

# Montogue

## Quiz HY401

### Water Quality and Treatment

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## Problems

### Problem 1

A water sample has the ion composition shown below. True or false?

Ion	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	HCO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>
Concentration (mg/L)	85	25	11	268	35	67

1. ( ) The total hardness of the sample is greater than 300 mg/L as CaCO<sub>3</sub>.
2. ( ) The carbonate hardness of the sample is greater than 240 mg/L as CaCO<sub>3</sub>.
3. ( ) The noncarbonate hardness of the sample is greater than 110 mg/L as CaCO<sub>3</sub>.

### Problem 2

Raw water has the following composition: alkalinity = 250 mg/L as CaCO<sub>3</sub>, pH = 7.0,  $\alpha_1 = 0.75$  (at  $T = 10^\circ\text{C}$ ), calcium = 90 mg/L, magnesium = 4 mg/L. Determine the necessary amount of 70%-purity lime to soften the water if the final hardness required is 40 mg/L as CaCO<sub>3</sub>.

- A)  $m' = 310$  mg/L as CaO
- B)  $m' = 405$  mg/L as CaO
- C)  $m' = 495$  mg/L as CaO
- D)  $m' = 580$  mg/L as CaO

### Problem 3

Regarding coagulation, filtration, oxygen demand, and other aspects of water quality and treatment, true or false?

1. ( ) Dry alum is corrosive, but becomes harmless when in contact with water. Therefore, alum to be used in water treatment processes should be stored in humid conditions.
2. ( ) Coagulants such as alum, iron salts and sodium aluminate depress alkalinity and decrease pH levels, and for this reason must be supplied with additional alkalinity, often in the form of lime or soda ash.
3. ( ) When added to water, lime increases pH and reacts with the carbonate alkalinity to precipitate calcium carbonate. If sufficient lime is added to reach a high pH, magnesium hydroxide is also precipitated. This latter precipitation enhances clarification because of the flocculant nature of Mg(OH)<sub>2</sub>.
4. ( ) Diatomaceous earth is used as a filter aid in small water treatment facilities for the removal of cysts, algae, and asbestos fibers. The main constituent of this material is aluminum oxide, Al<sub>2</sub>O<sub>3</sub>.
5. ( ) Perlite is a glass-like volcanic rock used as a filter aid in water treatment processes. One of the advantages of perlite relatively to diatomaceous earth is its relative purity, since DE may foul filtering liquids with dissolved salts and colloidal clays. However, perlite is highly acidic and its implementation in water treatment must be complemented with alkalinity-producing agents such as lime.

6. ( ) One of the effects of increasing temperatures in freshwater is the concomitant decrease in oxygen solubility.

7. ( ) The biochemical oxygen demand (BOD) is a measure of the biochemically oxidizable material present in the water sample expressed in terms of the oxygen required to consume it. The greater the BOD<sub>5</sub> of a drinking water sample, the less the number of pathogens and other potentially harmful microorganisms in the water. The optimal value of BOD<sub>5</sub> for drinking water is between 3.0 and 5.0 mg O/L of water.

8. ( ) The ultimate BOD of a sample was measured as 510 mg/L after a 30-day incubation period. The rate constant is 0.05 day<sup>-1</sup> for the reaction. Accordingly, the BOD<sub>5</sub> for this sample is greater than 100 mg/L.

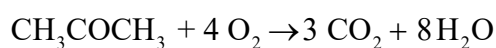
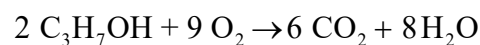
#### Problem 4

When 1 L of water sample is collected for analysis, an insect weighing 80 mg is accidentally trapped in the bottle. The initial dissolved oxygen is 11 mg/L. Assume that 20% of the insect's fresh weight is readily biodegradable and has the approximate formula CH<sub>2</sub>O. Also, assume that microbes are present that will metabolize the insect. If the laboratory does not analyze the sample until biodegradation is complete, what DO will they measure?

- A) DO = zero
- B) DO = 3.4 mg/L
- C) DO = 6.6 mg/L
- D) DO = 9.6 mg/L

#### Problem 5

A 250 mL aliquot of wastewater contains 68 mg/L of *n*-propanol was spiked with 60 mL of 120 mg/L of acetone solution. Determine the chemical oxygen demand (COD) of the resulting solution. The oxidation reactions of propanol and acetone are provided below.



- A) COD = 67 mg O<sub>2</sub>/L
- B) COD = 121 mg O<sub>2</sub>/L
- C) COD = 183 mg O<sub>2</sub>/L
- D) COD = 240 mg O<sub>2</sub>/L

#### Problem 6

In drinking water treatment, what is the purpose of rapid mixing?

- A) Eliminate microorganisms that may not be extinguished in the disinfection process.
- B) Increase the viscosity of the filtrate and thereby accelerate subsequent treatment processes, especially filtration.
- C) Promote flocculation after the coagulant has been added.
- D) Promote chemical oxidation after oxidants such as ozone have been added.

## Problem 7

The following parameters have been specified for a water treatment filter. Estimate the area of the filter bed using the Letterman equation.

Filtration rate	8 m/h
Design flow into the filter	92 m <sup>3</sup> /day
Volume of water production per unit area of filter bed per filter run	20 m <sup>3</sup> water produced/m <sup>2</sup> filter plan area/filter run
Volume of water required per unit of filter bed area per backwash	17 m <sup>3</sup> backwash water/m <sup>2</sup> filter bed area/filter run
Filter down time per backwash	12 min downtime/filter run

- A)  $A_{\text{filter}} = 19.8 \text{ m}^2$
- B)  $A_{\text{filter}} = 31.1 \text{ m}^2$
- C)  $A_{\text{filter}} = 45.4 \text{ m}^2$
- D)  $A_{\text{filter}} = 57.8 \text{ m}^2$

## Problem 8

A water plant produces 200 gpm and the city wants to add 1.1 mg/L of fluoride. What should the feed rate of 25% sodium fluorosilicate be to achieve this concentration?

