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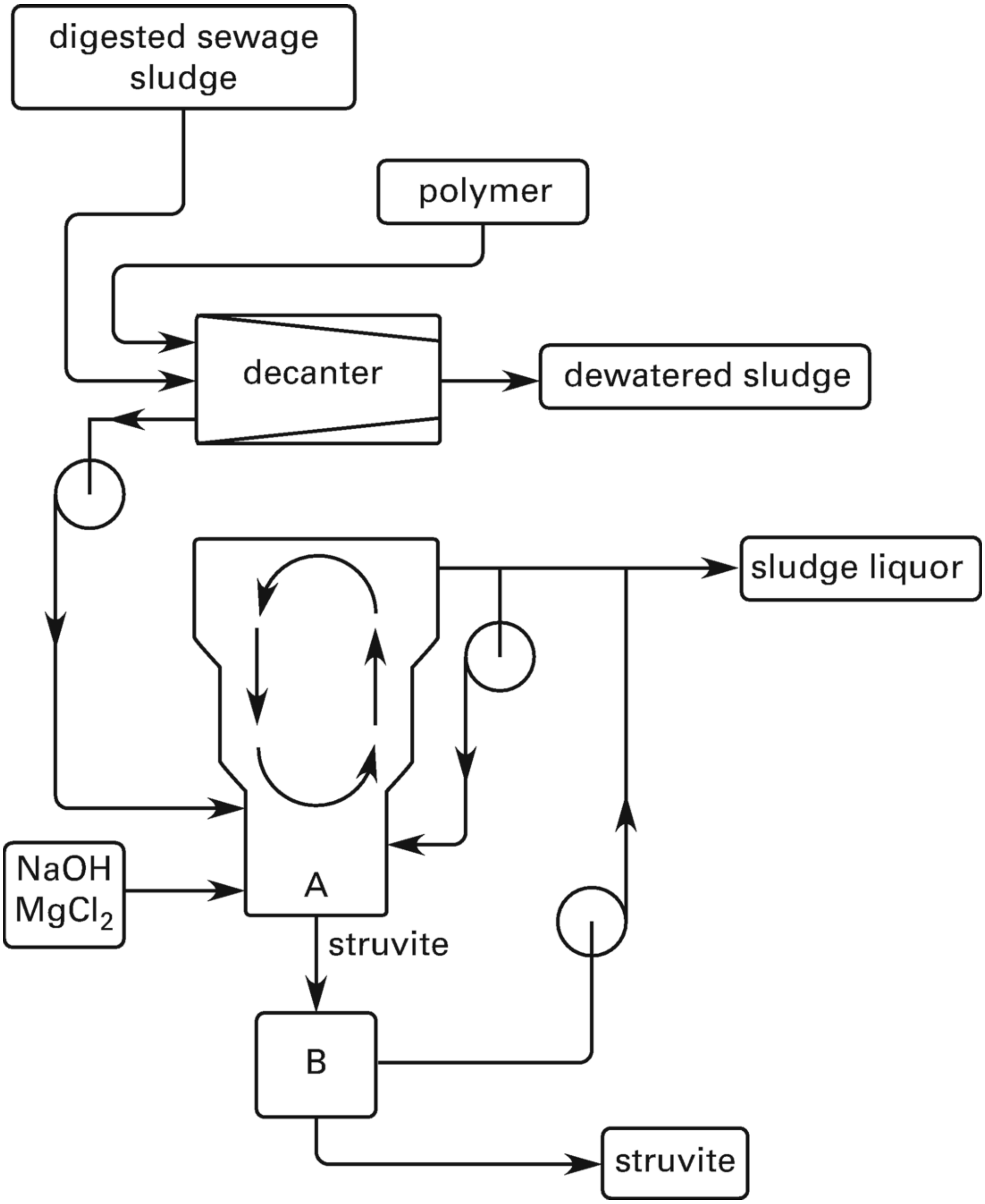
Chapter 26. Solid-Liquid Processes

Practice Problems

1.

One method of recovering phosphorus from wastewater streams is to precipitate magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$), commonly known as struvite, which is a potentially troublesome precipitate in pipelines. Struvite can be recovered in a controlled manner through various processes and can then be collected and applied as a phosphorus-based fertilizer in farmlands. One process for recovering struvite is shown.



