calculations:

$$\text{Solids, lb/day} =$$

$$\text{Pump Time, min/cyc} \times \text{Freq., cyc/day} \times \text{Rate, gpm} \times 8.34 \text{ lb/gal} \times \text{solids} \tag{16.123}$$

$$\text{Vol. Mat., lb/day} = \text{Time, min/cyc} \times \text{Freq., cyc/day} \times \text{Rate, gpm} \times 8.34 \times \%\text{ Solids} \times \%\text{ VM} \quad (16.124)$$

Example 16.94

$$\text{Solids, lb/day} = 15\text{ min/cyc} \times 24\text{ cyc/day} \times 120\text{ gpm} \times 8.34 \times 0.0370$$

$$= 13{,}331\text{ lb/day}$$

$$\text{VM, lb/day} = 15\text{ min/cyc} \times 24\text{ cyc/day} \times 120\text{ gpm} \times 8.34 \times 0.0370 \times .66$$

$$= 8{,}798\text{ lb/day}$$

16.12 BIOSOLIDS THICKENING

16.12.1 Thickening

Biosolids thickening (or concentration) is a unit process used to increase the solids content of the biosolids by removing a portion of the liquid fraction. In other words, biosolids thickening is all about volume reduction. By increasing the solids content, more economical treatment of the biosolids can be effected. Biosolids thickening processes include:

- Gravity thickeners
- Flotation thickeners
- Solids concentrators

Biosolids thickening calculations are based on the concept that the solids in the primary or secondary biosolids are equal to the solids in the thickened biosolids. The solids are the same. Primarily, water has been removed to thicken the biosolids, resulting in higher percent solids. In unthickened biosolids, the solids might represent 1 to 4% of the total pounds of biosolids. When some of the water is removed, those same-amount solids might represent 5 to 7% of the total pounds of biosolids.

Key point: The key to biosolids thickening calculations is that solids remain constant.

16.12.2 Gravity/Dissolved Air Flotation Thickener Calculations

Biosolids thickening calculations are based on the concept that the solids in the primary or secondary biosolids are equal to the solids in the thickened biosolids. Assuming a negligible amount of solids is lost in the thickener overflow, the solids are the same. Note that the water is removed to thicken the biosolids and results in higher percent solids.

16.12.2.1 Estimating Daily Sludge Production

The calculation for estimating the required biosolids-pumping rate provides a method to establish an initial pumping rate or to evaluate the adequacy of the current pump rate:

$$\text{Est. Pump Rate} = \frac{(\text{Influent TSS Conc.} - \text{Eff. TSS Conc.}) \times \text{Flow} \times 8.34}{\% \text{ Solids in Biosolids} \times 8.34 \times 1440 \text{ min/day}} \tag{16.125}$$

Example 16.95

Problem:

The biosolids withdrawn from the primary settling tank contain 1.5% solids. The unit influent contains 280 mg/L TSS, and the effluent contains 141 mg/L TSS. If the influent flow rate is 5.55 MGD, what is the estimated biosolids withdrawal rate in gallons per minute (assuming the pump operates continuously)?

Solution:

$$\text{Biosolids Withdrawal Rate, gpm} = \frac{(280 \text{ mg/L} - 141 \text{ mg/L}) \times 5.55 \text{ MGD} \times 8.34}{0.015 \times 8.34 \times 1440 \text{ min/day}}$$

$$= 36 \text{ gpm}$$

16.12.2.2 Surface Loading Rate, Gallons per Day per Square Foot

Surface loading rate (surface settling rate) is hydraulic loading — the amount of biosolids applied per square foot of gravity thickener.

$$\text{Surface Loading, gal/day/ft}^2 = \frac{\text{Biosolids Applied to the Thickener, gpd}}{\text{Thickener Area, ft}^2} \tag{16.126}$$

Example 16.96

Problem:

A 70-ft diameter gravity thickener receives 32,000 gpd of biosolids. What is the surface loading in gallons per square foot per day?

Solution:

$$\text{Surface Loading} = \frac{32{,}000 \text{ gpd}}{0.785 \times 70 \text{ ft} \times 70 \text{ ft}} = 8.32 \text{ gpd/ft}^2$$

16.12.2.3 Solids Loading Rate, Pounds per Day per Square Foot

The solids loading rate is the pounds of solids per day applied to 1 ft^2 of tank surface area. The calculation uses the surface area of the bottom of the tank. It assumes that the floor of the tank is flat and has the same dimensions as the surface:

$$\text{Surface Loading, lb/day/ft}^2 = \frac{\% \text{ Biosolids Solids} \times \text{Biosolids Flow, gpd} \times 8.34 \text{ lb/gal}}{\text{Thickener Area, ft}^2} \tag{16.127}$$

Example 16.97

Problem:

The thickener influent contains 1.6% solids. The influent flow rate is 39,000 gpd. The thickener is 50 ft in diameter and 10 ft deep. What is the solid loading in pounds per day?

Solution:

$$\text{Surface Loading, lb/day/ft}^2 = \frac{0.016 \times 39{,}000 \text{ gpd} \times 8.34 \text{ lb/gal}}{0.785 \times 50 \text{ ft} \times 50 \text{ ft}} = 2.7 \text{ lb/ft}^2$$

16.12.3 Concentration Factor (*Cf*)

The concentration factor (*CF*) represents the increase in concentration resulting from the thickener. It is a means of determining the effectiveness of the gravity thickening process.

$$\text{CF} = \frac{\text{Thickened Biosolids Concentration, \%}}{\text{Influent Biosolids Concentration, \%}} \tag{16.128}$$

Example 16.98

Problem:

The influent biosolids contain 3.5% solids. The thickened biosolids–solids concentration is 7.7%. What is the concentration factor?

Solution:

$$\text{CF} = \frac{7.7\%}{3.5\%} = 2.2$$

16.12.4 Air-to-Solids Ratio

Air–solids ratio is the ratio between the pounds of solids entering the thickener and the pounds of air applied:

$$\text{Air:Solids Ratio} = \frac{\text{Air Flow ft}^3\text{/min} \times 0.0785 \text{ lb/ft}^3}{\text{Biosolids Flow, gpm} \times \text{\% Solids} \times 8.34 \text{ lb/gal}} \tag{16.129}$$

Example 16.99

Problem:

The biosolids pumped to the thickener are 0.85% solids. The airflow is 13 ft^3/min. What is the air-to-solids ratio if the current biosolids flow rate entering the unit is 50 gpm?

Solution:

$$\text{Air:Solids Ratio} = \frac{13 \text{ cfm} \times 0.075 \text{ lb/ft}^3}{50 \text{ gpm} \times 0.0085 \times 8.34 \text{ lb/gal}} = 0.28$$

16.12.5 Recycle Flow in Percent

The amount of recycle flow is expressed as a percent:

$$\text{Recycle \%} = \frac{\text{Recycle Flow Rate, gpm} \times 100}{\text{Sludge Flow, gpm}} = 175\% \quad (16.130)$$

Example 16.100

Problem:

The sludge flow to the thickener is 80 gpm. The recycle flow rate is 140 gpm. What is the percent of recycle?

Solution:

$$\text{\% Recycle} = \frac{140 \text{ gpm} \times 100}{80 \text{ gpm}} = 175\%$$

16.12.6 Centrifuge Thickening Calculations

A centrifuge exerts a force on the biosolids thousands of times greater than gravity. Sometimes polymer is added to the influent of the centrifuge to help thicken the solids. The two most important factors that affect the centrifuge are the volume of the biosolids put into the unit (gallons per minute) and the pounds of solids put in. The water that is removed is called *centrate*.

Normally, hydraulic loading is measured as flow rate per unit of area. However, because of the variety of sizes and designs, hydraulic loading to centrifuges does not include area considerations and is expressed only as gallons per hour. The equations to be used if the flow rate to the centrifuge is given as gallons per day or gallons per minute are:

$$\text{Hydraulic Loading, gph} = \frac{\text{Flow, gpd}}{24 \text{ h/day}} \quad (16.131)$$

$$\text{Hydraulic Loading, gpm} = \frac{(\text{gpm flow})\,(60 \text{ min})}{\text{h}} \quad (16.132)$$

Example 16.101

Problem:

A centrifuge receives a waste-activated biosolids flow of 40 gpm. What is the hydraulic loading on the unit in gallons per hour?

Solution:

$$\text{Hydraulic Loading, gph} = \frac{(\text{gpm flow})\,(60 \text{ min})}{\text{h}}$$

$$= \frac{(40 \text{ gpm})\,(60 \text{ min})}{\text{h}}$$

$$= 2400 \text{ gph}$$

Example 16.102

Problem:

A centrifuge receives 48,600 gal of biosolids daily. The biosolids concentration before thickening is 0.9%. How many pounds of solids are received each day?

Solution:

$$\frac{48{,}600\text{ gal}}{\text{day}} \times \frac{8.34\text{ lb}}{\text{gal}} \times \frac{0.9}{100} = 3648\ \text{lb/day}$$

16.13 STABILIZATION

16.13.1 Biosolids Digestion

A major problem in designing wastewater treatment plants is the disposal of biosolids into the environment without causing damage or nuisance. It is even more difficult to dispose of untreated biosolids; they must be stabilized to minimize disposal problems. In most cases, the term *stabilization* is considered synonymous with digestion.

> *Key point*: The stabilization of organic matter is accomplished biologically using a variety of organisms. The microorganisms convert the colloidal and dissolved organic matter into various gases and into protoplasm. Because protoplasm has a specific gravity slightly higher than that of water, it can be removed from the treated liquid by gravity.

Biosolids digestion is a process in which biochemical decomposition of the organic solids occurs; in the decomposition process, the organics are converted into simpler and more stable substances. Digestion also reduces the total mass or weight of biosolids solids, destroys pathogens, and makes drying or dewatering the biosolids easier. Well-digested biosolids have the appearance and characteristics of a rich potting soil.

Biosolids may be digested under aerobic or anaerobic conditions. Most large municipal wastewater treatment plants use anaerobic digestion. Aerobic digestion finds application primarily in small, package-activated biosolids treatment systems.

16.13.2 Aerobic Digestion Process Control Calculations

The purpose of aerobic digestion is to stabilize organic matter, reduce volume, and eliminate pathogenic organisms. Aerobic digestion is similar to the activated biosolids process. Biosolids are aerated for 20 days or more and volatile solids are reduced by biological activity.

16.13.2.1 Volatile Solids Loading, Pounds per Square Foot per Day

Volatile solids (organic matter) loading for the aerobic digester is expressed in pounds of volatile solids entering the digester per day per cubic foot of digester capacity.

$$\text{Volatile Solids Loading, lb/day/ft}^3 = \frac{\text{Volatile Solids Added, lb/day}}{\text{Digester Volume, ft}^3} \tag{16.133}$$

Example 16.103

Problem:

An aerobic digester is 20 ft in diameter and has an operating depth of 20 ft. The biosolids added to the digester daily contain 1500 lb of volatile solids. What is the volatile solids loading in pounds per day per cubic foot?

