

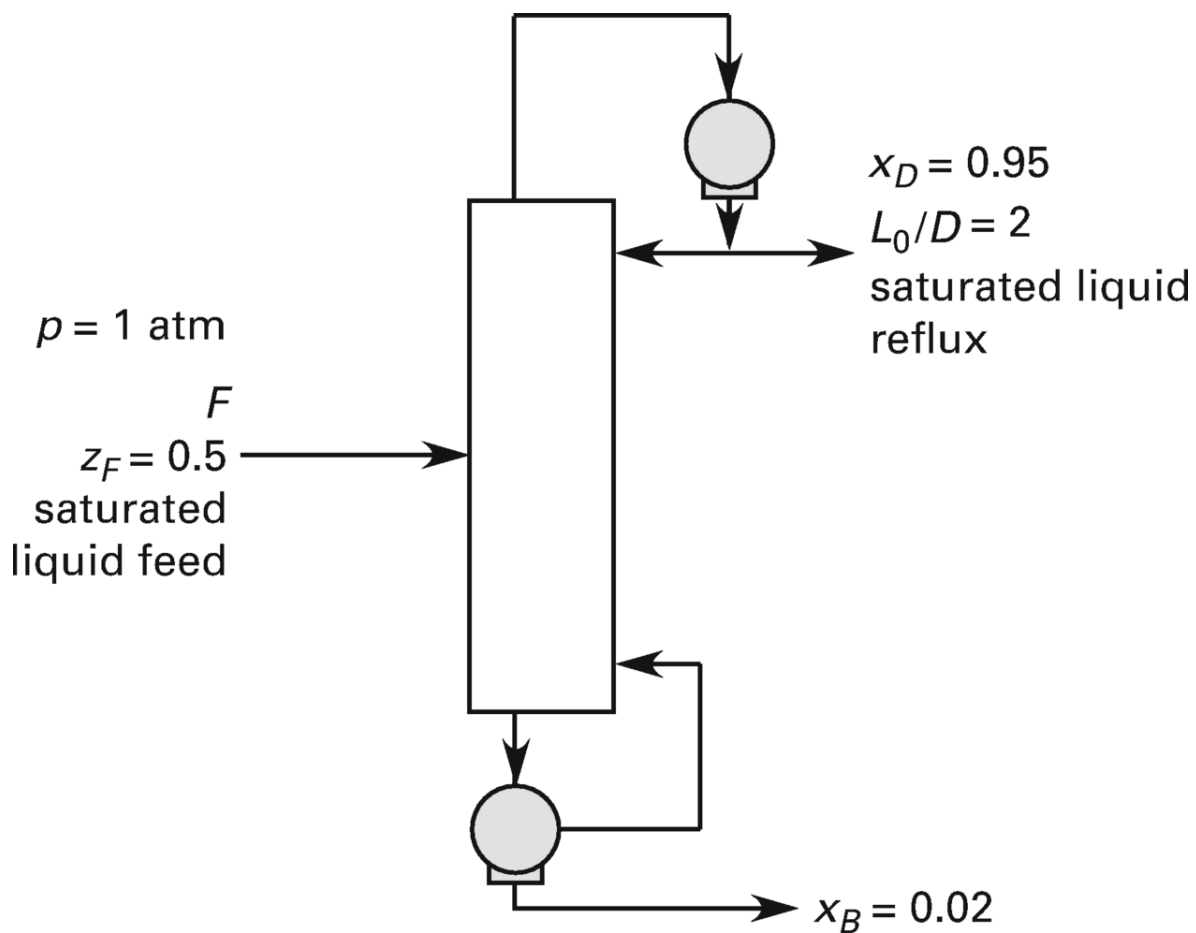
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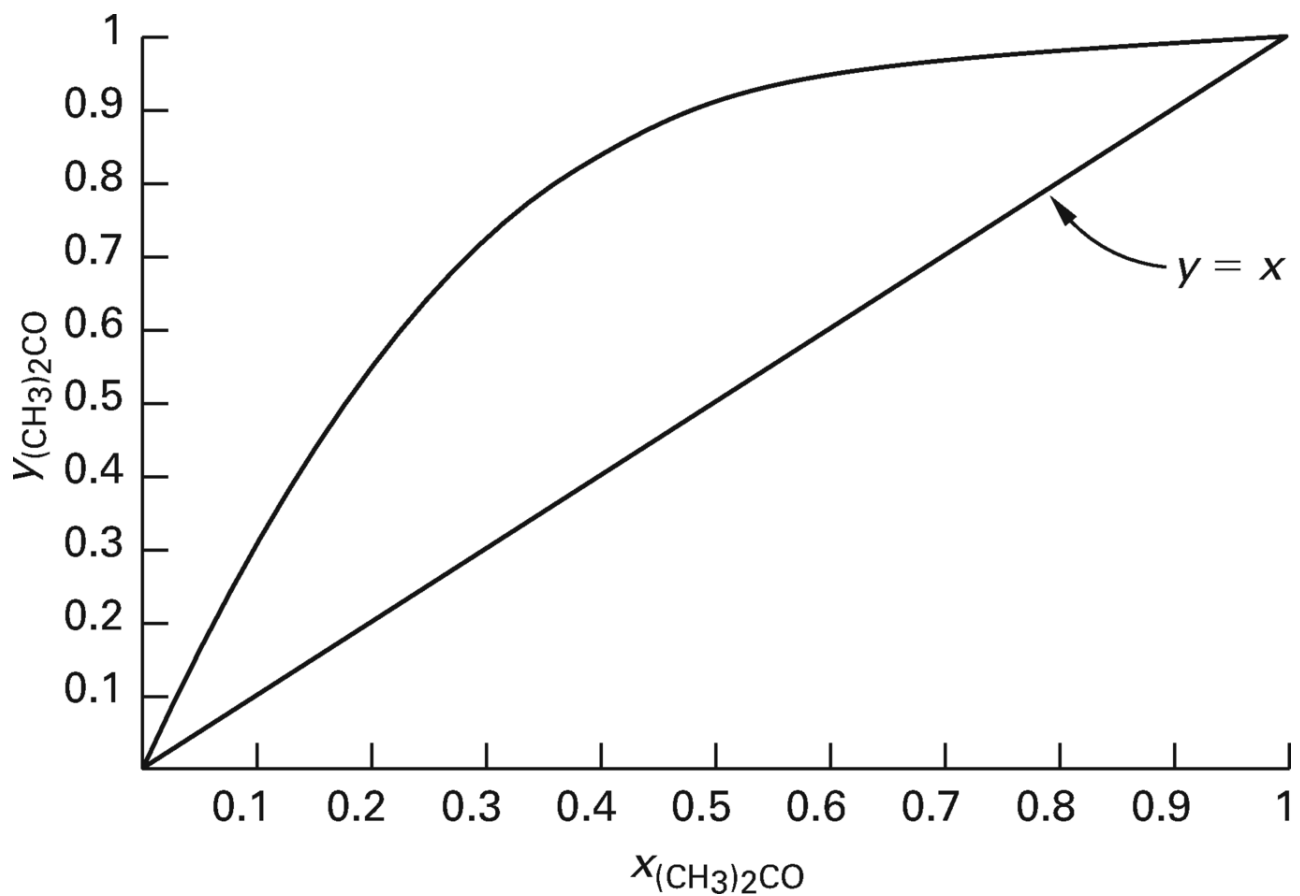
[Chapter 24. Vapor-Liquid Processes](#)