- A) Feed Rate = 23.9 lb/day
- B) Feed Rate = 78.1 lb/day
- C) Feed Rate = 121 lb/day
- D) Feed Rate = 174 lb/day

## Problem 9

Regarding sedimentation, separation processes, and specific water pollutants such as heavy metals and radionuclides, true or false?

1. ( ) With all other properties held constant, we can surmise that the sedimentation rate of warm wastewater in a sedimentation tank is greater than that of cold wastewater.
2. ( ) For optimal performance, a thickener (sedimentation equipment) should be designed so that the settling velocity of particles is substantially less than the upward fluid velocity.
3. ( ) Electrodialysis is an excellent method of treatment of weakly saline (brackish) waters. Purification by electrodialysis is especially effective in the separation of neutral species such as silica.
4. ( ) Reverse osmosis is especially effective in the removal of small organic molecules such as benzene.
5. ( ) The rejection of a reverse osmosis system is defined as  $(F - P)/F$ , where  $F$  is the concentration of solute species in the feed and  $P$  is the concentration of solute species in the product. The greater the pressure imparted on a typical RO system, the greater the rejection of solids will be.
6. ( ) Under anaerobic aqueous conditions, in the presence of organic matter or sulfate-reducing bacteria, the sulfate ion is reduced to sulfide ion,  $S^{2-}$ . Unlike bisulfide ( $HS^-$ ) and gaseous hydrogen sulfide ( $H_2S$ ), which have no odor and are nonvolatile, the sulfide ion has a pungent smell when disseminating through air.
7. ( ) Chemicals used in the fluoridation of drinking water include calcium fluoride ( $CaF_2$ ), fluorosilicic acid ( $H_2SiF_6$ ), and sodium fluorosilicate ( $Na_2SiF_6$ ). Calcium fluoride was the first compound used and serves as the reference standard.
8. ( ) The most widely used technology for removal of phosphate from water is chemical precipitation, in which a divalent or trivalent metal salt is introduced to the water and leads to the precipitation of an insoluble metal phosphate that is settled out by sedimentation. The most suitable metals are iron and aluminum, added as chlorides or sulfates.

9.( ) Lead is a heavy metal with well-documented toxicity if ingested with water. One way to counteract lead contamination is the addition of orthophosphates, which, if added even at a few mg/L, are successful in restoring the passivated surface on leaded materials, including lead service pipes, and reducing other lead releases.

10.( ) Mercury in drinking water can be efficiently treated by coagulation/filtration, lime softening, and reverse osmosis. Granular activated carbon, however, is not effective in eliminating both inorganic and organic mercury compounds.

11.( ) One of the additional problems associated with phosphate fertilizer runoff is its relatively high uranium content.

12.( ) Wells tend to have lower radon levels than public water supplies because of the high species mobility associated with public water systems, which, combined with its long half-life and reactivity of radon isotopes, make it a particularly dangerous contaminant.

### Problem 10

Suppose the detection limit of *Giardia* cysts is 0.015 cyst/L. Removals are about 3.5-log; assume 4-log for a conservative estimate. The pilot plant flow is 70 L/min for a 610 mm square filter column. Determine the number of cysts in a 1800 mL volume, to be metered into the flow over 120 min.

- A)  $n = 5.55 \times 10^5$  cysts
- B)  $n = 8.91 \times 10^5$  cysts
- C)  $n = 1.26 \times 10^6$  cysts
- D)  $n = 1.92 \times 10^5$  cysts

### Problem 11

A city has a clear well with 40 min detention time and uses chloramine as a disinfectant. The chloramine concentration is maintained at 3.1 mg/L and is mostly in the form of chloramine. Assume the concentration of heterotrophic plate count (HPC) bacteria for the flow entering the clear well is 10,000 organisms/mL (which is very high, but deliberately chosen for illustrative purposes). Estimate the average concentration of HPC bacteria leaving the clear well. The  $K$  constant for monochloramine eliminating 2-log (99%) kill HPC is 100.

- A)  $N = 17$  organisms/mL
- B)  $N = 33$  organisms/mL
- C)  $N = 50$  organisms/mL
- D)  $N = 67$  organisms/mL

### Problem 12

Regarding disinfection and other aspects of water quality and treatment, true or false?

- 1.( ) In chlorine disinfection, trihalomethanes are mainly formed by chlorination of dissolved methane.
- 2.( ) One of the limitations of chlorination is its limited efficiency in inactivating cysts of *Cryptosporidium* and *G. lamblia*. These microbes can, however, be removed by micro- and ultra-filtration or destroyed by large doses of UV light.
- 3.( ) Chlorine can react with phenols to yield chlorophenols, most of which cause much worse odor and toxicity problems than the natural compounds from which they are derived. One way to counteract chlorophenol formation is to provide the water with ammonia prior to chlorination.
- 4.( ) Chlorine residuals must be removed from wastewater effluents before they are released to natural waters because of the toxicity of chloramines to aquatic invertebrates, even at ppb levels. The most common method to accomplish this is through reaction with sulfite anions ( $\text{SO}_3^{2-}$ ), usually supplied to water in the form of sulfur dioxide.