Solution:

$$\text{Volatile Solids Loading, lb/day/ft}^3 = \frac{1500 \text{ lb/day}}{0.785 \times 20 \text{ ft} \times 20 \text{ ft} \times 20 \text{ ft}} = 0.24 \text{ lb/day/ft}^3$$

16.13.2.2 Digestion Time, Days

The theoretical time that biosolids remain in the aerobic digester is:

$$\text{Digestion Time, Days} = \frac{\text{Digester Volume, gallons}}{\text{Biosolids Added, gpd}} \qquad (16.134)$$

Example 16.104

Problem:

The digester volume is 240,000 gal. Biosolids are added to the digester at the rate of 15,000 gpd. What is the digestion time in days?

Solution:

$$\text{Digestion Time, Days} = \frac{240{,}000 \text{ gal}}{15{,}000 \text{ gpd}} = 16 \text{ days}$$

16.13.2.3 pH Adjustment

In many instances, the pH of the aerobic digester falls below the levels required for good biological activity. When this occurs, the operator must perform a laboratory test to determine the amount of alkalinity required to raise the pH to the desired level. The results of the lab test must then be converted to the actual quantity required by the digester:

$$\text{Digestion Time, Days} = \frac{\text{Chem. Used in Lab Test, mg} \times \text{Dig. Vol.} \times 3.785}{\text{Sample Vol., L} \times 454 \text{ g/lb} \times 1000 \text{ mg/g}} \qquad (16.135)$$

Example 16.105

Problem:

The pH of a 1-L sample of the aerobic digester contents will be increased to pH 7.1 by 240 mg of lime. The digester volume is 240,000 gal. How many pounds of lime are required to increase the digester pH to 7.3?

Solution:

$$\text{Chemical Required, lb} = \frac{240 \text{ mg} \times 240{,}000 \text{ gal} \times 3.785 \text{ L/gal}}{1\text{L} \times 454 \text{ g/lb} \times 1{,}000 \text{ mg/g}} = 480 \text{ lb}$$

16.13.3 Aerobic Tank Volume

The aerobic tank volume can be computed in situations in which no significant nitrification will occur by the following equation (WPCF, 1985):

$$V = \frac{Q_i(X_i + YS_i)}{X(K_d P_v + 1/\theta_C)} \tag{16.136}$$

where
V = volume of aerobic digester, cubic feet
Q_i = influent average flow rate to digester, cubic feet per day
X_i = influent suspended solids concentration, milligrams per liter
Y = fraction of the influent BOD consisting of raw primary sludge, in decimals
S_i = influent BOD, milligrams per liter
X = digester suspended solids concentration, milligrams per liter
K_d = reaction-rate constant, days^{-1}
P_v = volatile fraction of digester suspended solids, in decimals
θ = solids retention time, days

Example 16.106

Problem:
The pH of an aerobic digester has declined to 6.1. How much sodium hydroxide must be added to raise the pH to 7.0? The volume of the digester is 370 m^3. Results from jar tests show that 34 mg of caustic soda will raise the pH to 7.0 in a 2-L jar.

Solution:

$$\text{NaOH required per m}^3 = 34 \text{ mg/2L} = 17 \text{ mg/L}$$

$$= 17 \text{ g/m}^3$$

$$\text{NaOH to be added} = 17 \text{ g/m}^3 \times 370 \text{ m}^3$$

$$= 6290 \text{ g}$$

$$= 6.3 \text{ kg} = 13.9 \text{ lb}$$

16.13.4 Anaerobic Digestion Process Control Calculations

The purpose of anaerobic digestion is the same that of aerobic digestion: to stabilize organic matter, reduce volume, and eliminate pathogenic organisms. Equipment used in anaerobic digestion includes an anaerobic digester of the floating or fixed cover type. These include biosolids pumps for biosolids addition and withdrawal, as well as heating equipment such as heat exchangers, heaters and pumps, and mixing equipment for recirculation. Typical ancillaries include gas storage, cleaning equipment, and safety equipment such as vacuum relief and pressure relief devices, flame traps, and explosion-proof electrical equipment.

In the anaerobic process, biosolids enter the sealed digester where organic matter decomposes anaerobically. Anaerobic digestion is a two-stage process:

1. Sugars, starches, and carbohydrates are converted to volatile acids, carbon dioxide, and hydrogen sulfide.
2. Volatile acids are converted to methane gas.

We cover key anaerobic digestion process control calculations in the following subsections.

16.13.4.1 Required Seed Volume in Gallons

$$\text{Seed Volume (Gallons)} = \text{Digester Volume, gal} \times \text{\% Seed} \tag{16.137}$$

Example 16.107

Problem:

The new digester requires as seed 25% to achieve normal operation within the allotted time. If the digester volume is 280,000 gal, how many gallons of seed material are required?

Solution:

$$\text{Seed Volume} = 280{,}000 \times 0.25 = 70{,}000 \text{ gal}$$

16.13.4.2 Volatile Acids-to-Alkalinity Ratio

The volatile acids–alkalinity ratio can be used to control an anaerobic digester:

$$\text{Ratio} = \frac{\text{Volatile Acids Concentration}}{\text{Alkalinity Concentration}} \tag{16.138}$$

Example 16.108

Problem:

The digester contains 240 mg/L volatile acids and 1840 mg/L alkalinity. What is the volatile acids–alkalinity ratio?

Solution:

$$\text{Ratio} = \frac{240 \text{ mg/L}}{1840 \text{ mg/L}} = 0.13$$

Key point: Increases in the ratio normally indicate a potential change in the operating condition of the digester.

16.13.4.3 Biosolids Retention Time

The length of time the biosolids remain in the digester is:

$$\text{BRT} = \frac{\text{Digester Volume in Gallons}}{\text{Biosolids Volume added per day, gpd}}$$

Example 16.109

Problem:

Biosolids are added to a 520,000-gal digester at the rate of 12,600 gal/day. What is the biosolids retention time?

Solution:

$$\text{BRT} = \frac{520{,}000 \text{ gal}}{12{,}600 \text{ gpd}} = 41.3 \text{ days}$$

16.13.4.4 Estimated Gas Production (Cubic Feet per Day)

The rate of gas production is normally expressed as the volume of gas (cubic feet) produced per pound of volatile matter destroyed. The total cubic feet of gas that a digester will produce per day can be calculated by:

$$\begin{aligned}&\text{Gas production, ft}^3\text{/day} = \\ &\text{Vol. Matter In, lb/day} \times \text{\% Vol. Mat. Reduction} \times \text{Prod. Rate ft}^3\text{/lb}\end{aligned} \tag{16.140}$$

Key point: Multiplying the volatile matter added to the digester per day by the percent of volatile matter reduction (in decimal percent) gives the amount of volatile matter destroyed by the digestion process per day.

Example 16.110

Problem:

The digester reduces 11,500 lb of volatile matter per day. Currently, the volatile matter reduction achieved by the digester is 55%. The rate of gas production is 11.2 ft^3 of gas per pound of volatile matter destroyed.

Solution:

$$\text{Gas Prod.} = 11{,}500 \text{ lb/day} \times 0.55 \times 11.2 \text{ ft}^3\text{/lb} = 70{,}840 \text{ ft}^3\text{/day}$$

16.13.4.5 Volatile Matter Reduction (Percent)

Because of the changes occurring during biosolids digestion, the calculation used to determine percent of volatile matter reduction is more complicated:

$$\% \text{ Red.} = \frac{(\% \text{ Vol. Matter}_{in} - \% \text{ Vol. Matter}_{out}) \times 100}{[\% \text{ Vol. Matter}_{in} - (\% \text{ Vol. Matter}_{in} \times \% \text{ Vol. Matter}_{out})]} \tag{16.141}$$

Example 16.111

Problem:

Using the digester data provided here, determine the percent of volatile matter reduction for the digester: raw biosolids volatile matter, 71%, and digested biosolids volatile matter, 54%.

Solution:

$$\% \text{ Volatile Matter Reduction} = \frac{0.71 - 0.54}{[0.71 - (0.71 \times 0.54)]} = 52\%$$

16.13.4.6 Percent Moisture Reduction in Digested Biosolids

$$\% \text{ Moisture Reduction} = \frac{(\% \text{ Moisture}_{in} - \% \text{ Moisture}_{out}) \times 100}{[\% \text{ Moisture}_{in} - (\% \text{ Moisture}_{in} \times \% \text{ Moisture}_{out})]} \tag{16.142}$$

Key point: Percent of moisture = 100% minus percent of solids.

Example 16.112

Problem:

Using the digester data provided in the following table, determine the percent of moisture reduction and percent of volatile matter reduction for the digester.

	% Solids	% Moisture
Raw biosolids	9	91 (100 – 9)
Digested biosolids	15	85 (100 – 15)

Solution:

$$\% \text{ Moisture Reduction} = \frac{(0.91 - 0.85) \times 100}{[0.91 - (0.91 \times 0.85)]} = 44\%$$

16.13.4.7 Gas Production

In measuring the performance of a digester, gas production is one of the most important parameters. Typically, gas production ranges from 800 to 1125 L of digester gas per kilogram of volatile solids destroyed. Gas produced from a properly operated digester contains approximately 68% methane and 32% carbon dioxide. If carbon dioxide exceeds 35%, the digestion system is operating incorrectly. The quantity of methane gas produced can be calculated by these equations, in SI and British units, respectively, derived by McCarty (1964):

$$V = 350[Q(S_o - S)/(1000) - 1.42P_x] \tag{16.143}$$

$$V = 5.62[Q(S_o - S)8.34 - 1.42P_x] \tag{16.144}$$

where

V	=	volume of methane produced at standard conditions (0°C, 32°F and 1 atm), liters per day or cubic feet per day
350, 5.62	=	theoretical conversion factor for the amount of methane produced per kilogram (pound) of ultimate BOD oxidized, 350 L/kg or 5.62 ft³/lb
1000	=	1000 g/kg
Q	=	flow rate, cubic meters per or million gallons per day
S_o	=	influent ultimate BOD, milligrams per liter
S	=	effluent ultimate BOD, milligrams per liter
8.34	=	conversion factor, pounds/(million gallons per day) (milligrams per liter)
P_x	=	net mass of cell tissue produced, kilograms per day or pounds per day

For a complete-mix, high-rate, two-stage anaerobic digester (without recycle), the mass of biological solids synthesized daily, P_x, can be estimated by the following equations (in SI and British system units, respectively):

$$P_x = \frac{Y[Q(S_o - S)]}{1 + k_d\theta_c} \tag{16.145}$$

$$P_x = \frac{Y[Q(S_o - S)8.34]}{1 + k_d\theta_c} \tag{16.146}$$

where

Y = yield coefficient, kilograms per kilogram or pounds per pound

k_d = endogenous coefficient, per day

θ_c = mean cell residence time, days

Other terms have been defined previously.

Example 16.113

Problem:

Determine the amount of methane generated per kilogram of ultimate BOD stabilized. Use Glucose, $C_6H_{12}O_6$, as BOD.