In this process, struvite is precipitated by dosing $MgCl_2$ and increasing the pH by adding caustic soda (NaOH). Process equipment A and B are, respectively,

(A)

a dryer and a crystallizer

(B)

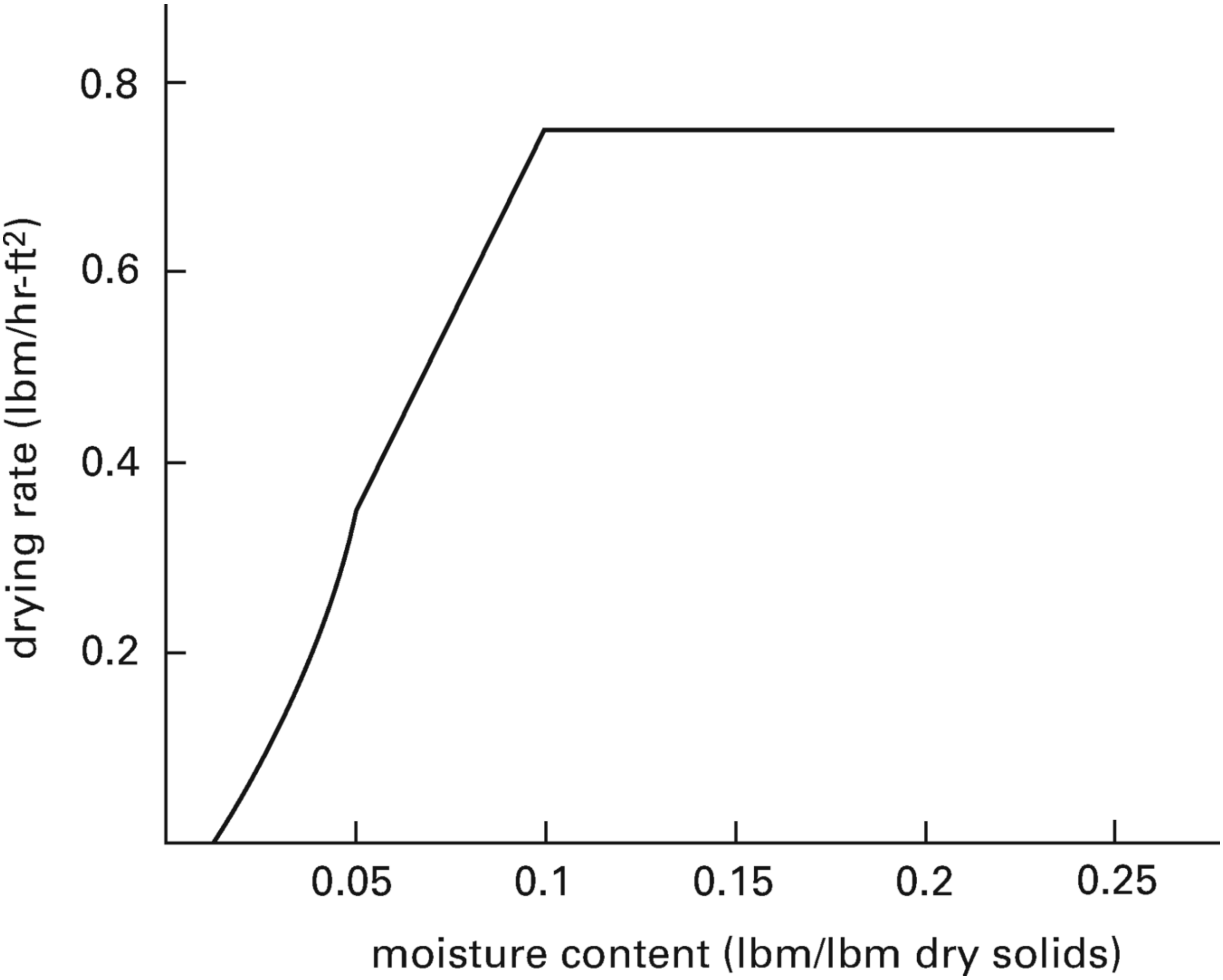
a crystallizer and a dryer
(C)

a flotation column and a microfiltration/reverse osmosis package

(D)

a microfiltration/reverse osmosis package and a flotation column
2.

A batch of material with a 20% moisture content must be dried to a 2.5% moisture content. The drying curve is shown. The initial damp solids weight is 700 lbm, and the drying surface is 0.2 ft^2/lbm dry weight. Estimate the total drying time given that the drying rate in falling rate period II is e^X.



(A)

1 hr

(B)

1.6 hr

(C)