5.( ) Bromide ion is present in water affected by sea salts and brines. One of the additional benefits of chlorine in disinfection is the fact that chlorine residual is capable of oxidizing bromide ions ( $\text{Br}^-$ ), a toxic anion, to bromate ( $\text{BrO}_3^-$ ), a stable, harmless anion.

6.( ) Monochloramine is significantly less effective than chlorine as a biocide, but has excellent performance in the control of *Legionella* due to its high persistence, low reactivity, and ability to penetrate biofilms better than chlorine.

7.( ) One of the advantages of chlorine dioxide over other chlorine-based chemicals used in water treatment is the fact that  $\text{ClO}_2$  is quite volatile and can be stripped from a water solution by aeration. Furthermore, unlike  $\text{Cl}_2$ , chlorine dioxide does not react with ammonia or with trihalomethane precursors when prepared with no free residual chlorine.

8.( ) Ozone is a strong oxidant with bactericidal properties similar to those of chlorine. One of the advantages of ozone over chlorine is the fact that the germicidal performance of the former is generally unaffected by changes in pH. In contrast, chlorine-based compounds such as hydrochlorous acid depends on an alkaline pH, preferably greater than 8, to produce an optimal disinfectant effect.

9.( ) Ozonation can be associated with the addition of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), which, much like the disinfection reactions of ozone itself, can be used to produce hydroxyl radicals, a very reactive oxidant.

## Solutions

### P.1 ■ Solution

1. **True.** Given the molecular mass of calcium carbonate, 100 da, we have

$$\text{meq/L} = \frac{\text{mg/L}}{\text{equivalent weight}} = \frac{100}{2} = 50 \text{ for CaCO}_3$$

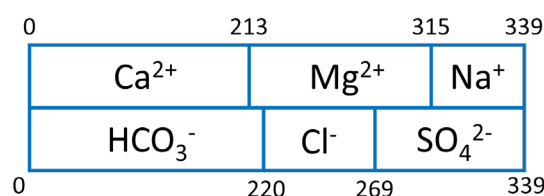
The species concentration expressed as mg/L of  $\text{CaCO}_3$  is calculated as

$$\text{mg/L as CaCO}_3 = \text{meq/L species} \times 50 = \frac{(\text{mg/L of species}) \times 50}{\text{Equivalent weight of species}}$$

The calculations are summarized in the following table.

Ion Species	Molecular Weight	Equivalent Weight	Concentration		
			mg/L	meq/L	mg/L as $\text{CaCO}_3$
$\text{Ca}^{2+}$	40.1	20	85	4.25	213
$\text{Mg}^{2+}$	24.3	12.2	25	2.05	102
$\text{Na}^+$	23	23	11	0.48	24
			Total:	6.78	339
$\text{HCO}_3^-$	61	61	268	4.39	220
$\text{Cl}^-$	35.5	35.5	35	0.99	49
$\text{SO}_4^{2-}$	96	48	67	1.40	70
			Total:	6.78	339

Water softening problems often involve the construction of *equivalent bar diagrams*. The diagram shows the relative proportions of the chemical species important to the water softening process. Cations are placed above anions. The calcium equivalent should be placed first on the cationic scale and be followed by magnesium and other divalent species and then by the monovalent species sodium equivalent. The bicarbonate equivalent should be placed first on the anionic scale and immediately be followed by the chloride equivalent and then by the sulfate equivalent. The diagram in question is shown below.



The total hardness is the sum of the adjusted calcium and magnesium concentrations. Mathematically,

$$\text{Total Hardness} = 213 + 102 = 315 \text{ mg/L as CaCO}_3$$

**2. False.** The carbonate hardness is given by

$$\text{Carbonate hardness} = \text{Alkalinity} = 220 \text{ mg/L as CaCO}_3$$

**3. False.** The noncarbonate hardness is obtained by deducting the carbonate hardness from the total hardness; that is,

$$\text{Noncarbonate hardness} = 315 - 220 = 95 \text{ mg/L}$$

Another way to obtain the same result would be to sum the adjusted concentrations of sodium, chlorine, and sulfate ions (i.e., all diluted ions except carbonates, calcium, and magnesium).

## P.2 ■ Solution

The alkalinity of water is given by

$$\text{Alkalinity} = [\text{HCO}_3^-] + [\text{CO}_3^{2-}] + [\text{OH}^-] + [\text{H}^+]$$

Here we assume that, at pH = 7.0, all alkalinity is in bicarbonate form. The molar concentration of bicarbonate is

$$[\text{HCO}_3^-] = 250 \frac{\text{mg}}{\text{L}} \times \frac{1 \text{ g}}{1000 \text{ mg}} \times \frac{1 \text{ mol}}{61 \text{ g}} \times \frac{61 \text{ eq wt of HCO}_3^-}{50 \text{ eq wt of alkalinity}} = 5.0 \text{ mmol/L}$$

Given coefficient  $\alpha_1 = 0.75$ , the total carbonate species concentration can be estimated as

$$C_T = \frac{[\text{HCO}_3^-]}{\alpha_1} = \frac{5.0 \times 10^{-3}}{0.75} = 6.67 \times 10^{-3} \text{ mol/L}$$