Given:
Molecular weight of glucose: 180
Molecular weight of methane and carbon dioxide: 48
48/180 = 0.267
Oxidation of methane and carbon dioxide and water = 1.07 kg

Solution:

Step 1. Calculate the rate of the amount of methane generated per kilogram of BOD converted.

$$\frac{0.267}{1.07} = \frac{0.25}{1.0}$$

Thus, 0.25 kg of methane is produced by each kilogram of BOD stabilized.

Step 2. Calculate the volume equivalent of 0.25 kg of methane at the standard conditions (0°C and 1 atm).

$$\text{Volume} = (0.25 \times 1000 \text{ g})(1 \text{ mol}/16 \text{ g})(22.4 \text{ l/mol})$$

$$= 350 \text{ liters}$$

16.14 BIOSOLIDS DEWATERING AND DISPOSAL

16.14.1 Biosolids Dewatering

The process of removing enough water from liquid biosolids to change its consistency to that of a damp solid is called *biosolids dewatering*. Although the process is also called *biosolids drying,* the "dry" or dewatered biosolids may still contain a significant amount of water, often as much as 70%. At moisture contents of 70% or less, however, the biosolids no longer behave as a liquid and can be handled manually or mechanically.

Several methods are available to dewater biosolids. The particular types of dewatering techniques/devices used best describe the actual processes used to remove water from biosolids and change their form from a liquid to a damp solid. The commonly used techniques/devices include:

- Filter presses
- Vacuum filtration
- Sand drying beds

> *Key point*: Centrifugation is also used in the dewatering process. However, in this text we concentrate on the unit processes traditionally used for biosolids dewatering.

Note that an ideal dewatering operation would capture all of the biosolids at minimum cost and the resultant dry biosolids solids or cake would be capable of being handled without causing unnecessary problems. Process reliability, ease of operation, and compatibility with the plant environment would also be optimized.

16.14.2 Pressure Filtration Calculations

In pressure filtration, the liquid is forced through the filter media by a positive pressure. Several types of presses are available, but the most commonly used types are plate and frame presses and belt presses.

16.14.3 Plate and Frame Press

The plate and frame press consists of vertical plates held in a frame and pressed together between a fixed and moving end. A cloth filter medium is mounted on the face of each individual plate. The press is closed, and biosolids are pumped into the press at pressures up to 225 psi and passed through feed holes in the trays along the length of the press. Filter presses usually require a precoat material, such as incinerator ash or diatomaceous earth, to aid in solids retention on the cloth and to allow easier release of the cake.

Performance factors for plate and frame presses include feed biosolids characteristics, type and amount of chemical conditioning, operating pressures, and type and amount of precoat. Filter press calculations typically used in wastewater solids handling operations include solids loading rate; net filter yield; hydraulic loading rate; biosolids feed rate; solids loading rate; flocculant feed rate; flocculant dosage; total suspended solids; and percent recovery.

16.14.3.1 Solids Loading Rate

The solids loading rate is a measure of the pounds per hour of solids applied per square foot of plate area, as shown in Equation 16.147:

$$\text{Sol. Loading Rate, lb/h/ft}^2 = \frac{\text{(Biosolids, gph) (8.34, lb/gal) (\% Sol./100)}}{\text{Plate Area, ft}^2} \qquad (16.147)$$

Example 16.114

Problem:

A filter press used to dewater digested primary biosolids receives a flow of 710 gal during a 2-h period. The biosolids have a solids content of 3.3%. If the plate surface area is 120 ft^2, what is the solids loading rate in pounds per hour per square foot?

The flow rate is given as gallons per 2 h. First, express this flow rate as gallons per hour: 710 gal/2 h = 355 gal/h.

Solution:

$$\text{Sol. Loading Rate, lb/h/ft}^2 = \frac{\text{(Biosolids, gph) (8.34 lb/gal)} \dfrac{\text{(\% Sol./100)}}{100}}{\text{Plate Area, ft}^2}$$

$$= \frac{\text{(b355 gph) (8.34 lb/gal)} \dfrac{(3.3)}{100}}{120 \text{ ft}^2}$$

$$= 0.81 \text{ lb/h/ft}^2$$

> *Key point*: The solids loading rate measures the pounds per hour of solids applied to each square foot of plate surface area. However, this does not reflect the time when biosolids feed to the press is stopped.

16.14.3.2 Net Filter Yield

Operated in the batch mode, biosolids are fed to the plate and frame filter press until the space between the plates is completely filled with solids. The biosolids flow to the press is then stopped and the plates are separated, allowing the biosolids cake to fall into a hopper or conveyor below. The *net filter yield,* measured in pounds per hour per square foot, reflects the run time, as well as the down time of the plate and frame filter press. To calculate the net filter yield, simply multiply the solids loading rate (in pounds per hour per square foot) by the ratio of filter run time to total cycle time as:

$$\text{N.F.Y.} = \frac{\text{(Biosolids, gph) (8.34 lb/gal) (\% Sol/100)}}{\text{Plate Area, ft}^2} \; \frac{\text{Filter Run Time}}{\text{Total Cycle Time}} \qquad (16.148)$$

Example 16.115

Problem:

A plate and frame filter press receives a flow of 660 gal of biosolids during a 2-h period. The solids concentration of the biosolids is 3.3% and the surface area of the plate is 110 ft^2. If the down time for biosolids cake discharge is 20 min, what is the net filter yield in pounds per hour per square foot?

Solution:

First, calculate solids loading rate; then multiply that number by the corrected time factor:

$$\text{Sol. Loading Rate} = \frac{\text{(Biosolids, gph) (8.34 lb/gal) (\% Sol./100)}}{\text{Plate Area, ft}^2}$$

$$= \frac{\text{(330 gph) (8.34 lb/gal) (3.3/100)}}{100\ \text{ft}^2}$$

$$= 0.83\ \text{lb/h/ft}^2$$

Next, calculate net filter yield, using the corrected time factor:

$$\frac{\text{Net Filter Yield, lb/h/ft}^2 = (0.83\ \text{lb/h/ft}^2)\ (2\ \text{h})}{2.33\ \text{h}}$$

$$= 0.71\ \text{lb/h/ft}^2$$

16.14.4 Belt Filter Press

The belt filter press consists of two porous belts. The biosolids are sandwiched between the two porous belts (see Figure 16.9). The belts are pulled tightly together as they are passed around a series of rollers to squeeze water out of the biosolids. Polymer is added to the biosolids just before they get to the unit. The biosolids are then distributed across one of the belts to allow for some of the water to drain by gravity. The belts are then put together with the biosolids between them.

16.14.4.1 Hydraulic Loading Rate

Hydraulic loading for belt filters is a measure of gallons per minute of flow per foot or belt width.

$$\text{Hydraulic Loading Rate, gpm/ft} = \frac{\text{Flow, gpm}}{\text{Belt Width, ft}} \qquad (16.149)$$

Example 16.116

Problem:

A 6-ft wide belt press receives a flow of 110 gpm of primary biosolids. What is the hydraulic loading rate in gallons per minute per foot?

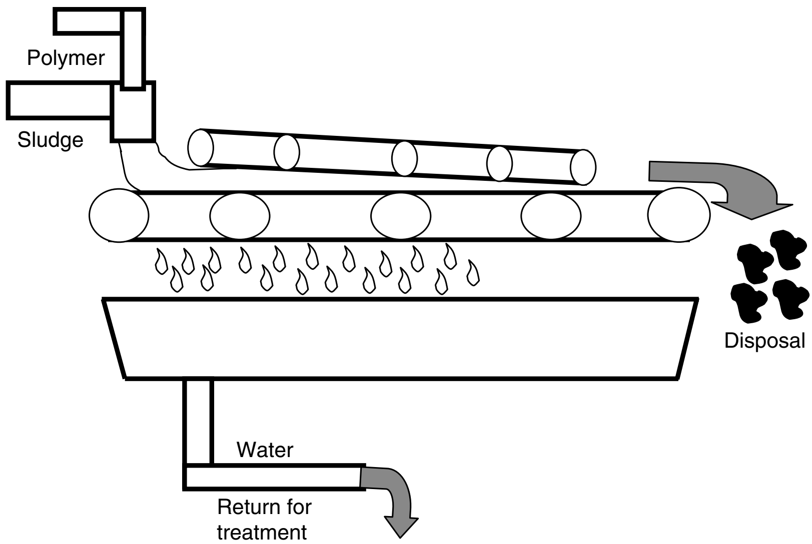

Figure 16.9 Belt filter press. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

Solution:

$$\text{Hydraulic Loading Rate, gpm/ft} = \frac{\text{Flow, gpm}}{\text{Belt Width, ft}}$$

$$= \frac{110 \text{ gpm}}{6 \text{ ft}}$$

$$= 18.3 \text{ gpm/ft}$$

Example 16.117

Problem:

A belt filter press 5 ft wide receives a primary biosolids flow of 150 gpm. What is the hydraulic loading rate in gallons per minute per square foot?

Solution:

$$\text{Hydraulic Loading Rate, gpm/ft} = \frac{\text{Flow, gpm}}{\text{Belt Width, ft}}$$

$$= \frac{150 \text{ gpm}}{5 \text{ ft}}$$

$$= 30 \text{ gpm/ft}$$

16.14.4.2 Biosolids Feed Rate

The biosolids feed rate to the belt filter press depends on several factors, including the biosolids pounds per day that must be dewatered; the maximum solids feed rate in pounds per hour that will produce an acceptable cake dryness; and the number of hours per day the belt press is in operation. The equation used in calculating biosolids feed rate is:

$$\text{Biosolids Feed Rate, lb/h} = \frac{\text{Biosolids to be dewatered, lb/day}}{\text{Operating Time, h/day}} \tag{16.150}$$

Example 16.118

Problem:

The amount of biosolids to be dewatered by the belt filter press is 20,600 lb/day. If the belt filter press is to be operated 10 h each day, what should the biosolids feed rate be to the press in pounds per hour?

Solution:

$$\text{Biosolids Feed Rate, lb/h} = \frac{\text{Biosolids to be dewatered, lb/day}}{\text{Operating Time, h/day}}$$

$$= \frac{\text{20,600 lb/day}}{\text{10 h/day}}$$

$$= \text{2060 lb/h}$$

16.14.5 Solids Loading Rate

The solids loading rate may be expressed as pounds per hour or as tons per hour. In either case, the calculation is based on biosolids flow (or feed) to the belt press and percent of milligrams per liter concentration of total suspended solids (TSS) in the biosolids. The equation used in calculating solids loading rate is:

$$\text{Sol. Load. Rate, lb/h} = \text{(Feed, gpm) (60 min/h) (8.34 lb/gal) (\% TSS/100)} \tag{16.151}$$

Example 16.119

Problem:

The biosolids feed to a belt filter press is 120 gpm. If the total suspended solids concentration of the feed is 4%, what is the solids loading rate, in pounds per hour?