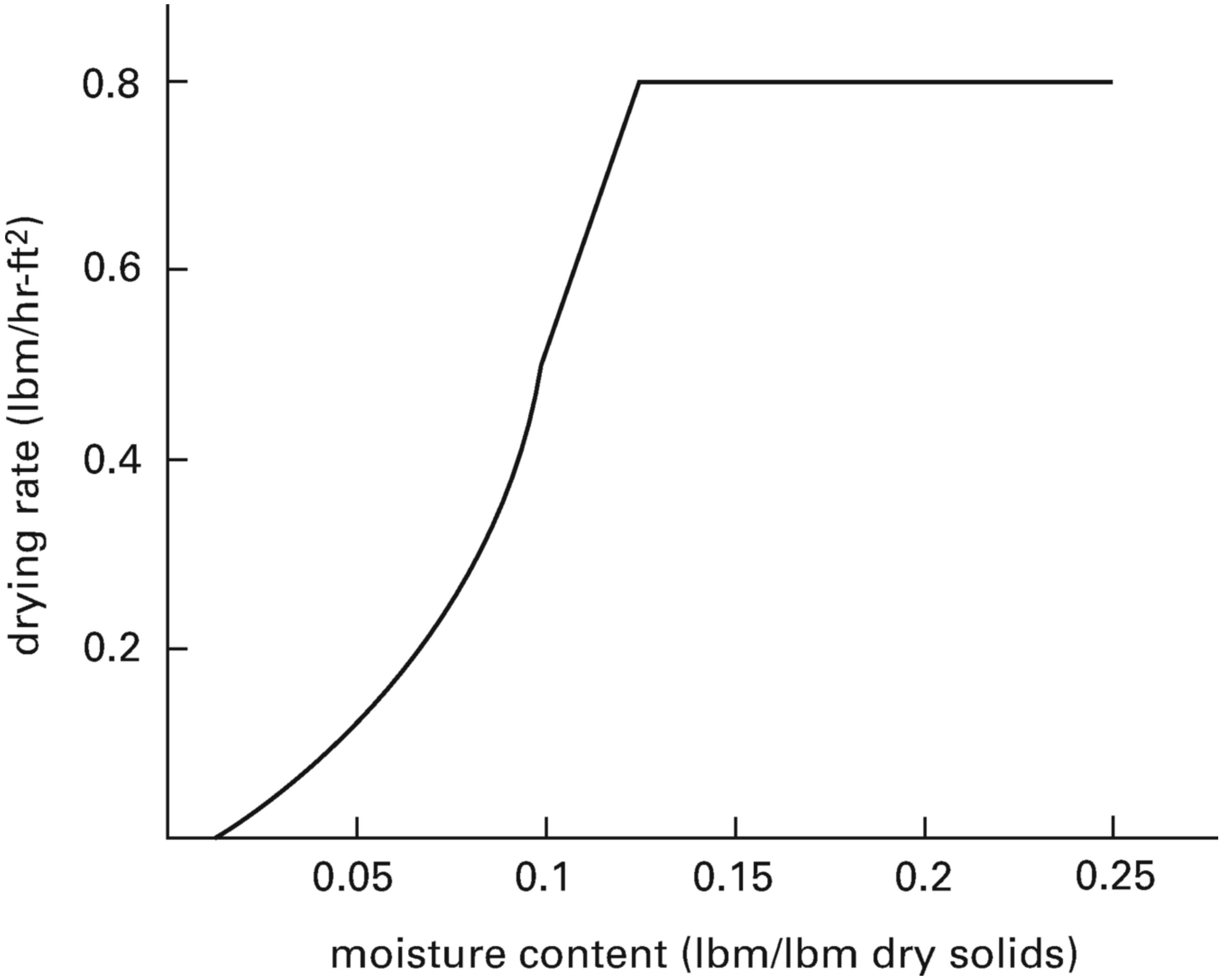
2 hr

(D)

2.4 hr

3.

A batch of material that has a 22.5% moisture content must be dried to a 2.5% moisture content. The drying curve is shown. The initial, total moist solids mass is 1000 lbm, and the drying surface is 0.4 ft^2/lbm (dry mass basis). Estimate the total drying time given that the drying rate in falling rate period II is e^{5X}.



(A)

0.36 hr

(B)

0.52 hr

(C)

0.76 hr

(D)

0.91 hr

4.

Stormwater washes over a farm field and into an adjacent watershed. Which of the following phenomena is most likely to occur?

(A)

leaching

(B)

distillation

(C)