Assuming there are no carbonate ions, we have

$$C_T = [\text{H}_2\text{CO}_3] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}] \rightarrow [\text{H}_2\text{CO}_3] = C_T - [\text{HCO}_3^-]$$

$$\therefore [\text{H}_2\text{CO}_3] = 6.67 \times 10^{-3} - 5.0 \times 10^{-3} = 1.67 \times 10^{-3} \text{ mol/L}$$

or 104 mg/L. Expressing this in terms of CaCO<sub>3</sub>, it follows that

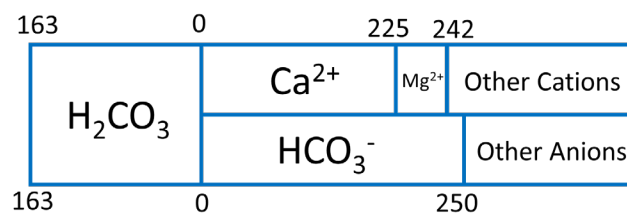
$$[\text{H}_2\text{CO}_3] = 104 \times \frac{50}{32} = 163 \text{ mg/L as CaCO}_3$$

The raw water adjusted concentrations of Ca and Mg as CaCO<sub>3</sub> are, in turn,

$$[\text{Ca}^{2+}] = 90 \times 100/40 = 225 \text{ mg/L as CaCO}_3$$

$$[\text{Mg}^{2+}] = 4 \times 100/24.3 = 17 \text{ mg/L as CaCO}_3$$

The bar diagram for this water is shown in continuation.



The calcium carbonate hardness is 225 mg/L and the magnesium carbonate hardness is 17 mg/L. The total hardness is 225 + 17 = 242 mg/L. Since the final hardness required is 40 mg/L as CaCO<sub>3</sub>, magnesium hardness removal would not be required. The amount  $m$  of lime needed is equal to the carbonic acid concentration plus the calcium carbonate hardness; in mathematical terms,

$$m = 163 + 225 = 388 \text{ mg/L as CaCO}_3$$

or, given the molar mass of CaO = 56 g/mol,

$$m = 388 \times \frac{56}{100} \text{ mg/L} = 217 \text{ mg/L as CaO}$$

The purity of lime is 70%. Accordingly, the total amount of lime needed is

$$m' = 217/0.70 = \boxed{310 \text{ mg/L as CaO}}$$

The magnesium hardness level of 17 mg/L as CaCO<sub>3</sub> remains in the softened water theoretically. The limit of calcium achievable is 30 to 50 mg/L of CaCO<sub>3</sub> and would remain in the water unless using 5 to 10% excess of lime. Hardness levels less than 50 mg/L as CaCO<sub>3</sub> are seldom achieved in plant operation.

★ The correct answer is **A**.

### P.3 ■ Solution

**1. False.** The fact that alum easily dissolves in water is in fact one of the main reasons why it has corrosive properties. One of the products formed when alum reacts with water is sulfuric acid, which is highly corrosive to metals and tissue. Thus, stored alum to be used in water treatment procedures should be kept away from any sources of moisture.

**2. False.** While it is true that alum and iron salts such as ferric chloride are acidic, one of the compounds mentioned in the statement, sodium aluminate (Na<sub>2</sub>Al<sub>2</sub>O<sub>4</sub>), in fact *increases* the alkalinity of water. Thus, use of this compound in water treatment processes must be carried out with care not to exceed pH and alkalinity guidelines. Nevertheless, the fact that this latter compound does not deplete alkalinity may be viewed as an advantage over the aforementioned coagulants.

**3. True.** In addition to its alkalinity-producing properties, magnesium hydroxide is also a flocculant. Magnesium hydroxide produces more CaCO<sub>3</sub> equivalent alkalinity on an equal weight basis when compared to hydrated lime and caustic soda, and hence lowers chemical consumption. What's more, magnesium hydroxide is non-hazardous and non-corrosive, in contrast to, say, caustic soda. Given these and other reasons, some water treatment facilities have introduced Mg(OH)<sub>2</sub> as the alkaline agent of choice.

**4. False.** The main constituent of diatomaceous earth is silicon dioxide, SiO<sub>2</sub>, which corresponds to about 80 percent of natural DE. Alumina comes second, corresponding to no more than 6 percent of DE. Other components of natural DE include iron oxide, calcium oxide, and magnesium oxide.

**5. False.** While it is true that the inherent purity of perlite may be interpreted as an advantage, the claim that perlite is acidic is false. Perlite is a form of natural glass, and as such is chemically inert. The pH of perlite in water is about 7.

**6. True.** As temperatures rise, less oxygen can be held in solution. The saturation concentration of oxygen in a natural unpolluted 0°C freshwater at sea level is about 14 mg/L, but this value drops almost 50% at temperatures common in tropical sea level freshwaters (≈30°C).

**7. False.** The greater the BOD<sub>5</sub>, the greater the demand for oxygen in the water sample, and the greater the number of microbes present in the water. Accordingly, the BOD<sub>5</sub> of drinking water should be close to zero; a sample with BOD<sub>5</sub> between 3.0 and 5.0 mg O/L is only moderately clean.

**8. True.** The BOD reaction follows first-order kinetics, which implies that the BOD after  $t$  days of incubation may be described by the relation

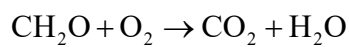
$$BOD_t = U(1 - e^{-kt})$$

where  $BOD_t$  is the biochemical oxygen demand after  $t$  days,  $U = 510$  mg/L is the ultimate BOD, and  $k = 0.05$  day<sup>-1</sup> is the rate constant for the reaction. Thus, with  $t = 5$ , we have

$$BOD_5 = 510 \times (1 - e^{-0.05 \times 5}) = 113 \text{ mg/L}$$

#### P.4 ■ Solution

The chemical reaction for oxidation of organic matter is



This equation shows that 1 mole of  $\text{O}_2$  oxidizes 1 mole of  $\text{CH}_2\text{O}$ . Accordingly, the moles of  $\text{CH}_2\text{O}$  biodegraded will equal the moles of  $\text{O}_2$  consumed during biodegradation. The number of moles of  $\text{O}_2$  initially present in the bottle is given by

$$n_{\text{DO}} = \frac{11 \times 10^{-3} \text{ g/L}}{32 \text{ g/mol}} = 3.44 \times 10^{-4} \text{ mol/L}$$