Solution:

$$\text{Sol. Load Rate, lb/h} = \text{(Feed, gpm) (60 min/h) (8.34 lb/gal) (\% TSS/100)}$$

$$= \text{(120 gpm) (60 min/h) (8.34 lb/gal) (4/100)}$$

$$= \text{2402 lb/h}$$

16.14.6 Flocculant Feed Rate

The flocculant feed rate may be calculated like all other milligrams-per-liter to pounds-per-day calculations:

$$\text{Flocculant Feed, lb/h} = \frac{\text{(Floc., mg/L) (Feed Rate, MGD) (8.34 lb/gal)}}{\text{24 h/day}} \quad (16.152)$$

Example 16.120

Problem:

The flocculent concentration for a belt filter press is 1% (10,000 mg/L). If the flocculent feed rate is 3 gpm, what is the flocculent feed rate in pounds per hour?

Solution:

First, calculate pounds per day of flocculent using the milligrams-per-liter to pounds-per-day calculation. Note that the gallons-per-minute feed flow must be expressed as million-gallons-per-day feed flow:

$$= \frac{\text{(3 gpm) (1440 min/day)}}{1{,}000{,}000} = 0.00432 \text{ MGD}$$

$$\text{Flocculant Feed, lb/day} = \text{(mg/L Floc) (Feed Rate, MGD) (8.34 lb/gal)}$$

$$= \text{(10,000 mg/L) (0.00432 MGD) (8.34 lb/gal)}$$

$$= 360 \text{ lb/day}$$

Then, convert pounds per day of flocculent to pounds per hour:

$$= \frac{\text{360 lb/day}}{\text{24 h/day}} = 15 \text{ lb/h}$$

16.14.7 Flocculant Dosage

Once the solids loading rate (tons per hour) and flocculant feed rate (pounds per hour) have been calculated, the flocculant dose in pounds per ton can be determined. The equation used to determine flocculant dosage is

$$\text{Flocculant Dosage, lb/ton} = \frac{\text{Flocculant, lb/h}}{\text{Solids Treated, ton/h}} \quad (16.153)$$

Example 16.121

Problem:

A belt filter has solids loading rate of 3100 lb/h and a flocculant feed rate of 12 lb/h. Calculate the flocculant dose in pounds per ton of solids treated.

Solution:

First, convert pounds per hour of solids loading to tons per hour of solids loading:

$$\frac{3100 \text{ lb/h}}{2000 \text{ lb/ton}} = 1.55 \text{ ton/h}$$

Now calculate pounds of flocculant per ton of solids treated:

$$\text{Flocculant Dosage, lb/ton} = \frac{\text{Flocculant, lb/h}}{\text{Solids Treated, ton/h}}$$

$$\frac{12 \text{ lb/h}}{1.55 \text{ ton/h}}$$

$$= 7.8 \text{ lb/ton}$$

16.14.8 Total Suspended Solids

The feed biosolids solids comprise two types of solids: suspended solids and dissolved solids. Suspended solids that will not pass through a glass fiber filter pad can be further classified as total suspended solids (TSS), volatile suspended solids, and/or fixed suspended solids. They can also be separated into three components based on settling characteristics: settleable solids, floatable solids, and colloidal solids. Total suspended solids in wastewater are normally in the range of 100 to 350 mg/L. Dissolved solids that will pass through a glass fiber filter pad can also be classified as total dissolved solids (TDS), volatile dissolved solids, and fixed dissolved solids. Total dissolved solids are normally in the range of 250 to 850 mg/L.

Two lab tests can be used to estimate the TSS concentration of the feed biosolids concentration of the feed biosolids to the filter press: the total residue test, which measures suspended and dissolved solids concentrations, and the total filterable residue test, which measures only the dissolved solids concentration. Subtracting the total filterable residue from the total residue yields the total nonfilterable residue (TSS), as shown in Equation 16.154:

$$\begin{aligned}&\text{Total Res., mg/L} - \text{Total Filterable Residue, mg/L} = \\ &\text{Total Non-Filterable Residue, mg/L}\end{aligned} \tag{16.154}$$

Example 16.122

Lab tests indicate that the total residue portion of a feed biosolids sample is 22,000 mg/L. The total filterable residue is 720 mg/L. On this basis, what is the estimated total suspended solids concentration of the biosolids sample?

$$\text{Total Res., mg/L} - \text{Total Filterable Residue, mg/L} = \text{Total Non-Filterable Residue, mg/L}$$

$$22{,}000 \text{ mg/L} - 720 \text{ mg/L} = 21{,}280 \text{ mg/L Total SS}$$

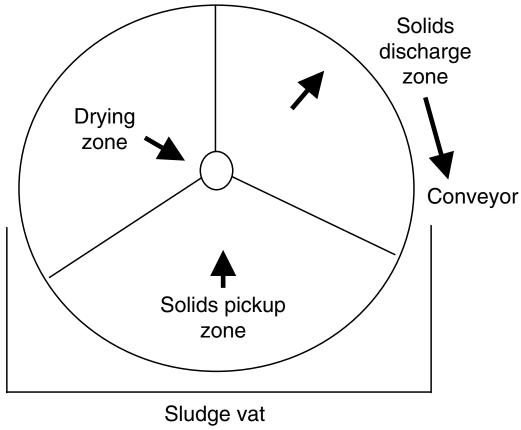

Figure 16.10 Vacuum filter. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

16.14.9 Rotary Vacuum Filter Dewatering Calculations

The rotary vacuum filter (see Figure 16.10) is a device used to separate solid material from liquid. The vacuum filter consists of a large drum with large holes in it covered with a filter cloth. The drum is partially submerged and rotated through a vat of conditioned biosolids. The rotary vacuum filter is capable of excellent solids capture and high-quality supernatant/filtrate; solids concentrations of 15 to 40% can be achieved.

16.14.9.1 Filter Loading

The filter loading for vacuum filters is a measure of pounds per hour of solids applied per square foot of drum surface area. The equation used in this calculation is:

$$\text{Filter Loading, lb/h/ft}^2 = \frac{\text{Solids to Filter, lb/h}}{\text{Surface Area, ft}^2} \tag{16.155}$$

Example 16.123

Problem:

Digested biosolids are applied to a vacuum filter at a rate of 70 gpm, with a solids concentration of 3%. If the vacuum filter has a surface area of 300 ft^2, what is the filter loading in pounds per hour per square foot?

Solution:

$$\text{Filter Loading, lb/h/ft}^2 = \frac{\text{(Biosolids, gpm) (60 min/h) (8.34 lb/gal) (\% Sol./100)}}{\text{Surface Area, ft}^2}$$

$$= \frac{\text{(70 gpm) (60 min/h) (8.34 lb/gal) (3/100)}}{\text{300 ft}^2}$$

$$= 3.5\ \text{lb/h/ft}^2$$

16.14.10 Filter Yield

One of the most common measures of vacuum filter performance is filter yield, the pounds per hour of dry solids in the dewatered biosolids (cake) discharged per square foot of filter area. It can be calculated using Equation 16.156:

$$\text{Filter Yield, lb/h/ft}^2 = \frac{(\text{Wet Cake Flow, lb/h})\dfrac{(\%\text{ Solids in Cake})}{100}}{\text{Filter Area, ft}^2} \tag{16.156}$$

Example 16.124

Problem:

The wet cake flow from a vacuum filter is 9000 lb/h. If the filter area is 300 ft^2 and the percent solids in the cake is 25%, what is the filter yield in pounds per hour per square foot?

Solution:

$$\text{Filter Yield, lb/h/ft}^2 = \frac{(\text{Wet Cake Flow, lb/h})\dfrac{(\%\text{ Solids in Cake})}{100}}{\text{Filter Area, ft}^2}$$

$$= \frac{(9000\text{ lb/h})\dfrac{(25)}{100}}{300\text{ ft}^2}$$

$$= 7.5\text{ lb/h ft}^2$$

16.14.11 Vacuum Filter Operating Time

The vacuum filter operating time required to process given pounds per day of solids can be calculated using Equation 16.156. The vacuum filter operating time, of course, is the unknown factor, designated by *x*.

Example 16.125

Problem:

A total of 4000 lb/day of primary biosolids solids are to be processed by a vacuum filter. The vacuum filter yield is 2.2 lb/h/ft^2. The solids recovery is 95%. If the area of the filter is 210 ft^2, how many hours per day must the vacuum filter remain in operation to process these solids?

Solution:

$$\text{Filter Yield, lb/h/ft}^2 = \frac{\dfrac{\text{Sol. To Filter, lb/day}}{\text{Filter Oper., lb/day}}}{\text{Filter Area, ft}^2}\ \frac{(\%\text{ Recovery})}{100}$$

$$2.2 \text{ lb/h/ft}^2 = \frac{\dfrac{4000 \text{ lb/day}}{\text{x h/day Oper.}}}{210 \text{ ft}^2} \frac{(95)}{100}$$

$$2.2 \text{ lb/h/ft}^2 = \frac{(4000 \text{ lb/day})}{\text{x h/day}} \frac{(1)}{210 \text{ ft}^2} \frac{(95)}{100}$$

$$\text{x} = \frac{(4000)(1)(95)}{(2.2)(210)(100)}$$

$$\text{x} = 8.2 \text{ h/day}$$

16.14.12 Percent Solids Recovery

The function of the vacuum filtration process is to separate the solids from the liquids in the biosolids processed. Therefore, the percent of feed solids "recovered" (sometimes referred to as the percent solids "capture") is a measure of the efficiency of the process. Equation 16.157 is used to determine percent solids recovery:

$$\% \text{ Sol. Rec.} = \frac{(\text{Wet Cake Flow, lb/h}) \dfrac{(\% \text{ Sol. in Cake})}{100}}{(\text{Biosolids Feed, lb/h}) \dfrac{(\% \text{ Sol. in Feed})}{100}} \times 100 \qquad (16.157)$$

Example 16.126

Problem:

The biosolids feed to a vacuum is 3400 lb/day, with a solids content of 5.1%. If the wet cake flow is 600 lb/h with 25% solids content, what is the percent solids recovery?

Solution:

$$\% \text{ Sol. Rec.} = \frac{(\text{Wet Cake Flow, lb/h}) \dfrac{(\% \text{ Sol. in Cake})}{100}}{(\text{Biosolids Feed, lb/h}) \dfrac{(\% \text{ Sol. in Feed})}{100}} \times 100$$

$$\% \text{ Sol. Rec.} = \frac{(600 \text{ lb/h}) \dfrac{(25)}{100}}{(3400 \text{ lb/h}) \dfrac{(5.1)}{100}} \times 100$$

$$= \frac{150 \text{ lb/h}}{173 \text{ lb/h}} \times 100$$

$$\% \text{ Sol. Rec.} = 87\%$$

16.14.13 Sand Drying Beds

Drying beds are generally used for dewatering well-digested biosolids. Biosolids drying beds consist of a perforated or open joint drainage system in a support media, usually gravel or wire mesh. Drying beds are usually separated into workable sections by wood, concrete, or other materials and may be enclosed or opened to the weather. They may rely entirely on natural drainage and evaporation processes or may use a vacuum to assist the operation.