sublimation

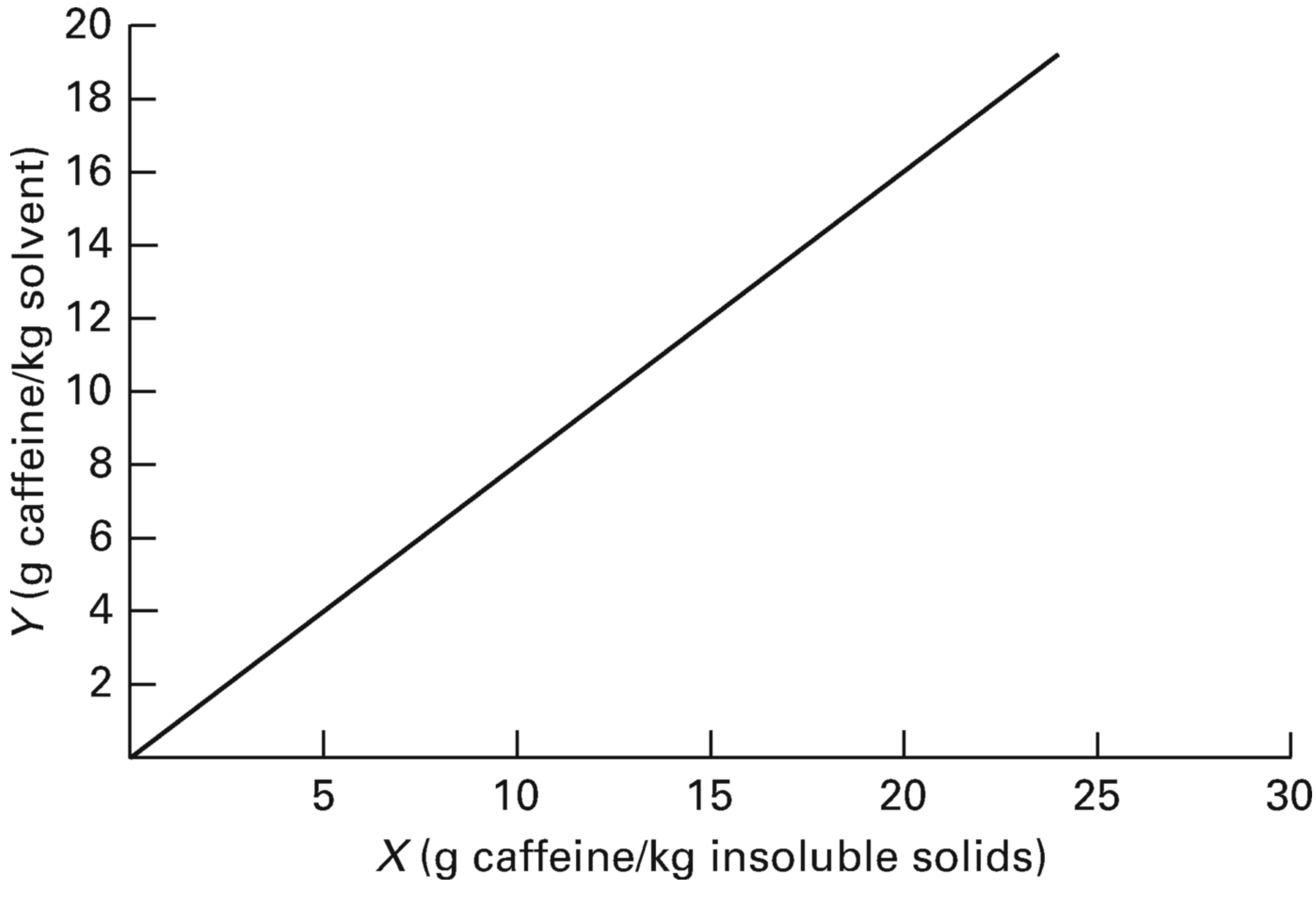
(D)

chemosynthesis
5.

A proprietary solvent leaches caffeine from coffee beans. Analyses indicate that nothing else dissolves in this solvent except caffeine. The equilibrium relationship is known to be $Y = 0.8X$ for caffeine in the solvent, where

$$Y = \frac{\text{g caffeine}}{\text{kg solvent}}$$
$$X = \frac{\text{g caffeine}}{\text{kg insoluble solids}}$$

Starting with pure solvent and coffee beans that have 20 g caffeine/kg beans, the goal is to reduce the caffeine content in the beans to 5% of the original content (i.e., 1 g caffeine/kg beans).



Determine the minimum amount of solvent required to achieve this separation using a countercurrent, equilibrium-staged system.

(A)

0.8 kg solvent/kg insoluble solids

(B)

0.84 kg solvent/kg insoluble solids

(C)

1.2 kg solvent/kg insoluble solids

(D)

1.25 kg solvent/kg insoluble solids
6.

Which of the following statements about the leaching process is NOT correct?

(A)

Solution mining is a leaching process used to recover minerals through boreholes drilled into a deposit that occurs *in situ*.

(B)

If the density and viscosity of liquid is constant from stage to stage, the overflow and underflow rates are both constant and the operating line is straight.

(C)

In leaching, equilibrium occurs when the concentration of the underflow at a given stage equals the concentration of the overflow at the same stage.

(D)

A Pachuca tank is an air-lift reactor used in oxidative leaching processes where the solids settling velocity is small.

7.

A saturated solution contains 3300 lbm of potassium chloride (KCl) at 212°F. The solution is slowly cooled in a crystallizer to 176°F. The solubility of potassium chloride is 56.37 g per 100 g of solution at 212°F and 48.5 g per 100 g of solution at 176°F. The loss of water by evaporation is negligible. The mass of KCl that crystallizes is most nearly

(A)

0.14 lbm

(B)

460 lbm

(C)

3200 lbm

(D)

3300 lbm

8.

Which pair of membrane filtration processes can remove both dissolved solids and salts (ions) from a water or wastewater stream?