The biodegradable mass of insect is  $0.20 \times 80 = 16$  mg. Given the molar mass of organic matter =  $12 + 2 \times 1 + 16 = 30$  g/mol, the biodegradable mass in question is, when expressed in moles,

$$\text{Moles of biodegradable organic matter} = \frac{16 \times 10^{-3} \text{ g/L}}{30 \text{ g/mol}} = 5.33 \times 10^{-4} \text{ mol/L}$$

Since the moles of biodegradable organic matter exceed the moles of DO in the 1 L sample, biodegradation of the insect will consume all of the DO in the sample and there will be some biodegradable organic matter left over. The mass of organic matter biodegraded is  $(3.44 \times 10^{-4}) \times 30 = 10.3$  mg, and the mass of biodegradable matter remaining is  $16 - 10.3 = 5.7$  mg. Since all of the dissolved DO has been consumed, the laboratory will find the water anaerobic, with no DO. There will be  $80 - 10.3 = 69.7$  mg of insect remaining, of which 5.7 mg is still biodegradable. Note that the concentration of BOD degraded (10.3 mg/L) is similar to the concentration of DO consumed (11 mg/L), being only about 6.5% less.

★ The correct answer is **A**.

#### P.5 ■ Solution

The mass of propanol present in the aliquot is

$$m_{\text{propanol}} = 0.25 \text{ L} \times \frac{68 \text{ mg}}{1 \text{ L}} = 17 \text{ mg}$$

The oxygen requirement for this amount of propanol is

$$m_{\text{O}_2} = 0.017 \text{ g Propanol} \times \frac{1 \text{ mol C}_3\text{H}_7\text{OH}}{60 \text{ g C}_3\text{H}_7\text{OH}} \times \frac{9 \text{ mol O}_2}{2 \text{ mol C}_3\text{H}_7\text{OH}} \times \frac{32 \text{ g O}_2}{1 \text{ mol O}_2} = 0.0408 \text{ g O}_2$$

or 40.8 mg  $\text{O}_2$ . Similarly, we have a mass of acetone such that

$$m_{\text{acetone}} = 0.06 \text{ L} \times \frac{120 \text{ mg}}{\text{L}} = 7.2 \text{ mg}$$

the oxygen requirement for which follows as

$$m_{\text{O}_2} = 0.0072 \text{ g Acetone} \times \frac{1 \text{ mol Acetone}}{58 \text{ g Acetone}} \times \frac{4 \text{ mol O}_2}{1 \text{ mol Acetone}} \times \frac{32 \text{ g O}_2}{1 \text{ mol O}_2} = 0.0159 \text{ g O}_2$$



or 15.9 mg O<sub>2</sub>. The total volume of sample + spiking solution is 250 + 60 = 310 mL, so we ultimately have a COD given by

$$\text{COD} = \frac{40.8 + 15.9 \text{ mg}}{310 \text{ mL}} \times \frac{1000 \text{ mL}}{1 \text{ L}} = \boxed{183 \text{ mg O}_2/\text{L}}$$

★ The correct answer is **C**.

## P.6 ■ Solution

In the case of hydrolyzing metal salts, the primary purpose of the rapid mix is to quickly disperse the salt so that contact between the simpler hydrolysis products and the particles occurs before the metal hydroxide precipitate has formed. Rapid dispersal before precipitation helps ensure that the coagulant is distributed uniformly among the particles. A high-energy, rapid-mix is needed to properly disperse coagulant, promote particle collisions, and thereby achieve good coagulation. Over-mixing does not affect coagulation, but insufficient mixing will leave this step incomplete.

★ The correct answer is **C**.

## P.7 ■ Solution

One investigator (Letterman, 1977) proposed the following equation for the design flow to a given filter,

$$Q_{\text{design}} = A_{\text{filter}} \times \text{number of filter runs per unit time} \times \text{net water production per unit area}$$

The number of filter runs per day is

$$N(\text{filter runs/day}) = \left( \frac{1440 \text{ min/day}}{WP/v + TB} \right)$$

where  $WP$  is the volume of water production per unit area of filter bed per filter run ( $\text{m}^3$  water produced/ $\text{m}^2$  filter plain area/filter run),  $v$  is the filtration rate ( $\text{m}^3/\text{m}^2/\text{min}$ ), and  $TB$  is the filter down time per backwash (min downtime/filter run). The “net water production” per filter run per unit area, in turn, is

$$NWP = WP - VB$$

where  $VB$  is the volume of water required per unit of filter bed area per backwash ( $\text{m}^3$  backwash water/ $\text{m}^2$  filter bed area/filter run). Substituting the two foregoing expressions in the Letterman equation, we obtain

$$Q_{\text{design}} = A_{\text{filter}} \times \left[ \frac{1440 \text{ min/d}}{(WP/v + TB) \times (WP - VB)} \right]$$

Solving for the plan area of filter bed gives

$$A_{\text{filter}} = Q_{\text{design}} \times \left[ \frac{1440 \text{ min/d}}{(WP/v + TB) \times (WP - VB)} \right]^{-1}$$

Substituting  $v = 8 \text{ m/h} = 0.133 \text{ m/min}$ ,  $Q_{\text{design}} = 92 \text{ m}^3/\text{day}$ ,  $WP = 20 \text{ m}^3$  water produced/ $\text{m}^2$  filter plan area/filter run,  $VB = 17 \text{ m}^3$  backwash water/ $\text{m}^2$  filter bed area/filter run, and  $TB = 12 \text{ min}$  downtime/filter run, it follows that

$$A_{\text{filter}} = 92 \times \left[ \frac{1440 \text{ min/d}}{(20/0.133 + 12) \times (20 - 17)} \right]^{-1} = \boxed{31.1 \text{ m}^2}$$

A rule of thumb for American practice is that the area of a single filter bed should be less than 93 m<sup>2</sup>, or 1000 ft<sup>2</sup>. Our result is about a third of this recommended limit.