The oldest biosolids dewatering technique, sand drying beds consist of 6 to 12 in. of coarse sand underlain by layers of graded gravel ranging from 0.133 to 0.25 in. at the top and 0.75 to 1.5 in. at the bottom. The total gravel thickness is typically about 1 ft. Graded natural earth (4 to 6 in.) usually makes up the bottom, with a web of drain tile placed on 20- to 30-ft centers. Sidewalls and partitions between bed sections are usually of wooden planks or concrete and extend about 14 in. above the sand surface.

16.14.14 Sand Drying Beds Process Control Calculations

Typically, three calculations are used to monitor sand drying bed performance: total biosolids applied, solids loading rate, and biosolids withdrawal to drying beds.

16.14.14.1 Total Biosolids Applied

The total gallons of biosolids applied to sand drying beds may be calculated using the dimensions of the bed and depth of biosolids applied, as shown by Equation 16.158:

$$\text{Volume, gal} = (\text{length, ft})\,(\text{width, ft})\,(\text{depth, ft})\,(7.48,\ \text{gal/ft}^3) \tag{16.158}$$

Example 16.127

Problem:

A drying bed is 220 ft long and 20 ft wide. If biosolids are applied to a depth of 4 in., how many gallons of biosolids are applied to the drying bed?

Solution:

$$\text{Volume, gal} = (\text{l})\,(\text{w})\,(\text{d})\,(7.48,\ \text{gal/ft}^3)$$

$$= (220\ \text{ft})\,(20\ \text{ft})\,(0.33\ \text{ft})\,(7.48\ \text{gal/ft}^3)$$

$$= 10{,}861\ \text{gal}$$

16.14.14.2 Solids Loading Rate

The biosolids loading rate may be expressed as pounds per year per square foot. The loading rate is dependent on biosolids applied per applications; pounds; percent solids concentration; cycle length; and square feet of sand bed area. The equation for biosolids loading rate is:

$$\text{Sol. Load. Rate, lb/yr/ft}^2 = \frac{\dfrac{\text{lb Biosolids Applied}}{\text{Days of Application}}\,(365\ \text{day/yr})\,\dfrac{(\%\ \text{Solids})}{100}}{(\text{length, ft})\,(\text{width, ft})} \tag{16.159}$$

Example 16.128

Problem:

A biosolids bed is 210 ft long and 25 ft wide. A total of 172,500 lb of biosolids is applied during each application to the sand drying bed. The biosolids have a solids content of 5%. If the drying and removal cycle requires 21 days, what is the solids loading rate in pounds per year per square foot?

Solution:

$$\text{Sol. Load. Rate, lb/yr/ft}^2 = \frac{\dfrac{\text{lb Biosolids Applied}}{\text{Days of Application}}(365\text{ day/yr})\dfrac{(\%\text{ Solids})}{100}}{\text{Bed area, ft}^2}$$

$$= \frac{\dfrac{172{,}500\text{ lb}}{21\text{ Days}}(365\text{ day/yr})\dfrac{(5)}{100}}{(210\text{ ft})(25\text{ ft})}$$

$$= 37.5\text{ lb/yr/ft}^2$$

16.14.14.3 Biosolids Withdrawal to Drying Beds

Pumping digested biosolids to drying beds, thus making the dried biosolids useful as a soil conditioner, is one method among many for dewatering biosolids. Depending upon the climate of a region, the drying bed depth may range from 8 to 18 in. Therefore, the area covered by these drying beds may be substantial. For this reason, the use of drying beds is more common for smaller plants than for larger ones.

When calculating biosolids withdrawal to drying beds, use:

$$\text{Biosolids Withdrawn, ft}^3 = (0.785)(D^2)(\text{Drawdown, ft}) \tag{16.160}$$

Example 16.129

Problem:

Biosolids are withdrawn from a digester with a diameter of 40 ft. If the biosolids are drawn down 2 ft, how many cubic feet are sent to the drying beds?

Solution:

$$\text{Biosolids Withdrawn, ft}^3 = (0.785)(D^2)(\text{ft drop})$$

$$= (0.785)(40\text{ ft})(40\text{ ft})(2\text{ ft})$$

$$= 2512\text{ ft}^3\text{ withdrawn}$$

16.14.15 Biosolids Disposal

In the disposal of biosolids, land application, in one form or another, has become not only necessary (because of the banning of ocean dumping in the U.S. in 1992 and the shortage of landfill space since then) but also quite popular as a beneficial reuse practice. *Beneficial reuse* means that the biosolids are disposed of in an environmentally sound manner by recycling nutrients and soil conditions. Biosolids are being applied throughout the U.S. to agricultural and forest lands.

For use in land applications, the biosolids must meet certain conditions. They must comply with state and federal biosolids management/disposal regulations and must also be free of materials dangerous to human health (toxicities and pathogenic organisms, for example) and/or dangerous to the environment (toxicity, pesticides, and heavy metals, for example). Biosolids are applied to land by direct injection, by application and incorporation (plowing in), or by composting.

16.15 LAND APPLICATION CALCULATIONS

Land application of biosolids requires precise control to avoid problems. Use of process control calculations is part of overall process control. Calculations include determining disposal cost; plant available nitrogen (PAN); application rate (dry tons and wet tons per acre); metals loading rates; maximum allowable applications based upon metals loading; and site life based on metals loading.

16.15.1 Disposal Cost

The cost of disposal of biosolids can be determined by:

$$\text{Cost} = \text{Wet Tons Biosolids Produced/Year} \times \%\ \text{Solids} \times \text{Cost/dry ton} \tag{16.161}$$

Example 16.130

Problem:

The treatment system produces 1925 wet tons of biosolids for disposal each year. The biosolids are 18% solids. A contractor disposes of the biosolids for $28.00 per dry ton. What is the annual cost for biosolids disposal?

Solution:

$$\text{Cost} = 1925\ \text{wet tons/year} \times 0.18 \times \$28.00/\text{dry ton} = \$9702$$

16.15.2 Plant Available Nitrogen (PAN)

One factor considered when applying biosolids to land is the amount of nitrogen in the biosolids available to the plants grown on the site. This includes ammonia nitrogen and organic nitrogen. The organic nitrogen must be mineralized for plant consumption; only a portion of the organic nitrogen is mineralized per year. The mineralization factor (f_1) is assumed at 0.20. The amount of ammonia nitrogen available is directly related to the time elapsed between applying the biosolids and incorporating (plowing) the biosolids into the soil. We provide volatilization rates based upon the following example:

$$\text{PAN, lb/dry ton} = [(\text{Or. Nit., mg/kg} \times f_1) + (\text{Amm. Nit., mg/kg} \times V_1)] \times 0.002 \text{ lb/dry ton} \quad (16.162)$$

where:
f_1 = mineral rate for organic nitrogen (assume 0.20)
V_1 = volatilization rate ammonia nitrogen
V_1 = 1.00 if biosolids are injected
V_1 = 0.85 if biosolids are plowed in within 24 h
V_1 = 0.70 if biosolids are plowed in within 7 days

Example 16.131

Problem:
The biosolids contain 21,000 mg/kg of organic nitrogen and 10,500 mg/kg of ammonia nitrogen and are incorporated into the soil within 24 h after application. What is the PAN per dry ton of solids?

Solution:

$$\text{PAN, lb/dry ton} = [(21{,}000 \text{ mg/kg} \times 0.20) + (10{,}500 \times 0.85)] \times 0.002$$

$$= 26.3 \text{ lb PAN/dry ton}$$

16.15.3 Application Rate Based on Crop Nitrogen Requirement

In most cases, the application rate of domestic biosolids to crop lands is controlled by the amount of nitrogen the crop requires. The biosolids application rate based upon the nitrogen requirement is determined by:

1. Using an agriculture handbook to determine the nitrogen requirement of the crop to be grown
2. Determining the amount of biosolids in dry tons required to provide this much nitrogen

$$\text{Dry ton/acre} = \frac{\text{Plant Nitrogen Requirement, lb/acre}}{\text{Plant Available Nitrogen, lb/dry ton}} \quad (16.163)$$

Example 16.132

Problem:
The crop to be planted on the land application site requires 150 lb nitrogen per acre. What is the required biosolids application rate if the PAN of the biosolids is 30 lb/dry ton?

Solution:

$$\text{Dry ton/acre} = \frac{\text{150 lb nitrogen nitrogen/acre}}{\text{30 lb/dry ton}} = 5 \text{ dry ton/acre}$$

16.15.4 Metals Loading

When biosolids are applied to land, metals concentrations are closely monitored and their loading on land application sites calculated:

$$\text{Loading, lb/acre} = \text{Metal Conc., mg/kg} \times 0.002\ \text{lb/dry ton} \times \text{Appl. Rate, dry ton/acre} \quad (16.164)$$

Example 16.133

Problem:

The biosolids contain 14 mg/kg of lead. Biosolids are currently applied to the site at a rate of 11 dry tons per acre. What is the metals loading rate for lead in pounds per acre?

Solution:

$$\text{Loading, lb/acre} = 14\ \text{mg/kg} \times 0.002\ \text{lb/dry ton} \times 11\ \text{dry ton} = 0.31\ \text{lb/acre}$$

16.15.5 Maximum Allowable Applications Based upon Metals Loading

If metals are present, they may limit the total number of applications that a site can receive. Metals loadings are normally expressed in terms of the maximum total amount of metal that can be applied to a site during its use:

$$\text{Applications} = \frac{\text{Max. Allowable Cumulative Load for the Metal, lb/ac}}{\text{Metal Loading, lb/acre/application}} \quad (16.165)$$

Example 16.134

Problem:

The maximum allowable cumulative lead loading is 48.0 lb/acre. Based upon the current loading of 0.35 lb/acre, how many applications of biosolids can be made to this site?

Solution:

$$\text{Applications} = \frac{48.0\ \text{lb/acre}}{0.35\ \text{lb/acre}} = 137\ \text{applications}$$

16.15.6 Site Life Based on Metals Loading

The maximum number of applications based upon metals loading and the number of applications per year can be used to determine the maximum site life:

$$\text{Applications} = \frac{\text{Maximum Allowable Applications}}{\text{Number of Applications Planned/Year}} \quad (16.166)$$

Example 16.135

Problem:

Biosolids are currently applied to a site twice annually. Based upon the lead content of the biosolids, the maximum number of applications is determined at 135 applications. Based upon the lead loading and the applications rate, how many years can this site be used?

Solution:

$$\text{Site Life} = \frac{135 \text{ applications}}{2 \text{ applications/yr}} = 68 \text{ yr} \tag{16.167}$$

Key point: When more than one metal is present, the calculations must be performed for each metal. The site life is the lowest value generated by these calculations.

16.16 BIOSOLIDS TO COMPOST

The purpose of composting biosolids is to stabilize the organic matter, reduce volume, eliminate pathogenic organisms, and produce a product that can be used as a soil amendment or conditioner. Composting is a biological process in which dewatered solids are usually mixed with a bulking agent (hardwood chips, for example) and stored until biological stabilization occurs. The composting mixture is ventilated during storage to provide sufficient oxygen for oxidation and to prevent odors. After the solids are stabilized, they are separated from the bulking agent. The composted solids are then stored for curing and later applied to farmlands or used in other beneficial ways. Expected performance of the composting operation for percent volatile matter reduction and percent moisture reduction ranges from 40 to 60%. Performance factors related to biosolids composting include moisture content; temperature; pH; nutrient availability; and aeration.