(A)

microfiltration and ultrafiltration

(B)

ultrafiltration and nanofiltration

(C)

nanofiltration and reverse osmosis

(D)

reverse osmosis and electrodialysis reversal

Solutions

1.

Equipment A is a crystallizer and equipment B is a dryer. Option A puts the equipment in the wrong order. Options C and D are not appropriate for this purpose.

The answer is (B).

2.

Constant Rate Period:

NCEES Handbook: Specific Drying Applications contains equations for each step in this problem. The moisture content of the material is reduced from the initial moisture content of 20% to the critical moisture content, X_c, in the constant rate period. The initial material has 20% moisture, so the initial moisture content, X_1, is

$$\begin{aligned} X_1 &= \frac{X_T}{L_s} \\ &= \frac{\left(0.2\ \frac{\text{lbm moisture}}{\text{lbm total}}\right)(700\ \text{lbm total})}{\left((1-0.2)\ \frac{\text{lbm dry solids}}{\text{lbm total}}\right)(700\ \text{lbm total})} \\ &= 0.25\ \text{lbm moisture/lbm dry solids} \end{aligned}$$

From the given drying curve, the critical moisture content, X_c, is

$$X_c = 0.1\ \text{lbm moisture/lbm dry solids}$$

Reading from the drying curve, in the constant rate period, the drying rate, N_c, is

$$N_c = 0.75\ \text{lbm moisture/hr-ft}^2$$

In the constant rate drying period, the drying time, t_c, is

$$\begin{aligned} t_c &= \left(\frac{L_s}{A}\right)\left(\frac{X_1 - X_c}{N_c}\right) \\ &= \left(\frac{\text{lbm dry solids}}{0.2\ \text{ft}^2}\right) \\ &\quad \times \left(\frac{0.25\ \frac{\text{lbm moisture}}{\text{lbm dry solids}} - 0.1\ \frac{\text{lbm moisture}}{\text{lbm dry solids}}}{0.75\ \frac{\text{lbm moisture}}{\text{hr-ft}^2}}\right) \\ &= 1\ \text{hr} \end{aligned}$$

Falling Rate Period I:

In falling rate period I, the initial drying rate, N_1, is N_c.

$$N_1 = N_c = 0.75\ \text{lbm moisture/hr-ft}^2$$

From the drying curve, the final drying rate, N_2, is

$$N_2 = 0.35 \text{ lbm moisture/hr-ft}^2$$

The initial moisture content, X_1, is the critical moisture content, X_c.

$$X_1 = X_c = 0.1 \text{ lbm moisture/lbm dry solids}$$

From the drying curve, the final moisture content, X_2, is

$$X_2 = 0.05 \text{ lbm moisture/lbm dry solids}$$

Since the drying curve in falling rate period I is linear, the total drying time, t_I, is

$$\begin{aligned}
t_\text{I} &= \left(\frac{L_s}{A}\right)\left(\frac{X_1 - X_2}{N_1 - N_2}\right)\ln\frac{N_1}{N_2} \\
&= \left(\frac{\text{lbm dry solids}}{0.2 \text{ ft}^2}\right) \\
&\quad \times \left(\frac{0.1 \dfrac{\text{lbm moisture}}{\text{lbm dry solids}} - 0.05 \dfrac{\text{lbm moisture}}{\text{lbm dry solids}}}{0.75 \dfrac{\text{lbm moisture}}{\text{hr-ft}^2} - 0.35 \dfrac{\text{lbm moisture}}{\text{hr-ft}^2}}\right) \\
&\quad \times \left(\ln\frac{0.75 \dfrac{\text{lbm moisture}}{\text{hr-ft}^2}}{0.35 \dfrac{\text{lbm moisture}}{\text{hr-ft}^2}}\right) \\
&= 0.48 \text{ hr}
\end{aligned}$$

Falling Rate Period II:

In falling rate period II, the drying rate, N_II, is given as

$$N_\text{II} = e^X$$

From the drying curve, the initial moisture content, X_1, is

$$X_1 = 0.05 \text{ lbm moisture/lbm dry solids}$$

From the problem statement, the final material has 2.5% moisture. The final moisture content, X_2, is

$$\begin{aligned}
X_2 &= \frac{X_T}{L_s} = \frac{0.025}{1 - 0.025} = \frac{0.025 \text{ lbm moisture}}{0.975 \text{ lbm dry solids}} \\
&= 0.026 \text{ lbm moisture/lbm dry solids}
\end{aligned}$$

In falling rate period II, the drying time, t_II, is

$$\begin{aligned}
t_\text{II} &= \left(\frac{L_s}{A}\right)\int_{X_2}^{X_1}\frac{dX}{N} \\
&= \left(\frac{1}{0.2}\right)\int_{0.026}^{0.05} e^{-X}\,dX \\
&= (5)\left(-e^{-X}\Big|_{0.026}^{0.05}\right) \\
&= (5)\left(-e^{-0.05} - \left(-e^{-0.026}\right)\right) \\
&= 0.12 \text{ hr}
\end{aligned}$$

The total drying time, t_D, is the sum of the drying times for each period.

$$t_D = t_c + t_\text{I} + t_\text{II} = 1 \text{ hr} + 0.48 \text{ hr} + 0.12 \text{ hr} = 1.6 \text{ hr}$$

The answer is (B).