Practice Problems

[1.](#)

A distillation column with a total condenser and a partial reboiler is used to separate an acetone-acetic acid mixture. The feed,  $F$ , is saturated liquid containing 50 mol% acetone ( $z_F = 0.5$ ). The desired distillate composition is 95 mol% acetone ( $x_D = 0.95$ ), and the desired bottoms composition is 2 mol% acetone ( $x_B = 0.02$ ). The external reflux ratio,  $L_0/D$ , is 2, and the reflux is a saturated liquid. The column pressure is 1 atm. The equilibrium data are shown.



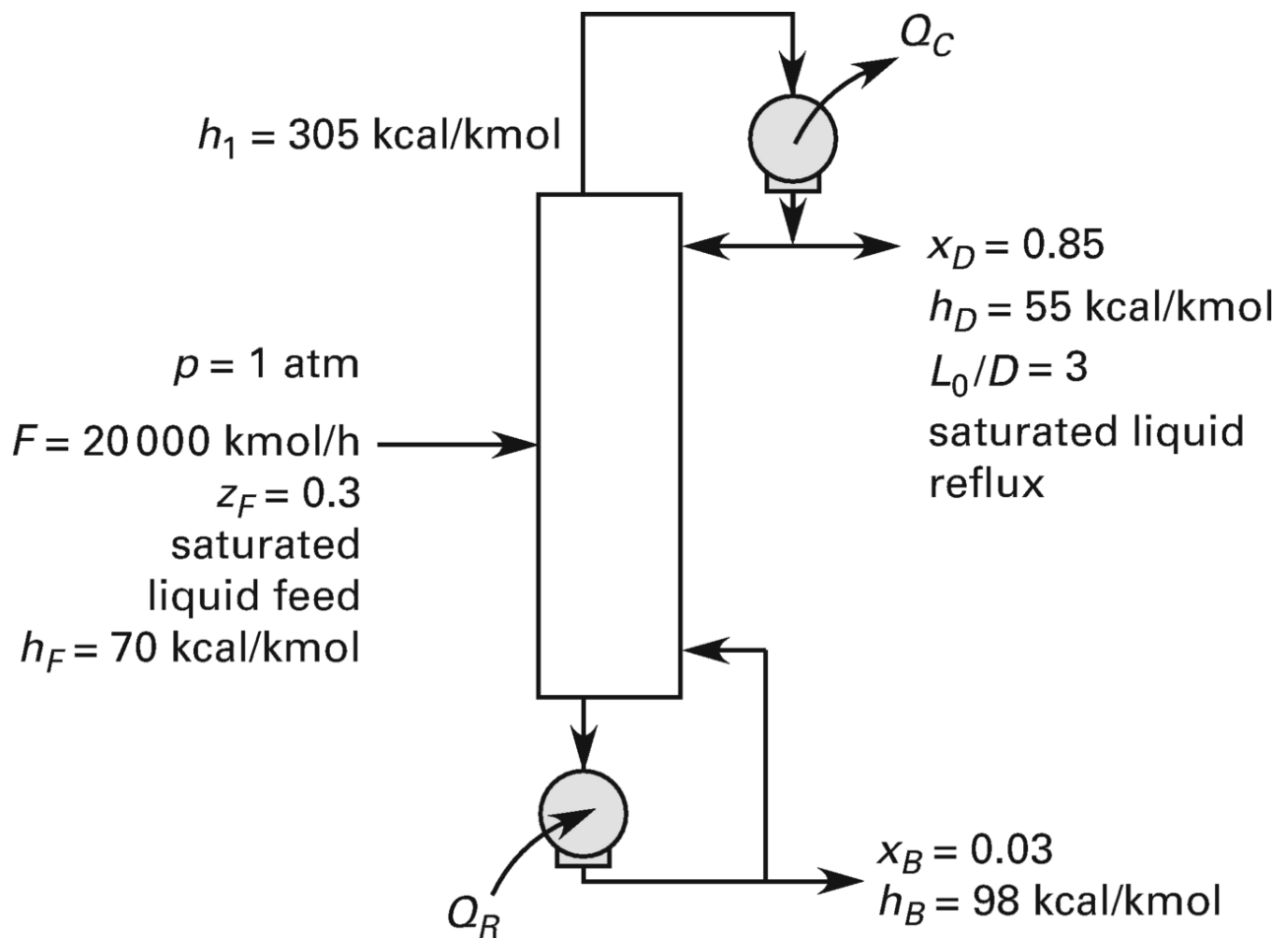


Assuming constant molar overflow, what is the optimum number of stages required to achieve the separation?

- (A)  
4 equilibrium stages and 1 partial reboiler
- (B)  
5 equilibrium stages and 1 partial reboiler
- (C)  
5 equilibrium stages
- (D)  
6 equilibrium stages and 1 partial reboiler

[2.](#)

A distillation column with a total condenser and a partial reboiler is used to separate an ethanol-water mixture at 40°C. The feed,  $F$ , is saturated liquid containing 30 mol% ethanol ( $z_F = 0.3$ ). The design distillate composition is 85 mol% ethanol ( $x_D = 0.85$ ), and the design bottoms composition is 3 mol% ethanol ( $x_B = 0.03$ ). The external reflux ratio,  $L_0/D$ , is 3, and the reflux is a saturated liquid. The column pressure is 1 atm. Refer to the illustration for additional data, including enthalpies,  $h$ , of the streams.



What is the heat duty of the reboiler?

(A)

$0.28 \times 10^6 \text{ kcal/h}$

(B)

$5.47 \times 10^6 \text{ kcal/h}$

(C)