The biosolids must contain sufficient moisture to support the biological activity. If the moisture level is too low (40% or less), biological activity will be reduced or stopped. If the moisture level exceeds approximately 60%, it prevents sufficient airflow through the mixture.

The composting process operates best when temperatures are maintained within an operating range of 130 to 140°F; biological activities provide enough heat to increase the temperature well above this range. Forced air ventilation or mixing is used to remove heat and maintain the desired operating temperature range. The temperature of the composting solids, when maintained at the required levels, is sufficient to remove pathogenic organisms.

The influent pH can affect the performance of the process if it is extreme (less than 6.0 or greater than 11.0). The pH during composting may have some impact on the biological activity, but does not appear to be a major factor. Composted biosolids generally have a pH in the range of 6.8 to 7.5.

The critical nutrient in the composting process is nitrogen. The process works best when the ratio of nitrogen to carbon is in the range of 26 to 30 carbon to one nitrogen. Above this ratio, composting is slowed. Below this ratio, the nitrogen content of the final product may be less attractive as compost.

Aeration is essential to provide oxygen to the process and to control the temperature. In forced air processes, some means of odor control should be included in the design of the aeration system.

16.16.1 Composting Calculations

Pertinent composting process control calculations include determining percent of moisture of compost mixture and compost site capacity.

16.16.1.1 Blending Dewatered Biosolids with Composted Biosolids

Blending composted material with dewatered biosolids is similar to blending two different percent solids biosolids. The percent solids (or percent moisture) content of the mixture will always fall somewhere between the percent solids (or percent moisture) concentrations of the two materials being mixed. Equation 16.168 is used to determine percent moisture of mixture:

$$\text{\% Moist. of Mixture} = \frac{(\text{Biosolids, lb/day})\dfrac{(\text{\% Moist.})}{100} + (\text{Compost, lb/day})\dfrac{(\text{\% Moist.})}{100}}{(\text{Biosolids, lb/day}) + (\text{Compost, lb/day})} \times 100 \quad (16.168)$$

Example 16.136

Problem:

If 5000 lb/day of dewatered biosolids is mixed with 2000 lb/day of compost, what is the percent moisture of the blend? The dewatered biosolids have a solids content of 25% (75% moisture) and the compost has 30% moisture content.

Solution:

$$\text{\% Moist. of Mixture} = \frac{(\text{Biosolids, lb/day})\dfrac{(\text{\% Moist.})}{100} + (\text{Compost, lb/day})\dfrac{(\text{\% Moist.})}{100}}{(\text{Biosolids, lb/day}) + (\text{Compost, lb/day})} \times 100$$

$$= \frac{(5000\ \text{lb/day})\dfrac{(75)}{100} + (2000\ \text{lb/day})\dfrac{(30)}{100}}{(5000\ \text{lb/day}) + (2000\ \text{lb/day})} \times 100$$

$$= \frac{3750\ \text{lb/day} + 600\ \text{lb/day}}{7000\ \text{lb/day}}$$

$$= 62\%$$

16.16.1.2 Compost Site Capacity Calculation

An important consideration in compost operation is the solids processing capability (fill time), pounds per day or pounds per week. Equation 16.169 is used to calculate site capacity:

$$\text{Fill Time, days} = \frac{\text{Total Available Capacity, yd}^3}{\dfrac{\text{Wet Compost, lb/day}}{\text{Compost Bulk Density, lb/yd}^3}} \quad (16.169)$$

Example 16.137

Problem:

A composting facility has an available capacity of 7600 yd^3. If the composting cycle is 21 days, how many pounds per day of wet compost can be processed by this facility? Assume a compost bulk density of 900 lb/yd^3.

Solution:

$$\text{Fill Time, days} = \frac{\text{Total Available Capacity, yd}^3}{\dfrac{\text{Wet Compost, lb/day}}{\text{Compost Bulk Density, lb/yd}^3}}$$

$$21 \text{ days} = \frac{7600 \text{ yd}^3}{\dfrac{\text{x lb/day}}{900 \text{ lb/yd}^3}}$$

$$21 \text{ days} = \frac{(7600 \text{ yd}^3)(900 \text{ lb/yd}^3)}{\text{x lb/day}}$$

$$\text{x lb/day} = \frac{(7600 \text{ yd}^3)(900 \text{ lbs/yd}^3)}{21 \text{ days}}$$

$$\text{x} = 325{,}714 \text{ lb/day}$$

16.17 WASTEWATER LAB CALCULATIONS

16.17.1 The Wastewater Lab

Wastewater treatment plants are sized to meet the need (hopefully for the present and the future). No matter what the size of the treatment plant is, some space or area within the plant is designated as the "lab" area (ranging from closet-size to fully equipped and staffed environmental laboratories). Wastewater laboratories usually perform a number of different tests and provide operators with the information necessary to operate the treatment facility. Laboratory testing usually includes pH, COD, total phosphorus, fecal coliform count, and BOD (seeded) test. The standard reference for performing wastewater testing is *Standard Methods for the Examination of Water and Wastewater*.

In this subsection, we focus on wastewater lab tests that involve various calculations. Specifically, we focus on calculations used to determine proportioning factor for composite sampling; BOD; molarity and moles; normality; settleability; settleable solids; biosolids total; fixed and volatile solids; suspended solids and volatile suspended solids; and biosolids volume index and biosolids density index.

16.17.2 Composite Sampling Calculation (Proportioning Factor)

In preparing oven-baked food, a cook pays close attention in setting the correct oven temperature. Usually, the cook sets the temperature at the correct setting and then moves on to some other chore; the oven thermostat makes sure that the oven-baked food is cooked at the correct temperature. Unlike the cook, in wastewater treatment plant operations, the operator does not have the luxury of setting a plant parameter and then walking off and forgetting about it. To optimize plant operations, various adjustments to unit processes must be made on an on-going basis.

The operator makes unit process adjustments based on local knowledge (experience) and on lab test results. However, before lab tests can be performed, samples must be taken. Two basic types of samples are in common use: grab samples and composite samples. The type of sample taken depends on the specific test, the reason the sample is being collected, and the requirements in the plant discharge permit.

A *grab sample* is a discrete sample collected at one time and one location. It is primarily used for any parameter whose concentration can change quickly (dissolved oxygen, pH, temperature, and total chlorine residual, for example) and is representative only of the conditions at the time of collection. A *composite sample* consists of a series of individual grab samples taken at specified time intervals and in proportion to flow. The individual grab samples are mixed together in proportion to the flow rate at the time the sample was collected to form the composite sample. The composite sample represents the character of the wastewater over a period of time.

16.17.3 Composite Sampling Procedure and Calculation

Because knowledge of the procedure used in processing composite samples is important (a basic requirement) to the wastewater operator, in this subsection, we cover the actual procedure used.

Procedure:

1. Determine the total amount of sample required for all tests to be performed on the composite sample.
2. Determine the treatment system's average daily flow.
   Key point: Average daily flow can be determined by using several months of data; this provides a more representative value.
3. Calculate a proportioning factor:

$$\text{Prop. Factor (PF)} = \frac{\text{Total Sample Volume Required, mm}}{\text{\# of Samples to be Calculated} \times \text{Av. Daily Flow, MGD}} \tag{16.170}$$

   Key point: Round the proportioning factor to the nearest 50 units (50, 100, 150, etc.) to simplify calculation of the sample volume.
4. Collect the individual samples in accordance with the schedule (once per hour, once per 15 min, etc.).
5. Determine flow rate at the time the sample was collected.
6. Calculate the specific amount to add to the composite container:

$$\text{Required Volume, mL} = \text{Flow}^{T} \times \text{PF} \tag{16.171}$$

   where T = time sample was collected.

7. Mix the individual sample thoroughly, measure the required volume, and add to composite storage container.
8. Refrigerate the composite sample throughout the collection period.

Example 16.138

Problem:

The effluent testing requires 3645 mL of sample. The average daily flow is 4.05 MGD. Using the flows given in the following table, calculate the amount of sample to be added at each of the times shown:

Time	Flow, MGD
8 A.M.	3.88
9 A.M.	4.10
10 A.M.	5.05
11 A.M.	5.25
12 Noon	3.80
1 P.M.	3.65
2 P.M.	3.20
3 P.M.	3.45
4 P.M.	4.10

Solution:

$$\text{Proportioning Factor (PF)} = \frac{3650\text{ mL}}{9\text{ Samples} \times 4.05\text{ MGD}}$$

$$= 100$$

$$\text{Volume}_{8\text{ AM}} = 3.88 \times 100 = 388\ (400)\text{ mL}$$
$$\text{Volume}_{9\text{ AM}} = 4.10 \times 100 = 410\ (400)\text{ mL}$$
$$\text{Volume}_{10\text{ AM}} = 5.05 \times 100 = 505\ (500)\text{ mL}$$
$$\text{Volume}_{11\text{ AM}} = 5.25 \times 100 = 525\ (550)\text{ mL}$$
$$\text{Volume}_{12\text{ N}} = 3.80 \times 100 = 380\ (400)\text{ mL}$$
$$\text{Volume}_{1\text{ PM}} = 3.65 \times 100 = 365\ (350)\text{ mL}$$
$$\text{Volume}_{2\text{ PM}} = 3.20 \times 100 = 320\ (300)\text{ mL}$$
$$\text{Volume}_{3\text{ PM}} = 3.45 \times 100 = 345\ (350)\text{ mL}$$
$$\text{Volume}_{4\text{ PM}} = 4.10 \times 100 = 410\ (400)\text{ mL}$$

16.17.4 Biochemical Oxygen Demand (BOD) Calculations

BOD_5 measures the amount of organic matter that can be biologically oxidized under controlled conditions (5 days at 20°C in the dark). Several criteria are used in selecting which BOD_5 dilutions should be used for calculating test results. Consult a laboratory testing reference manual (such as *Standard Methods*) for this information. Two basic calculations are used for BOD_5. The first is used for unseeded samples and the second must be used whenever BOD_5 samples are seeded. We introduce both methods and provide examples next.

16.17.4.1 BOD_5 (Unseeded)

$$BOD_5\text{ (Unseeded)} = \frac{(DO_{start}\text{, mg/L} - DO_{final}\text{, mg/L}) \times 300\text{ mL}}{\text{Sample Volume, mL}} \tag{16.172}$$

Example 16.139

Problem:

The BOD_5 test is completed. Bottle 1 of the test had dissolved oxygen (DO) of 7.1 mg/L at the start of the test. After 5 days, bottle 1 had a DO of 2.9 mg/L. Bottle 1 contained 120 mg/L of sample. Determine 30 D_5 (unseeded).