3.

Constant Rate Period:

NCEES Handbook: Specific Drying Applications contains equations for each step in this problem. The moisture content of the material is reduced from the initial moisture content of 22.5% to the critical moisture content, X_c, in the constant rate period. The initial material has 22.5% moisture, so by definition the initial moisture content, X_1, is

$$\begin{aligned} X_1 &= \%\,\text{moisture in solids} = \frac{m_w}{m_s} \\ &= \frac{\left(0.225\ \dfrac{\text{lbm moisture}}{\text{lbm total}}\right)(1000\ \text{lbm total})}{\left((1-0.225)\ \dfrac{\text{lbm dry solids}}{\text{lbm total}}\right)(1000\ \text{lbm total})} \\ &= 0.29\ \text{lbm moisture/lbm dry solids} \end{aligned}$$

From the given drying curve, the critical moisture content, X_c, is

$$X_c = 0.125\ \text{lbm moisture/lbm dry solids}$$

Reading from the drying curve, in the constant rate period, the drying rate, N_c, is

$$N_c = 0.8\ \text{lbm moisture/hr-ft}^2$$

In the constant rate drying period, the drying time, t_c, is

$$t_c = \left(\frac{m_s}{A}\right)\left(\frac{X_1-X_2}{N_c}\right) = \left(\frac{m_s}{A}\right)\left(\frac{X_1-X_c}{N_c}\right)$$

The ratio, m_s/A, which is the drying surface per 1 lb_m (dry weight basis), is equal to (1 lb_m dry solids)/0.4 ft^2.

$$\begin{aligned} t_c &= \left(\frac{1\ \text{lb}_\text{m}\ \text{dry solids}}{0.4\ \text{ft}^2}\right)\left(\frac{0.29\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{lb}_\text{m}\ \text{dry solids}} - 0.125\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{lb}_\text{m}\ \text{dry solids}}}{0.8\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{hr-ft}^2}}\right) \\ &= 0.52\ \text{hr} \end{aligned}$$

Linear Falling Rate Period I:

In falling rate period I, the initial drying rate, N_1, is N_c.

$$N_1 = N_c = 0.8\ \text{lbm moisture/hr-ft}^2$$

From the drying curve, the final drying rate, N_2, is

$$N_2 = 0.5\ \text{lbm moisture/hr-ft}^2$$

The initial moisture content, X_1, is the critical moisture content, X_c.

$$X_1 = X_c = 0.125\ \text{lbm moisture/lbm dry solids}$$

From the drying curve, the final moisture content, X_2, is

$$X_2 = 0.10\ \text{lbm moisture/lbm dry solids}$$

Since the drying curve in falling rate period I is linear, the total drying time, t_I, is

$$\begin{aligned} t_I &= \left(\frac{m_s}{A}\right)\left(\frac{X_1-X_2}{N_1-N_2}\right)\ln\frac{N_1}{N_2} \\ &= \left(\frac{1\ \text{lb}_\text{m}\ \text{dry solids}}{0.4\ \text{ft}^2}\right)\left(\frac{0.125\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{lb}_\text{m}\ \text{dry solids}} - 0.10\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{lb}_\text{m}\ \text{dry solids}}}{0.8\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{hr-ft}^2} - 0.5\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{hr-ft}^2}}\right)\left(\ln\frac{0.8\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{hr-ft}^2}}{0.5\ \dfrac{\text{lb}_\text{m}\ \text{moisture}}{\text{hr-ft}^2}}\right) \\ &= 0.098\ \text{hr}\quad (0.10\ \text{hr}) \end{aligned}$$

Falling Rate Period II:

In falling rate period II, the drying rate N_{II}, is given as

$$N_{\text{II}} = e^{5X}$$

From the drying curve, the initial moisture content, X_1, is

$$X_1 = 0.10 \text{ lbm moisture/lbm dry solids}$$

From the problem statement, the final material has 2.5% moisture. The final moisture content, X_2, is

$$\begin{aligned} X_1 &= \%\,\text{moisture in solids} = \frac{m_w}{m_s} = \frac{0.025 \text{ lb}_\text{m} \text{ moisture}}{(1-0.025) \text{ lb}_\text{m} \text{ dry solids}} \\ &= 0.026 \text{ lb}_\text{m}\text{moisture/lb}_\text{m}\text{dry solids} \end{aligned}$$