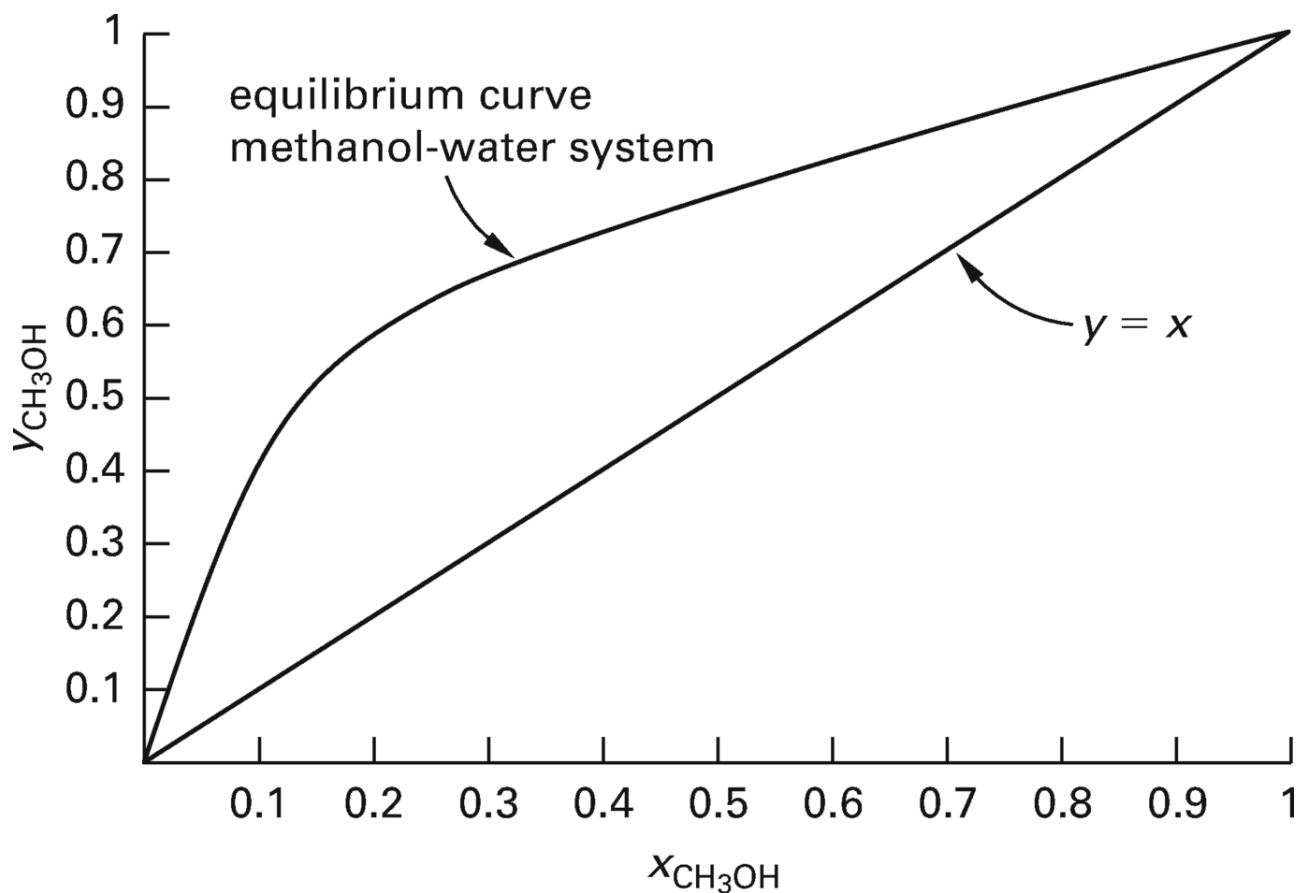
$6.87 \times 10^6 \text{ kcal/h}$

(D)

$8.27 \times 10^6 \text{ kcal/h}$

3.

A byproduct stream contains 20 mol% methanol in water. An equilibrium-stage distillation column is needed to remove the methanol from this stream and to recycle the water stream to another process. The column operates at 1 atm, using 50% more than the minimum internal reflux ratio, a total condenser, and