Solution:

$$BOD_5 \text{ (Unseeded)} = \frac{(7.1\text{mg/L} - 2.9\text{ mg/L}) \times 300\text{ mL}}{120\text{ mL}} = 10.5\text{ mg/L}$$

16.17.4.2 BOD_5 (Seeded)

If the BOD_5 sample has been exposed to conditions that could reduce the number of healthy, active organisms, the sample must be seeded with organisms. Seeding requires using a correction factor to remove the BOD_5 contribution of the seed material:

$$\text{Seed Correction} = \frac{\text{Seed Material BOD}_5 \times \text{Seed in Dilution, mL}}{300\text{ mL}} \tag{16.173}$$

$$BOD_5 \text{ (Seeded)} = \frac{[(DO_{start}\text{, mg/L} - DO_{final}\text{, mg/L}) - \text{Seed Corr.}] \times 300}{\text{Sample Volume, mL}} \tag{16.174}$$

Example 16.140

Problem:

Using the data provided in the following table, determine the BOD_5:

BOD_5 of seed material		90 mg/L
Dilution #1	Milliliters of seed material	3 mL
	Milliliters of sample	100 mL
	Start DO	7.6 mg/L
	Final DO	2.7 mg/L

Solution:

$$\text{Seed Correction} = \frac{90\text{ mg/L} \times 3\text{ mL}}{300\text{ mL}} = 0.90\text{ mg/L}$$

$$BOD_5 \text{ (Seeded)} = \frac{[(7.6\text{ mg/L} - 2.7\text{ mg/L}) - 0.90] \times 300}{100\text{ mL}} = 12\text{ mg/L}$$

16.17.5 BOD 7-Day Moving Average

Because the BOD characteristic of wastewater varies from day to day, even hour to hour, operational control of the treatment system is most often accomplished based on trends in data rather than individual data points. The BOD 7-day moving average is a calculation of the BOD trend.

Key point: The 7-day moving average is called that because a new average is calculated each day, adding the new day's value and the six previous days' values:

$$\text{7-day Average BOD} = \frac{\underset{\text{Day 1}}{\text{BOD}} + \underset{\text{Day 2}}{\text{BOD}} + \underset{\text{Day 3}}{\text{BOD}} + \underset{\text{Day 4}}{\text{BOD}} + \underset{\text{Day 5}}{\text{BOD}} + \underset{\text{Day 6}}{\text{BOD}} + \underset{\text{Day 7}}{\text{BOD}}}{7} \quad (16.175)$$

Example 16.141

Problem:

Given the following primary effluent BOD test results, calculate the 7-day average.

Date	Milligrams per liter
June 1	200
June 2	210
June 3	204
June 4	205
June 5	222
June 6	214
June 7	218

Solution:

$$\text{7-day average BOD} = \frac{200 + 210 + 204 + 205 + 222 + 214 + 218}{7}$$

$$= 210 \text{ mg/L}$$

16.17.6 Moles and Molarity

Chemists have defined a very useful unit called the *mole.* Moles and molarity, a concentration term based on the mole, have many important applications in water/wastewater operations. A mole is defined as a gram molecular weight; that is, the molecular weight expressed as grams. For example, a mole of water is 18 g of water and a mole of glucose is 180 g of glucose. A mole of any compound always contains the same number of molecules. The number of molecules in a mole is called Avogadro's number and has a value of 6.022×10^{23}.

Interesting point: How big is Avogadro's number? An Avogadro's number of soft drink cans would cover the surface of the Earth to a depth of over 200 miles.
Key point: Molecular weight is the weight of one molecule; it is calculated by adding the weights of all the atoms present in one molecule. The units are atomic mass units (amu). The molecular weight is the weight of one molecule in daltons. The reason all moles have the same number of molecules is because the value of the mole is proportional to the molecular weight.

16.17.6.1 Moles

A mole is a quantity of a compound equal in weight to its formula weight. For example, the formula weight for water (H_2O; see Figure 16.11) can be determined using the periodic table of elements:

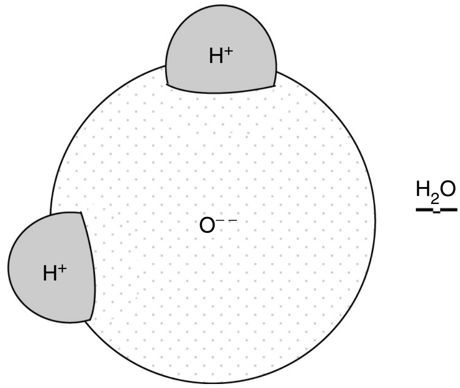

Figure 16.11 A molecule of water. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1*,* Lancaster, PA: Technomic Publishing Company.)

$$\begin{aligned} \text{Hydrogen (1.008)} \times 2 &= \ \ 2.016 \\ \text{Oxygen} &= 16.000 \\ \hline \text{Formula weight of } H_2O &= 18.016 \end{aligned}$$

Because the formula weight of water is 18.016, a mole is 18.016 units of weight. A *gram-mole* is 18.016 g of water. A *pound-mole* is 18.016 lb of water. For our purposes in this text, the term "mole" means "gram-mole." The equation used in determining moles is:

$$\text{Moles} = \frac{\text{Grams of Chemical}}{\text{Formula Wt of Chemical}} \qquad (16.176)$$

Example 16.142

Problem:

The atomic weight of a certain chemical is 66. If 35 g of the chemical are used in making up a 1-L solution, how many moles are used?

Solution:

$$\text{Moles} = \frac{\text{Grams of Chemical}}{\text{Formula Wt of Chemical}}$$

$$= \frac{66 \text{ g}}{35 \text{ g/mol}}$$

$$= 1.9 \text{ mol}$$

The *molarity* of a solution is calculated by taking the moles of solute and dividing by the liters of solution:

$$\text{Molarity} = \frac{\text{Moles of solute}}{\text{Liters of solution}} \tag{16.177}$$

Example 16.143

Problem:

What is the molarity of 2 mol of solute dissolved in 1 L of solvent?

Solution:

$$\text{Molarity} = \frac{2\text{ mol}}{1\text{ L}} = 2\text{M}$$

> *Key point*: Measurement in moles is a measurement of the *amount* of a substance. Measurement in molarity is a measurement of the *concentration* of a substance — the amount (moles) per unit volume (liters).

16.17.6.2 Normality

The molarity of a solution refers to its concentration (the solute dissolved in the solution). The normality of a solution refers to the number of equivalents of solute per liter of solution. Defining the chemical equivalent depends on the substance or type of chemical reaction under consideration. Because the concept of equivalents is based on the "reacting power" of an element or compound, it follows that a specific number of equivalents of one substance will react with the same number of equivalents of another substance. When the concept of equivalents is taken into consideration, chemicals are less likely to be wasted as excess amounts.

Keeping in mind that normality is a measure of the reacting power of a solution (1 equivalent of a substance reacts with 1 equivalent of another substance), we use the following equation to determine normality.

$$\text{Normality} = \frac{\text{No. of Equivalents of Solute}}{\text{Liters of Solution}} \tag{16.178}$$

Example 16.144

Problem:

If 2.0 equivalents of a chemical are dissolved in 1.5 L of solution, what is the normality of the solution?

Solution:

$$\text{Normality} = \frac{\text{No. of Equivalents of Solute}}{\text{Liters of Solution}}$$

$$\text{Normality} = \frac{2.0\text{ Equivalents}}{1.5\text{ L}} = 1.33\text{ N}$$

Example 16.145

Problem:

An 800-mL solution contains 1.6 equivalents of a chemical. What is the normality of the solution?

Solution:

First, convert 800 mL to liters:

$$= \frac{800 \text{ mL}}{1000 \text{ mL}} = 0.8 \text{ L}$$

Then, calculate the normality of the solution:

$$\text{Normality} = \frac{\text{No. of Equivalents of Solute}}{\text{Liters of Solution}}$$

$$= \frac{1.6 \text{ Equivalents}}{0.8 \text{ Liters}} = 2 \text{ N}$$

16.17.7 Settleability (Activated Biosolids Solids)

The settleability test is a test of the quality of the activated biosolids solids or activated sludge solids (mixed liquor suspended solids). Settled biosolids volume (SBV) or settled sludge volume (SSV) is determined at specified times during sample testing. Observations of 30 and 60 min are used for control. Subscripts (SBV_{30} or SSV_{30} and SBV_{60} or SSV_{60}) indicate settling time.

A sample of activated biosolids is taken from the aeration tank, poured into a 2000-mL graduated cylinder, and allowed to settle for 30 or 60 min. The settling characteristics of the biosolids in the graduated cylinder give a general indication of the settling of the MLSS in the final clarifier. From the settleability test, the percent of settleable solids can be calculated using:

$$\% \text{ Settleable Solids} = \frac{\text{mL Settled Solids}}{2000 \text{ mL Sample}} \times 100 \qquad (16.179)$$

Example 16.146

Problem:

The settleability test is conducted on a sample of MLSS. What is the percent of settleable solids if 420 mL settle in the 2000-mL graduate?

Solution:

$$\% \text{ Settleable Solids} = \frac{\text{mL Settled Solids}}{2000 \text{ mL Sample}} \times 100$$

$$= \frac{420 \text{ mL}}{2000 \text{ mL}} \times 100$$

$$= 21\%$$

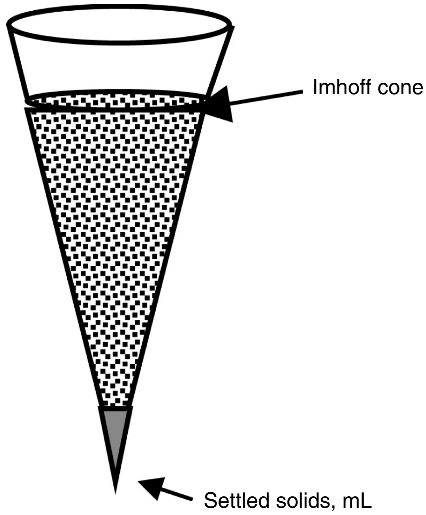

Figure 16.12 One-liter Imhoff cone. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

Example 16.147

Problem:

A 2000-mL sample of activated biosolids is tested for settleability. If the settled solids are measured as 410 mL, what is the percent of settled solids?

Solution:

$$\% \text{ Settleable Solids} = \frac{\text{mL Settled Solids}}{\text{2000 mL Sample}} \times 100$$

$$= \frac{410 \text{ mL}}{2000 \text{ mL}} \times 100$$

$$= 20.5\%$$

16.17.8 Settleable Solids

The settleable solids test is an easy, quantitative method to measure sediment found in wastewater. An Imhoff cone (a plastic or glass 1-L cone; see Figure 16.12) is filled with 1 L of sample wastewater, stirred, and allowed to settle for 60 min. The settleable solids test, unlike the settleability test, is conducted on samples from sedimentation tank or clarifier influent and effluent to determine percent of removal of settleable solids. The percent of settleable solids is determined by:

$$\% \text{ Settleable Solids Removed} = \frac{\text{Set. Solids Removed, mL/L}}{\text{Set. Solids in Influent, mL/L}} \times 100 \qquad (16.180)$$

Example 16.148

Problem:

Calculate the percent removal of settleable solids if the settleable solids of the sedimentation tank influent are 15 mL/L and the settleable solids of the effluent are 0.4 mL/L.