★ The correct answer is **B**.

## P.8 ■ Solution

The feed rate is given by

$$\text{Feed rate} = \frac{D \times C \times 8.34 \text{ lb/gal}}{\text{AFI} \times P}$$

where  $D = 1.1$  mg/L is the dosage,  $C = 2000 \times 1440/1,000,000 = 2.88$  MGD is the capacity,  $\text{AFI} = 0.606$  is the available fluoride ion capacity for sodium fluorosilicate (obtained from the ratio of molar mass of fluoride atoms to the molar mass of the molecule), and  $P = 0.25$  is chemical purity. Substituting the pertaining variables, we get

$$\text{Feed rate} = \frac{1.1 \times 2.88 \times 8.34 \text{ lb/gal}}{0.606 \times 0.25} = \boxed{174 \text{ lb/day}}$$

★ The correct answer is **D**.

## P.9 ■ Solution

**1. True.** Sedimentation is faster in liquids having low viscosities. Accordingly, sedimentation rates are higher at greater temperatures.

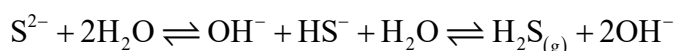
**2. False.** If the particle settling velocity is found to be less than the upward fluid velocity, particles will be entrained out in the overflow and poor clarification will ensue. For those particle sizes whose settling velocity approximately equals that of the upward fluid velocity, particles remain in a balanced suspension, i.e., they neither rise nor fall, and the concentration of solids in the clarification zone increases. This eventually results in a reduction of the settling velocity until the point where particles are entrained out in the overflow. The optimal conditions are attained when the settling velocity of particles is significantly greater than the upward fluid velocity, as it minimizes the concentration of solids in the clarification zone.

**3. False.** Since ED involves polarized membranes, it is only effective in the removal of ionic species. It is true, however, that ED is an efficient method for processing waters with low to moderate concentration of dissolved solids, usually no larger than 5000 ppm. Indeed, for waters at the low concentration end of the brackish scale, ED is the most cost effective process of all.

**4. False.** RO is not effective in the treatment of light organics such as benzene because such small organic solvent molecules can dissolve in the membrane and migrate to the treated water. In such cases, granular activated carbon and aeration are better treatment choices. Benzene is a known human carcinogen, and acute inhalation, as in the case of other organic solvents, may cause drowsiness and headaches. Its water solubility is about 2 grams per liter.

**5. True.** Reverse osmosis is a pressure-driven process. Low pressure makes the filtering unit produce less water and at lower quality. For example, rejection of sodium chloride in a typical RO system can fall from 90 percent at 300 pounds per square inch to 20 percent at 50 psi.

**6. False.** Sulfide ion, much like bisulfide, is nonvolatile and has no odor. The most malodorous of the three is hydrogen sulfide, which has a characteristic smell of rotten eggs. The reactions that describe the formation and decomposition of this family of compounds, starting with the strong base  $\text{S}^{2-}$ , are as follows.



Lowering the pH shifts the equilibrium to the right, creating more malodorous gas from the nonvolatile forms. At low pH, the gas can be removed from the water by air stripping – which, of course, does not destroy the compound, but rather displaces it from the solution to the atmosphere. The presence of the penetrating smell of  $\text{H}_2\text{S}$  in water is an indicator of the presence of sulfate-reducing bacteria.

**7. False.** The salt used as a source of F<sup>-</sup> ions is sodium fluoride, NaF, not calcium fluoride. The latter is a white, insoluble solid that occurs as part of the mineral fluorite. Sodium fluoride, in turn, is a white, readily soluble solid obtained from the processing of fluorapatite in the fertilizer industry. Adding 19 lb of sodium fluoride will yield a concentration of 1 mg/L – the recommended amount in many countries – in 1 million gallons of water.

**8. True.** Lime can be used to induce the precipitation of calcium phosphate. Anionic polymers may be used to assist solid separation.

**9. True.** Indeed, addition of orthophosphate helps to control corrosion and reduce leaching of lead (as well as copper into the water. The positive effect is observable even at concentrations of orthophosphate as low as 1 mg/L. One water conveyance operator in Ohio has reported a 90% reduction of lead levels in drinking water over a period of 20 years. The WHO's lead in drinking water guideline and the European Union's drinking water lead directive are 10 µg/L.

**10. False.** Besides the three aforementioned methods, granular activated carbon is also an EPA-sanctioned technique for the removal of mercury, be it organic or inorganic. Mercury is, in fact, one of the few heavy inorganics that can be efficiently eliminated with activated carbon. A typical combination of coagulation, sedimentation, and filtration removes 80% of inorganic mercury and about 20 – 40% of organic mercury. Mercury ions are readily methylated by both abiotic and biotic pathways, forming compounds such as methylmercury (CH<sub>3</sub>Hg<sup>+</sup>), which is a potent toxin because it is soluble in fatty tissues (lipophilic) of animals and, once infiltrated in the metabolism, may attack the central nervous system.