a partial reboiler. The other process can tolerate a maximum of 2 mol% methanol in the water stream. The methanol, containing as much as 10 mol% water, can also be sold to a commercial recycler. The byproduct stream flows at 80 000 mol/h and is approximately 30% vapor at 1 atm. The equilibrium data are shown.



The optimum feed location is at stage

(A)

1

(B)

2

(C)

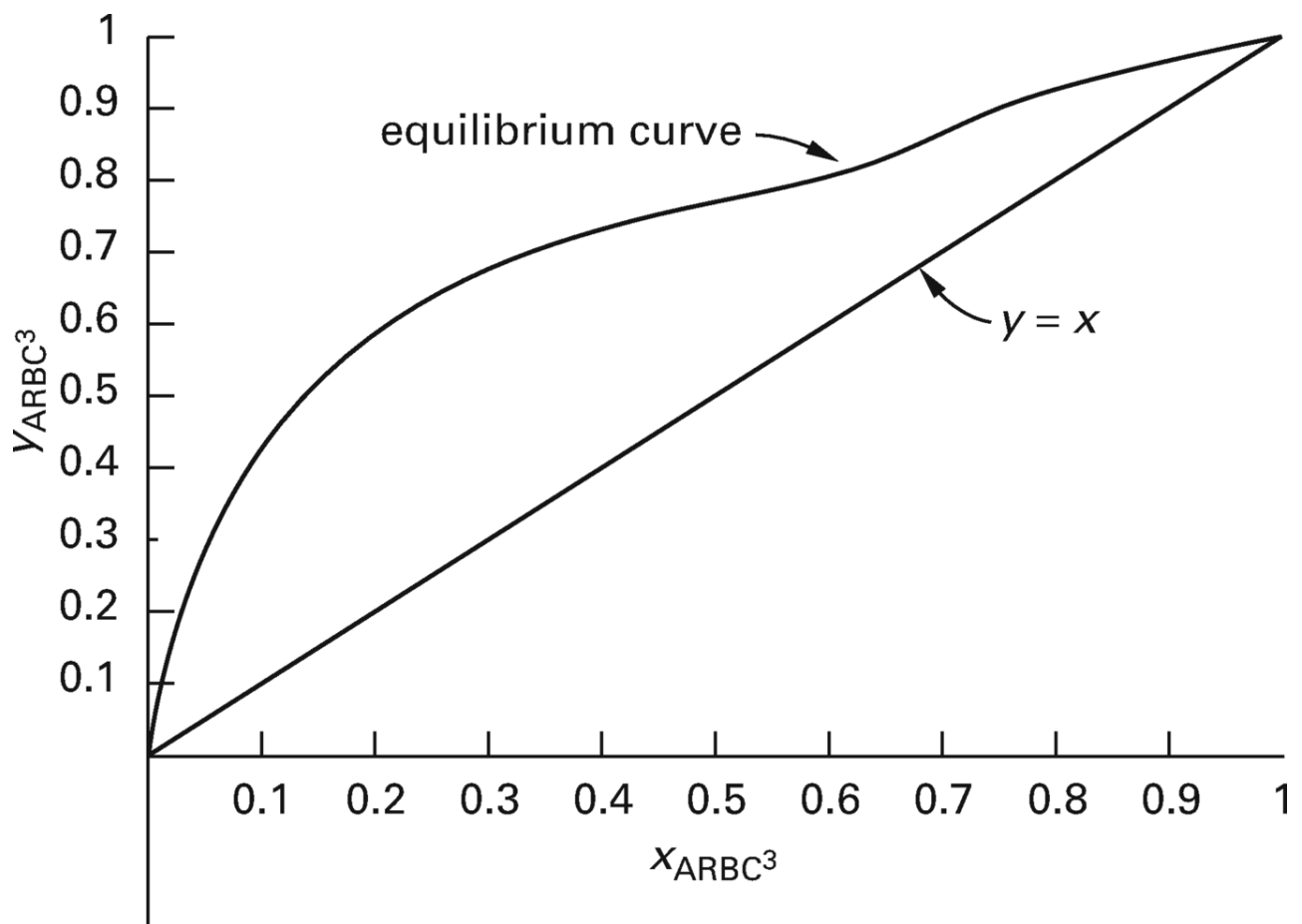
3

(D)