Solution:

First, subtract 0.4 mL/L from 15.0, which equals 14.6 mL/L removed settleable solids. Next, insert parameters into Equation 16.180:

$$\%\ \text{Set. Sol. Removed} = \frac{14.6\ \text{mL/L}}{15.0\ \text{mL/L}} \times 100$$

$$= 97\%$$

Example 16.149

Problem:

Calculate the percent removal of settleable solids if the settleable solids of the sedimentation tank influent are 13 mL/L and the settleable solids of the effluent are 0.5 mL/L.

Solution:

First, subtract 0.5 mL/L from 13 mL/L, which equals 12.5 mL/L of removed settleable solids:

$$\%\ \text{Set. Sol. Removed} = \frac{12.5\ \text{mL/L}}{13.0\ \text{mL/L}} \times 100$$

$$= 96\%$$

16.17.9 Biosolids Total Solids, Fixed Solids, and Volatile Solids

Wastewater consists of water and solids (see Figure 16.13). The total solids may be further classified as *volatile* (organics) or *fixed* (inorganics). Normally, total solids and volatile solids are expressed as percents; suspended solids are generally expressed as milligrams per liter.

In calculating percents or miligrams per liter of concentrations, certain concepts must be understood:

- Total solids — the residue left in the vessel after evaporation of liquid from a sample and subsequent drying in an oven at 103 to 105°C.
- Fixed solids — the residue left in the vessel after a sample is ignited (heated to dryness at 550°C).
- Volatile solids — the weight loss after a sample is ignited (heated to dryness at 550°C).

Determinations of fixed and volatile solids do not distinguish precisely between inorganic and organic matter because the loss on ignition is not confined to organic matter; it includes losses due to decomposition or volatilization of some mineral salts.

> *Key point*: When the word *biosolids* is used, it may be understood to mean a semiliquid mass composed of solids and water. The term *solids*, however, is used to mean dry solids after the evaporation of water.

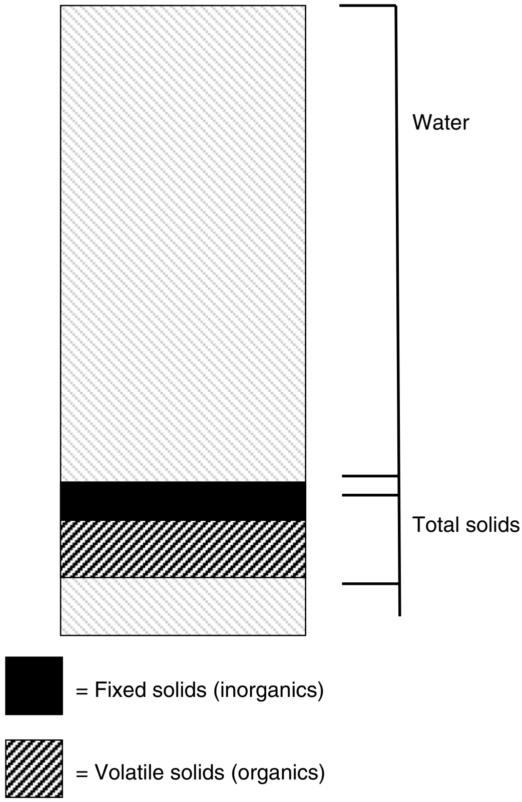

Figure 16.13 Composition of wastewater. (From Spellman, F.R., 1999, *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Lancaster, PA: Technomic Publishing Company.)

Percents of total solids and volatile solids are calculated as:

$$\% \text{ Total Solids } = \frac{\text{Total Solids Weight}}{\text{Biosolids Sample Weight}} \times 100 \tag{16.181}$$

$$\% \text{ Volatile Solids } = \frac{\text{Volatile Solids Weight}}{\text{Total Solids Weight}} \times 100 \tag{16.182}$$

Example 16.150

Problem:

Given the information below, determine the percent of solids in the sample and the percent of volatile solids in the biosolids sample:

	Biosolids Sample	After Drying	After Burning (Ash)
Weight of Sample & Dish	73.43 g	24.88	22.98
Weight of Dish (tare weight)	22.28 g	22.28	22.28

Solution:

Step 1. To calculate the percent of total solids, the grams of total solids (solids after drying) and grams of biosolids sample must be determined:

Total Solids	Biosolids Sample
24.88 g Total Solids and Dish	73.43 g Biosolids and Dish
–22.28 g Weight of Dish	–22.28 g Weight of Dish
2.60 g Total Solids	51.15 g Biosolids

$$\% \text{ Total Solids} = \frac{\text{Wt. of Total Solids}}{\text{Wt. of Biosolids Sample}} \times 100$$

$$= \frac{2.60 \text{ g}}{51.15 \text{ g}} \times 100$$

$$= 5\% \text{ Total Solids}$$

Step 2. To calculate the percent of volatile solids, the grams of total solids and grams of volatile solids must be determined. Because percent of total solids has already been calculated in Step 1, only volatile solids must be calculated:

Volatile Solids

24.88 g Sample and Dish before Burning
–22.98 g Sample and Dish after Burning
1.90 g Solids Lost in Burning

$$\% \text{ Volatile Solids} = \frac{\text{Weight of Volatile Solids}}{\text{Weight of Total Sample}} \times 100$$

$$= \frac{1.90 \text{ g}}{2.60 \text{ g}} \times 100$$

$$= 73\% \text{ Volatile Solids}$$

16.17.10 Wastewater Suspended Solids and Volatile Suspended Solids

Total suspended solids (TSS) are the amount of filterable solids in a wastewater sample. Samples are filtered through a glass fiber filter. The filters are dried and weighed to determine the amount of total suspended solids in milligrams per liter of sample. Volatile suspended solids (VSS) are solids lost on ignition (heating to 500°C). They are useful because they give a rough approximation of the amount of organic matter present in the solid fraction of wastewater, activated biosolids, and industrial wastes. With the exception of the required drying time, the suspended solids and volatile suspended solids tests of wastewater are similar to those of the total and volatile solids performed for biosolids (described earlier).

Key point: The total and volatile solids of biosolids are generally expressed as percents, by weight. The biosolids samples are 100 mL and are unfiltered.

Calculations of suspended solids and volatile suspended solids are demonstrated in the following example.

Example 16.151

Problem:

Given the following information regarding a primary effluent sample, calculate the milligrams per liter of suspended solids and the percent of volatile suspended solids of the sample:

	After Drying (before Burning)	After Burning (Ash)
Weight of Sample and Dish	24.6268 g	24.6232 g
Weight of Dish (tare wt.)	24.6222 g	24.6222 g

Sample Volume = 50 mL

Solution:

Step 1. To calculate the milligrams of suspended solids per liter of sample, it is necessary first to determine grams of suspended solids:

$$\begin{array}{rl} 24.6268\text{ g} & \text{Dish and Suspended Solids} \\ -\ 24.6222\text{ g} & \text{Dish} \\ \hline 00.0046\text{ g} & \text{Suspended Solids} \end{array}$$

Next, calculate milligrams per liter of suspended solids (using a multiplication factor of 20 [this number will vary with sample volume] to make the denominator equal to 1 L (1000 mL):

$$= \frac{0.0046\text{ g SS}}{50\text{ mL}} \times \frac{1000\text{ mg}}{1\text{ g}} \times \frac{20}{20} = \frac{92\text{ mg}}{1000\text{ mL}} = 92\text{ mg/L SS}$$

Step 2. To calculate percent of volatile suspended solids, it is necessary to know the weight of total suspended solids (calculated in Step 1) and volatile suspended solids:

$$\begin{array}{rl} 24.6268\text{ g} & \text{Dish and SS before Burning} \\ -\ 24.6232\text{ g} & \text{Dish and SS after Burning} \\ \hline 0.0036\text{ g} & \text{Solids Lost in Burning} \end{array}$$

$$\%V_{SS} = \frac{\text{Wt. of Volatile Solids}}{\text{Wt. of Suspended Solids}} \times 100$$

$$\% \text{ VSS} = \frac{0.0036 \text{ g VSS}}{0.0046 \text{ g}} \times 100$$

$$= 78\% \text{ VSS}$$

16.17.11 Biosolids Volume Index (BVI) and Biosolids Density Index (BDI)

Two variables are used to measure the settling characteristics of activated biosolids and to determine the return biosolids pumping rate. These are the volume of the biosolids (BVI) and the density of the biosolids (BDI) indices:

$$\text{BVI} = \frac{\% \text{ MLSS volume after 30 min settling}}{\% \text{ MLSS mg/L MLSS}} = \text{mL settled biosolids} \times 1000 \quad (16.183)$$

$$\text{BDI} = \frac{\text{MLSS (\%)}}{\% \text{ volume MLSS after 30 min settling}} \times 100 \quad (16.184)$$

These indices relate the weight of biosolids to the volume that the biosolids occupy. They show how well the liquids–solids separation part of the activated biosolids system is performing its function on the biological floc that has been produced and is to be settled out and returned to the aeration tanks or wasted. The better the liquid–solids separation is, the smaller the volume occupied by the settled biosolids and the lower the pumping rate required to keep the solids in circulation are.

Example 16.152

Problem:

The settleability test indicates that after 30 min, 220 mL of biosolids settle in the 1-L graduated cylinder. If the MLSS concentration in the aeration tank is 2400 mg/L, what is the biosolids volume?

Solution:

$$\text{BVI} = \frac{\text{Volume (determined by settleability test)}}{\text{Density (determined by the MLSS conc.)}} \quad (16.185)$$

$$\text{BVI} = \frac{220 \text{ mL/L}}{2400 \text{ mg/L}}$$

$$= \frac{220 \text{ mL/L}}{2400 \text{ mg/L}} \text{(convert milligrams to grams)} \frac{220 \text{ mL}}{2.4 \text{ g}}$$

$$= 92$$

The biosolids density index (BDI) is also a method of measuring the settling quality of activated biosolids; however, like the BVI parameter, it may or may not provide a true picture of the quality of the biosolids in question, unless compared with other relevant process parameters. It differs from

BVI in that the higher the BDI value is, the better the settling quality of the aerated mixed liquor is. Similarly, the lower the BDI is, the poorer the settling quality of the mixed liquor is.

BDI is the concentration in percent solids that the activated biosolids will assume after settling for 30 min. BDI will range from 2.00 to 1.33, and biosolids with values of one or more are generally considered to have good settling characteristics. In making the calculation of BDI, we simply invert the numerators and denominators and multiply by 100.

Example 16.153

Problem:

The MLSS concentration in the aeration tank is 2500 mg/L. If the activated biosolids settleability test indicates 225 mL settled in the 1-L graduated cylinder, what is the BDI?

Solution:

$$\text{BDI} = \frac{\text{Density (determined by the MLSS concentration)}}{\text{Volume (Determined by the settleability test)}} \times 100 \tag{16.186}$$

$$\text{BDI} = \frac{2500 \text{ mg}}{225 \text{ mL}} \times 100 \text{(convert milligrams to grams)} = \frac{2.5 \text{ g}}{225 \text{ mL}} \times 100$$

$$= 1.11$$

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