**11. True.** The high concentration of uranium in fertilizer runoff is due to the high uranium content of many phosphate rocks, which may contain 20 to 120 mg/kg of the element (the typical concentration in the Earth's crust is 2 to 3 mg/kg; levels in US streams are usually between 0.1 and 10 mg/L). The other main source of uranium in water is mine tailings.

**12. False.** Radon can travel long distances dissolved in groundwater and through voids and fissures in the vadose zone as a gas. It is, however, a chemically unreactive (noble) gas and, being over seven times heavier than air (its density at STP is 9.73 g/L), tends to collect in voids and low spots. As a result, radon is particularly problematic in wells and groundwater, not in PWSs. In addition, where radon is a known problem, public supplies can easily treat the water by aeration, venting the gas into the atmosphere. In the US, radon is particularly prevalent in groundwater associated with igneous rock, with the largest concentrations occurring in western states from Montana to Arizona and along the eastern seaboard from South Carolina to Maine.

## P.10 ■ Solution

If  $\log(C/C_0) = -4.0$  and  $C = 0.015$  cyst/L, the concentration of particles in the water follows as

$$\log\left(\frac{C}{C_0}\right) = \log R \rightarrow \log\left(\frac{0.015}{C_0}\right) = -4.0$$

$$\therefore C_0 = 150 \text{ cysts/L}$$

The flow rate for the contaminant metering procedure is

$$Q = \frac{1800 \text{ mL}}{120 \text{ min}} = 15 \text{ mL/min}$$

The concentration of cysts in the contaminant metering flow is given by

$$Q_{\text{cm}} \times C_{\text{cm}} = Q_{\text{pilot plant flow}} \times C_0 \rightarrow C_{\text{cm}} = \frac{Q_{\text{pilot plant flow}} \times C_0}{Q_{\text{cm}}}$$

$$\therefore C_{\text{cm}} = \frac{70 \times 150}{0.015} = 700,000 \text{ cysts/L}$$

Lastly, the number of cysts in the 1800-mL volume is established as

$$n = Q_{\text{cm}} \times C_{\text{cm}} \times \text{time} = 0.015 \times 700,000 \times 120 = \boxed{1.26 \times 10^6 \text{ cysts}}$$

That is, there are about 1.25 million cysts in the 1800-mL volume specified. Typical numbers for injection in a large pilot plant are generally around 10 million.

★ The correct answer is **C**.

## P.11 ■ Solution

The rate of inactivation of microorganisms is expressed as a first order reaction described by Chick's law,

$$\frac{dN}{dt} = -kN$$

which, after integration, becomes

$$\frac{N}{N_0} = 10^{-\frac{k}{2.3}t}$$

Here,  $N$  is the concentration of microorganisms at any time after  $t = 0$ ,  $N_0$  is the concentration of organisms at time  $t = 0$ ,  $k$  is the rate constant, and  $t$  is the time from the beginning of measurements. This equation was later refined to the form

$$\ln \frac{N}{N_0} = rC^n t$$

where  $C$  is the concentration of disinfectant,  $r$  is called the coefficient of specific lethality and  $n$  is an exponent sometimes called the coefficient of dilution. The equation above can be rearranged as

$$\frac{1}{r} \ln \frac{N}{N_0} = C^n t$$

For a given level of survival fraction, such as  $N/N_0 = 0.01$  (which corresponds to 99% or 2-log removal), the left-hand side of the equation above is a constant,  $K$ , so that

$$C^n t = K$$

If  $n = 1.0$ , the equation simplifies to

$$K = Ct$$

In the present case, we were given  $K = 100$  and the concentration 3.1 mg/L. Substituting and solving for time, we obtain

$$K = Ct \rightarrow 100 = 3.1 \times t$$

$$\therefore t = 32.3 \text{ min}$$

Appealing to Chick's law, we can determine the rate constant  $k$ ,

$$\ln \frac{N}{N_0} = -kt \rightarrow \ln \frac{1}{100} = -k \times 32.3$$

$$\therefore k = 0.143 \text{ min}^{-1}$$

We then apply Chick's law a second time, this time considering system conditions, with  $t = 40$  min as the detention time in the clear well and  $N_0 = 10,000$  organisms/mL as the initial concentration of organisms in the well. Accordingly,

$$\ln \frac{N}{N_0} = -kt \rightarrow \ln \frac{N}{10,000} = -0.143 \times 40$$

$$\therefore N = 32.8 \approx \boxed{33 \text{ org/mL}}$$

★ The correct answer is **B**.

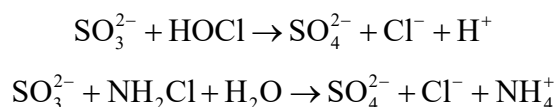
## P.12 ■ Solution

**1. False.** It was once thought that trihalomethanes result from the reaction of chlorine compounds with dissolved methane, but advanced investigations have revealed that THMs come from the reaction of HOCl with acetyl groups in natural organic matter, especially humic acids.

**2. True.** Indeed, chlorine produces limited results in the elimination of *Cryptosporidium* and *G. lamblia*, although a high dose and a sufficiently long exposure time and high-concentration chlorine residuals may produce the desired effect. According to the USEPA, at a temperature of 25°C and pH 8.0, with a chlorine residual in the range of 1 to 2.6 mg/L, a contact time of 54 to 65 minutes is needed to achieve a 3-log reduction in *G. lamblia*. Micro- and ultra-filtration can achieve *Cryptosporidium* removal efficiencies of the order of log-2 or more. Elimination can be attained by large doses of UV light, often in the order of 200 mW·s/cm<sup>2</sup> (about five times the typical dose used in ordinary water treatment, which is generally no greater than 40 mW·s/cm<sup>2</sup>).