4

[4.](#)

A new material, ARBC<sup>3</sup>, leaves the synthesis process mixed with 55 mol% water. The temperature of the ARBC<sup>3</sup>-water mixture is 80°C, and the molar flow rate is 5000 kmol/h. Distillation is being evaluated as a means of removing the water from this process stream. Empirical equilibrium data and several enthalpies of the feed composition are available. The enthalpy of the feed,  $H_F$ , at 80°C and 1 atm is 45 kcal/kmol. The enthalpy of the saturated vapor,  $H_V$ , at 1 atm pressure is 900 kcal/kmol. At 1 atm, the saturated liquid enthalpy,  $H_L$ , is 175 kcal/kmol. The target distillate composition,  $x_D$ , is 90 mol% ARBC<sup>3</sup>, and the desired bottoms composition,  $x_B$ , is 3 mol% ARBC<sup>3</sup>. As a starting point, a column with a total condenser and a partial reboiler is being evaluated. The external reflux ratio,  $L_0/D$ , is  $\frac{4}{3}$ , and the liquid reflux is saturated. Constant molar overflow is a valid assumption, as is operation at atmospheric pressure.



Counting from the top of the column, where is the optimum feed location?

(A)

stage 3

(B)

stage 4

(C)

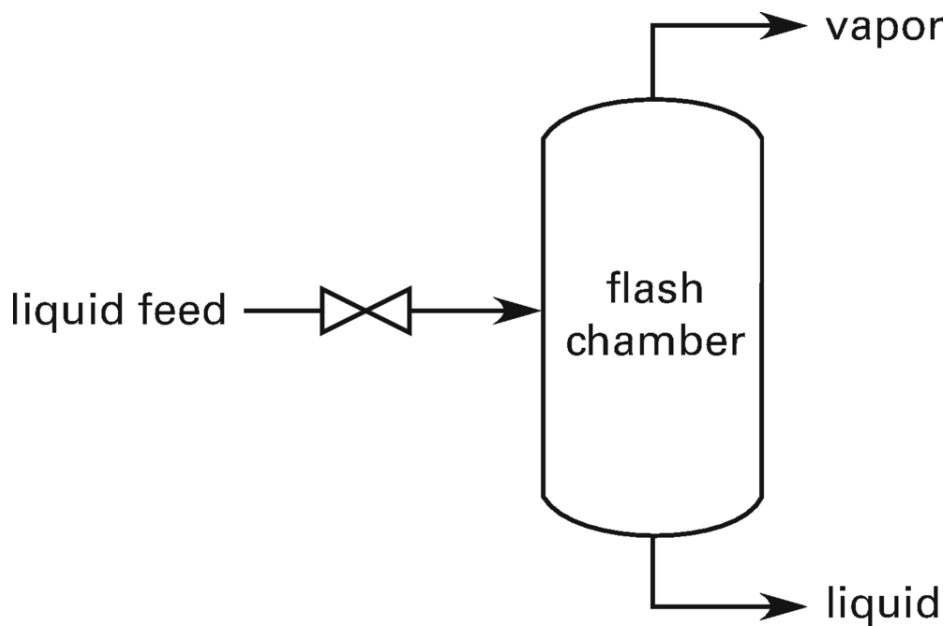
stage 6

(D)

stage 8

[5.](#)

A liquid stream is fed into a flash chamber. The output stream is composed of a vapor component and a liquid component.