In falling rate period II, the drying time, t_{II}, is

$$\begin{aligned} t_{II} &= \left(\frac{m_s}{A}\right) \int_{X_2}^{X_1} \frac{dX}{N} = \left(\frac{m_s}{A}\right) \int_{X_2}^{X_1} N^{-1}\, dX \\ &= \left(\frac{1 \text{ lb}_\text{m} \text{ dry solids}}{0.4 \text{ ft}^2}\right) \left(\int_{0.26}^{0.10} e^{-5\,X}\, dX \; \frac{\text{hr-ft}^2}{\text{lb}_\text{m} \text{ moisture}} \right) \\ &= \left(\frac{1}{0.4}\right) \left(\left(-\frac{1}{5}\right) e^{-5X} \Big|_{0.026}^{0.10} \right) \\ &= \left(\frac{1}{0.4}\right) \left(\left(-\frac{1}{5}\right) e^{-(5)(0.10)} - \left(\left(-\frac{1}{5}\right) e^{-(5)(0.026)} \right) \right) \\ &= \left(\frac{1}{0.4}\right) (-0.1213 - (-0.1756)) \\ &= 0.1358 \text{ hr} \quad (0.14 \text{ hr}) \end{aligned}$$

The total drying time, t_D, is the sum of the drying times for each period.

$$\begin{aligned} t_D &= t_c + t_{\text{I}} + t_{\text{II}} = 0.52 \text{ hr} + 0.10 \text{ hr} + 0.14 \text{ hr} \\ &= 0.76 \text{ hr} \end{aligned}$$

The answer is (C).
4.

The stormwater is a solvent. The nutrients in the farmland's soil are soluble solutes. The water washes away some or all of the solutes into the watershed. This process is called leaching. Nutrients like nitrogen-rich fertilizers are leached into the watershed. Option A is correct.

Distillation occurs when a liquid is converted to a vapor by vaporization. Sublimation occurs when a solid directly converts to a vapor. Chemosynthesis is the biological conversion of one or more carbon-containing molecules (usually carbon dioxide or methane) and nutrients into organic matter using the oxidation of inorganic compounds.

The answer is (A).

5.

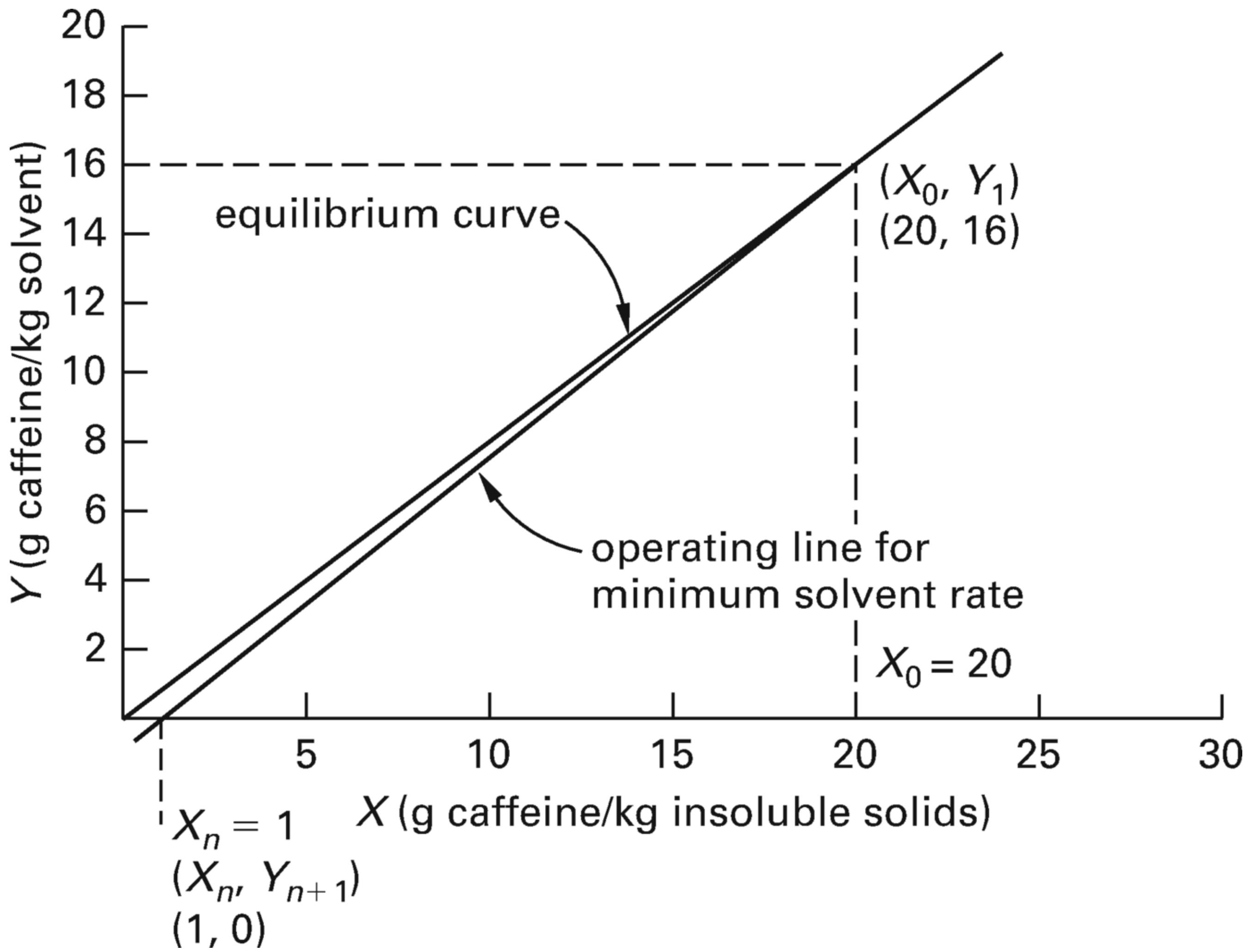
To find the minimum solvent required, use the McCabe-Thiele method to draw the operating curve.