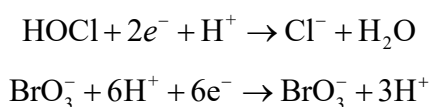
**3. True.** Indeed, odor thresholds of chlorinated phenols are in the ppb range, and, at the ppm level, chlorophenols make the water completely unfit for drinking or cooking. It is true that the addition of ammonia to water before chlorination leads to the formation of chloramines and thereby superposes, or at least delays, the formation of chlorophenols. For example, at equimolar concentrations of phenol and ammonium, the formation of monochloramine at pH 8 is approximately 10<sup>3</sup> times faster than the formation of monochlorophenol. Chloramines can react with phenol to yield the same chlorophenols formed by free chlorine, but at much slower rates (days to weeks).

**4. True.** Sulfite is the most widely used dechlorination agent. The ion reacts with hypochlorous acid and monochloramine via the following reactions:

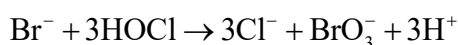


It should be noted, however, that exceedingly high doses of sulfite may lead to problems such as sulfate formation, suppressed dissolved oxygen content, and lower pH of the finished effluent.

**5. False.** Bromate is a suspected animal carcinogen from high dose testing, capable of causing oxidative DNA damage, and exposure to excessive levels of it has been associated with gastrointestinal, kidney, and hearing effects. The reactions in question are:



Globally,

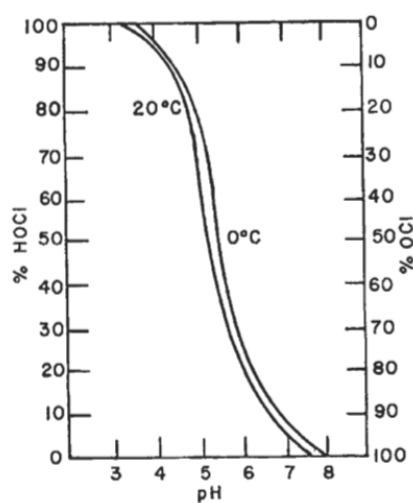


Bromate and other brominated compounds are a particularly worrisome hazard in ozonation. Disinfection by chlorine dioxide does not produce bromate. Since bromate is difficult to remove, it is best controlled by preventing its generation during water treatment. Use of purified hypochlorite with low bromate content and not ozonating water that contains bromide are two management possibilities.

**6. True.** Indeed, monochloramine is a rather poor primary disinfectant – free chlorine is 250 times more potent, ozone is up to 1500 times more potent – but offers excellent performance in the control of *Legionella*, the genus responsible for legionellosis, which is the most significant waterborne disease risk in the United States. After San Francisco switched from free chlorine to combined chlorine residuals in 2004, *Legionella* detections in hot water systems were reduced from 60 to 4 percent.

**7. True.** One of the most notable qualities of chlorine dioxide is its high water solubility, especially in cold water. Chlorine dioxide is about ten times more soluble in water than gaseous chlorine and does not hydrolyze when it enters water, but rather remains as a gas in solution. Watery solutions containing approximately 1%  $\text{ClO}_2$  ( $\approx 10$  g/L) can be safely stored for relatively long periods inasmuch as the solution is protected from light and heat, so as to protect the compound from decomposition and potentially explosive conditions ( $\text{ClO}_2$  is explosive under pressure). Chlorine dioxide is effective in oxidizing organic complexes of iron and manganese, imparts no taste and odor to treated water, and provides a highly stable, long-lasting oxidant residual. It is about twice as effective as  $\text{HOCl}$  from  $\text{Cl}_2$ , but also twice as expensive.

**8. False.** It is true that ozone is relatively independent of pH, and that chlorine substances are not. The statement errs, however, when it states that hypochlorous acid requires alkaline conditions to work effectively. In reality, the optimal pH for such compounds is in the neutral to mild acidic (i.e., 6.5 to 7) range – but, in the case of hypochlorous acid, not *too* acidic, as non-dissociated  $\text{HOCl}$  tends to predominate at low pH levels. The relative amounts of  $\text{HOCl}$  and  $\text{OCl}^-$  as a function of pH are shown in the following graph.



**9. True.** Decomposition of ozone in water produces  $\text{DO}$  and hydroxyl radicals. It is true that hydrogen peroxide can be used to augment the concentration of hydroxyl ions, a process known as advanced oxidation process (AOP). The hydroxyl free radical is the strongest available oxidizing agent available for water treatment, as it reacts at every molecular collision with many organic compounds. Other ways to enhance ozonation include use of UV radiation and raising the pH to around 10 – 11.

It should be noted that free radicals formed by the decomposition of ozone are generally less effective for microbial inactivation than molecular ozone, because microbial cells contain a high concentration of bicarbonate ions that quench the free radical reaction, and many microbial cells also contain enzymes to control the free radicals produced by aerobic respiration. This may lead one to surmise that free radicals provide little benefit in terms of microbial destruction.

## Answer Summary

Problem 1	T/F
Problem 2	A
Problem 3	T/F
Problem 4	A
Problem 5	C
Problem 6	C
Problem 7	B
Problem 8	D
Problem 9	T/F
Problem 10	C
Problem 11	B
Problem 12	T/F

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