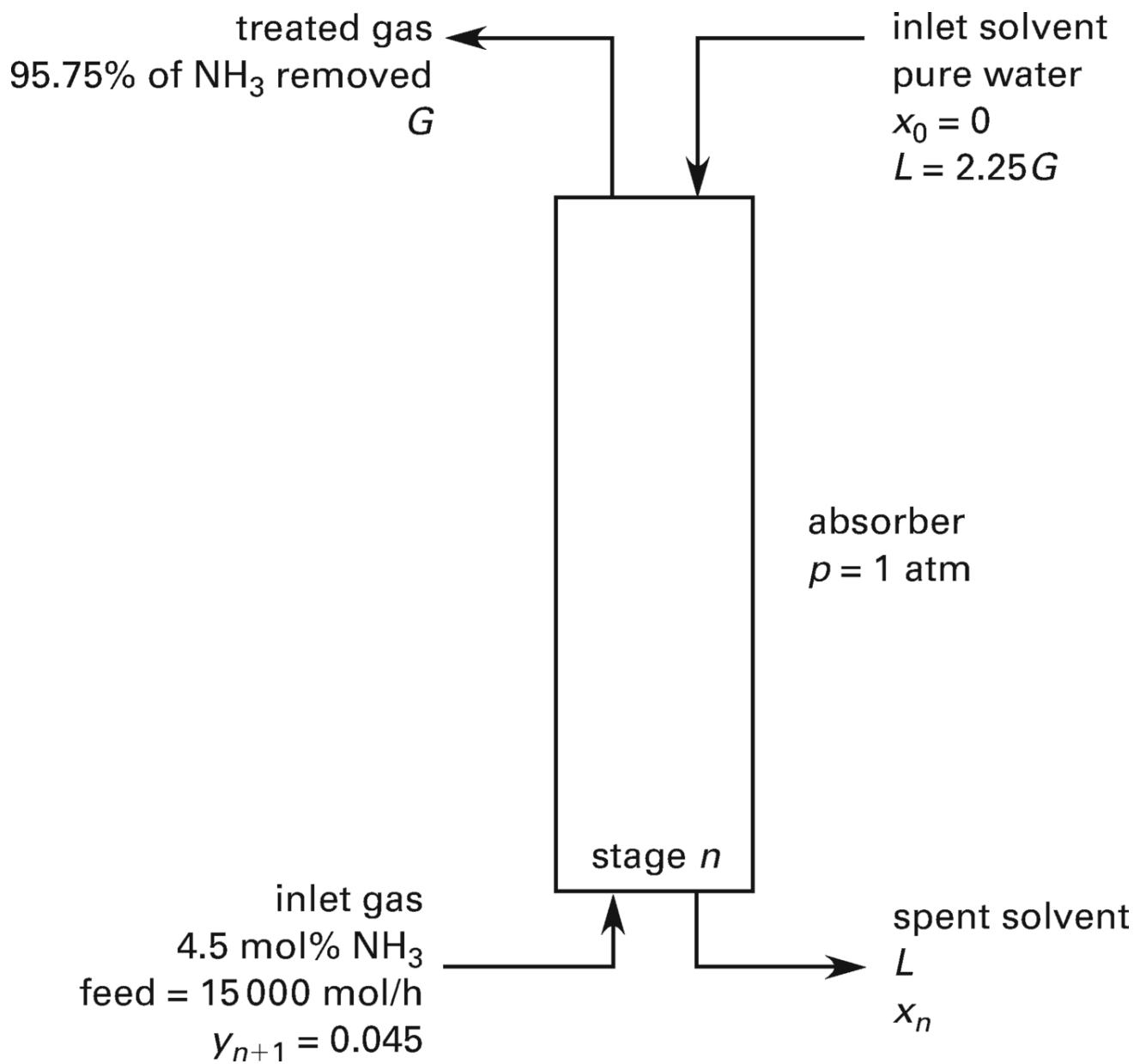
This process is

- (A)  
distillation
  - (B)  
leaching
  - (C)  
filtration
  - (D)  
sublimation
- [6.](#)

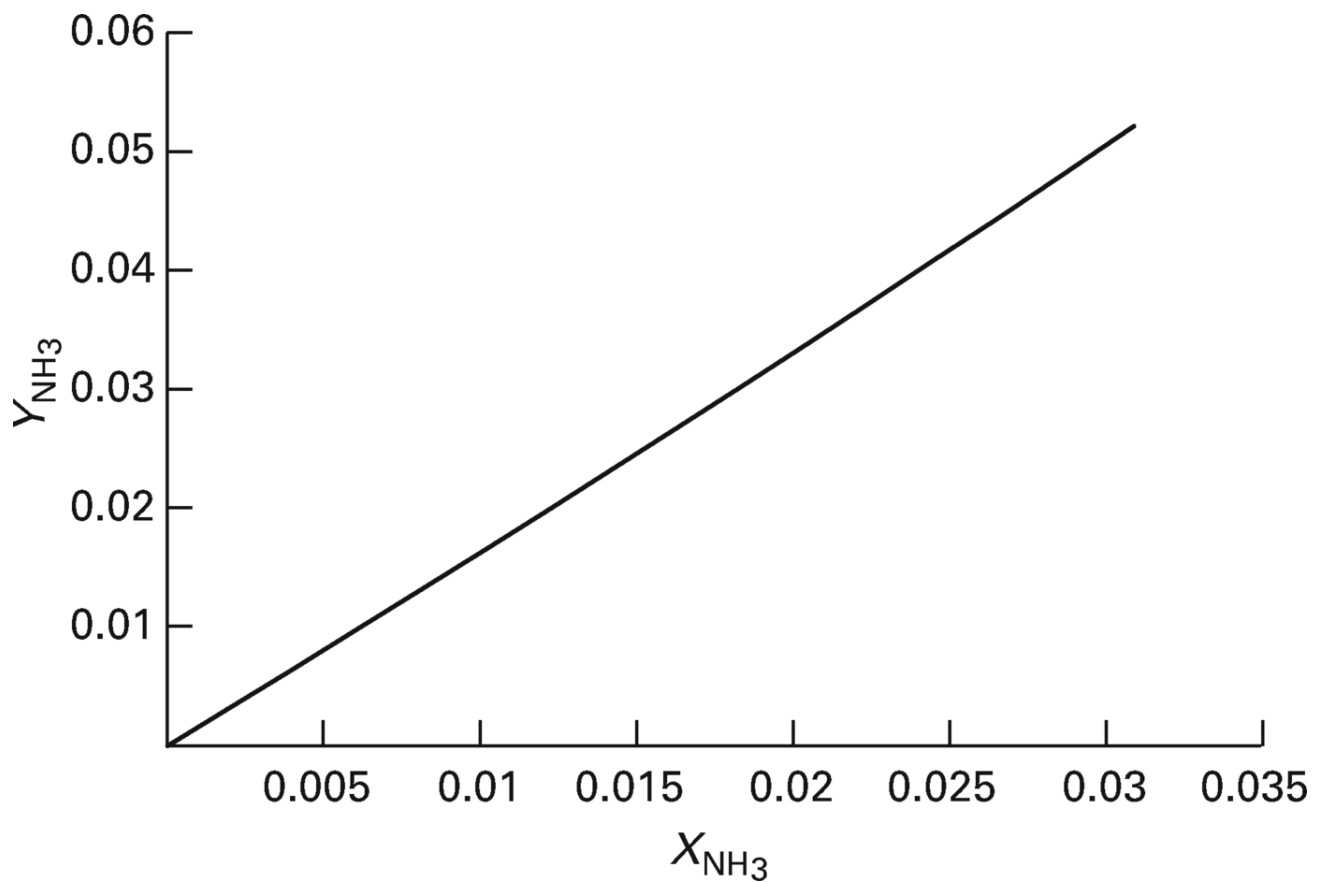
A mixture of hydrocarbons is flash distilled at 400°C and 40 atm. The feed rate is 100 mol/min, and the vapor flow rate is 55 mol/min. The feed composition for component A in the hydrocarbon mixture is 0.30, and the vapor-liquid equilibrium constant is 1.25. Most nearly, the vapor composition of component A is