The data given in the problem are shown in the following illustration.

The operating equation for leaching is

$$Y_{n+1} = \left(\frac{L_n}{V_{n+1}}\right) X_n + \frac{V_a Y_a - L_a X_a}{V_{n+1}}$$

The slope of the operating line represents the ratio of insoluble solids to solvent flow rates. For the operating line, only enough information is available to plot one point at $(X_1, Y_{n+1}) = (1, 0)$. However, the minimum solvent flow rate is related to the slope of the operating line that intersects the equilibrium curve (to create a pinch point) at the point where $X_0 = 20$ g caffeine/kg insoluble solids. Using these points and drawing this operating line on the equilibrium diagram reveals the corresponding value of $Y_1 = 16$ g caffeine/kg solvent.



The slope is

$$\begin{aligned}\text{slope} &= \frac{L_n}{V_{n+1}} = \frac{\Delta Y}{\Delta X} = \frac{Y_1 - Y_{n+1}}{X_0 - X_n} \\ &= \frac{16\,\frac{\text{g caffeine}}{\text{kg solvent}} - 0\,\frac{\text{g caffeine}}{\text{kg solvent}}}{\left(\begin{array}{c}20\,\frac{\text{g caffeine}}{\text{kg insoluble solids}} \\ -1\,\frac{\text{g caffeine}}{\text{kg insoluble solids}}\end{array}\right)} \\ &= 0.84 \text{ kg insoluble solids/kg solvent}\end{aligned}$$

The minimum amount of solvent needed is the reciprocal of the minimum slope.

$$\begin{aligned}\frac{L_n}{V_{n+1}} &= \frac{1}{\text{slope}} = \frac{1}{0.84\,\frac{\text{kg insoluble solids}}{\text{kg solvent}}} \\ &= 1.2 \text{ kg solvent/kg insoluble solids}\end{aligned}$$

Therefore, the separation requires a minimum of 1.2 kg of solvent per kg of coffee beans.

The answer is (C).
6.

Equilibrium in a leaching process is irrelevant to the underflow or overflow concentration at any stage; equilibrium is reached when all the solute is solved within the solvent in the liquid phase.

The answer is (C).

7.

The mass of potassium chloride in the saturated solution at the original temperature of 212°F, $m_{KCl,212}$, is known to be 3300 lbm. The solubility of potassium chloride at 212°F, $K_{KCl,212}$, is 56.37 g per 100 g of solution. The mass of water needed to dissolve the potassium chloride in the original solution is

$$m_{\text{water}} = \frac{m_{\text{KCl},212}}{K_{\text{KCl},212}} = \frac{3300\ \text{lbm}}{\frac{56.37\ \text{g}}{100\ \text{g}}} = 5854\ \text{lbm}$$

The mass of potassium chloride dissolved in the same amount of water at 176°F is

$$\begin{aligned} m_{\text{KCl},176} &= m_{\text{water}} K_{\text{KCl},176} = (5854\ \text{lbm}) \left(\tfrac{48.5\ \text{g}}{100\ \text{g}} \right) \\ &= 2839\ \text{lbm} \end{aligned}$$

The loss in the dissolved mass from 212°F to 176°F is the mass of potassium chloride that crystallizes.

$$\begin{aligned} m_{\text{KCl,crystal}} &= m_{\text{KCl},212} - m_{\text{KCl},176} \\ &= 3300\ \text{lbm} - 2839\ \text{lbm} \\ &= 461\ \text{lbm} \quad (460\ \text{lbm}) \end{aligned}$$

The answer is (B).

8.

Dissolved solids and salts contain very fine particles. Of the filtration processes listed, only reverse osmosis and electrodialysis reversal can remove particles as small as these from a liquid.

The answer is (D).