- (A)  
0.26
  - (B)  
0.33
  - (C)  
0.41
  - (D)  
0.53
- [7.](#)

An absorption tower uses water to remove ammonia from air. The tower operates at 1 atm and 27°C. Its inlet water is pure ( $x_0 = 0$ ), and its inlet gas has 0.045 mole fraction of ammonia ( $y_{n+1} = 0.045$ ). The tower removes 95.75% of the ammonia from the air. The feed rate is 15 000 mol/h, and the liquid-to-gas flow-rate ratio,  $L/G$ , is 2.25.



The equilibrium data for the ammonia-water system at 1 atm, in terms of mole ratios of ammonia,  $X$  and  $Y$ , are given by the following diagram.



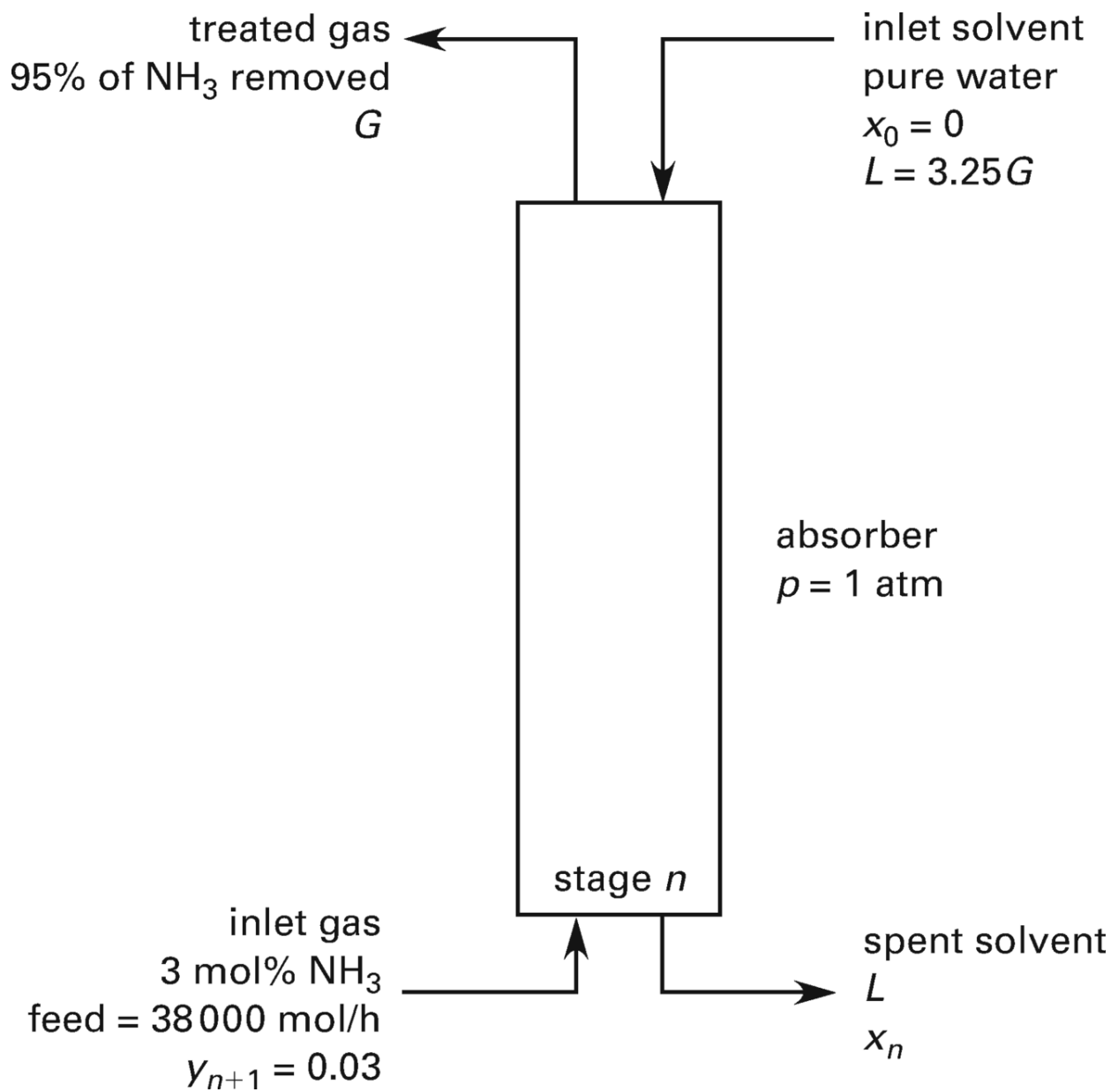
How many equilibrium states does this separation require?

- (A)  
6 equilibrium stages
- (B)  
7 equilibrium stages
- (C)  
8 equilibrium stages
- (D)  
9 equilibrium stages

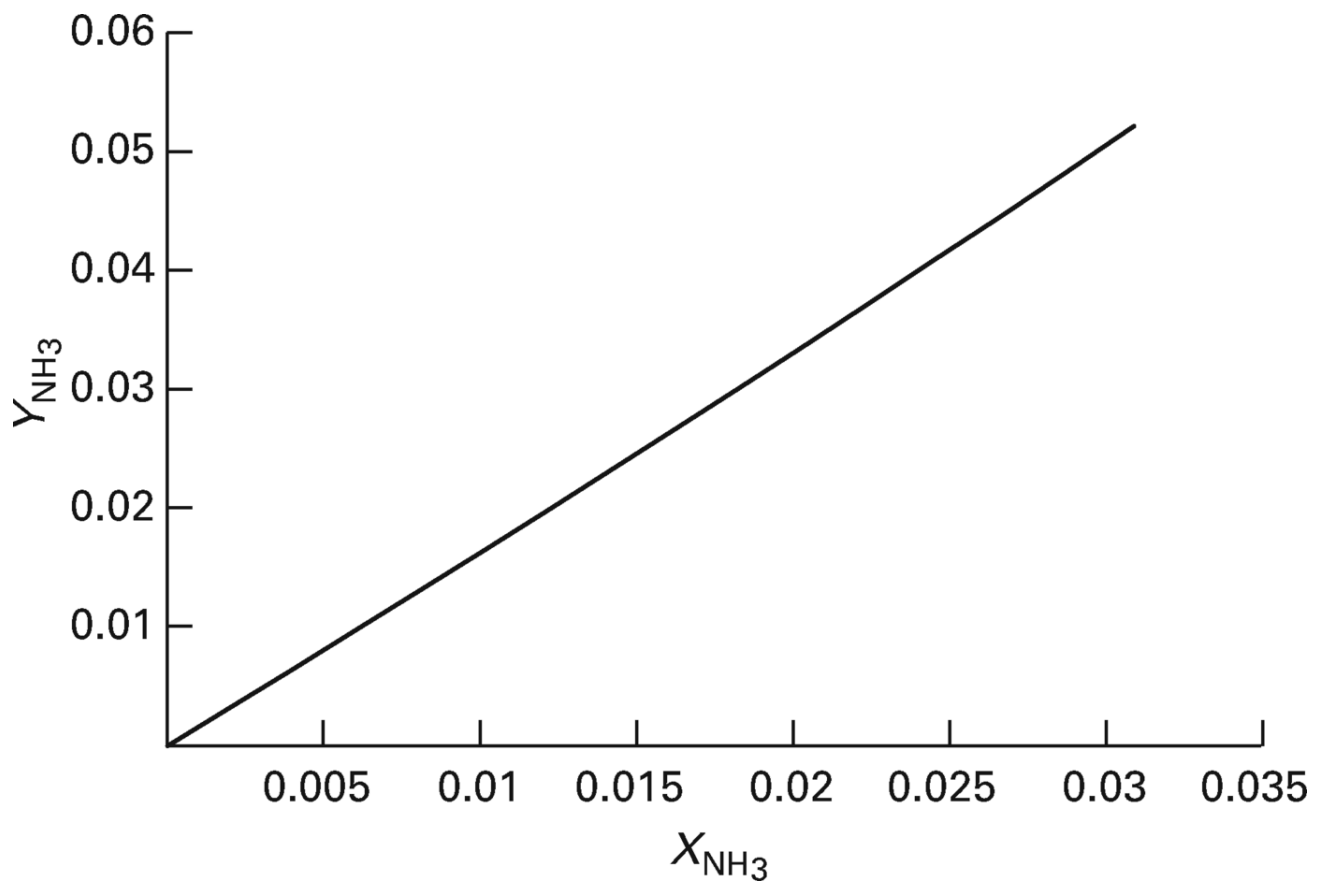
[8.](#)

An absorption tower uses water to remove ammonia from air. The tower operates at 1 atm and 27°C. The inlet water is pure ( $x_0 = 0$ ). The inlet gas is 0.03 mole fraction ammonia ( $y_{n+1} = 0.03$ ). The tower is required to remove 95% of the ammonia from the air. The inlet gas feed rate is 38 000 mol/h, and the liquid-to-gas flow rate ratio,  $L/G$ , is 3.25.





The equilibrium data for the ammonia-water system at 1 atm, in terms of the mole ratios of ammonia,  $X$  and  $Y$ , are given in the following diagram.



Approximately how many equilibrium stages does this separation require?

(A)

$$2\frac{1}{4}$$

(B)

$$3\frac{3}{5}$$

(C)

4

(D)

$$4\frac{1}{2}$$

9.

A mixture of water (component A) and ethanol (component B) containing 20 mol% of ethanol is maintained at a fixed temperature. At saturation, the partial vapor pressure of water is 0.552 psi, and that of ethanol is 2.848 psi. Assume the system is ideal and that it follows Raoult's law. Most nearly, the total pressure of the system is

(A)

0.47 psi

(B)

1.0 psi

(C)

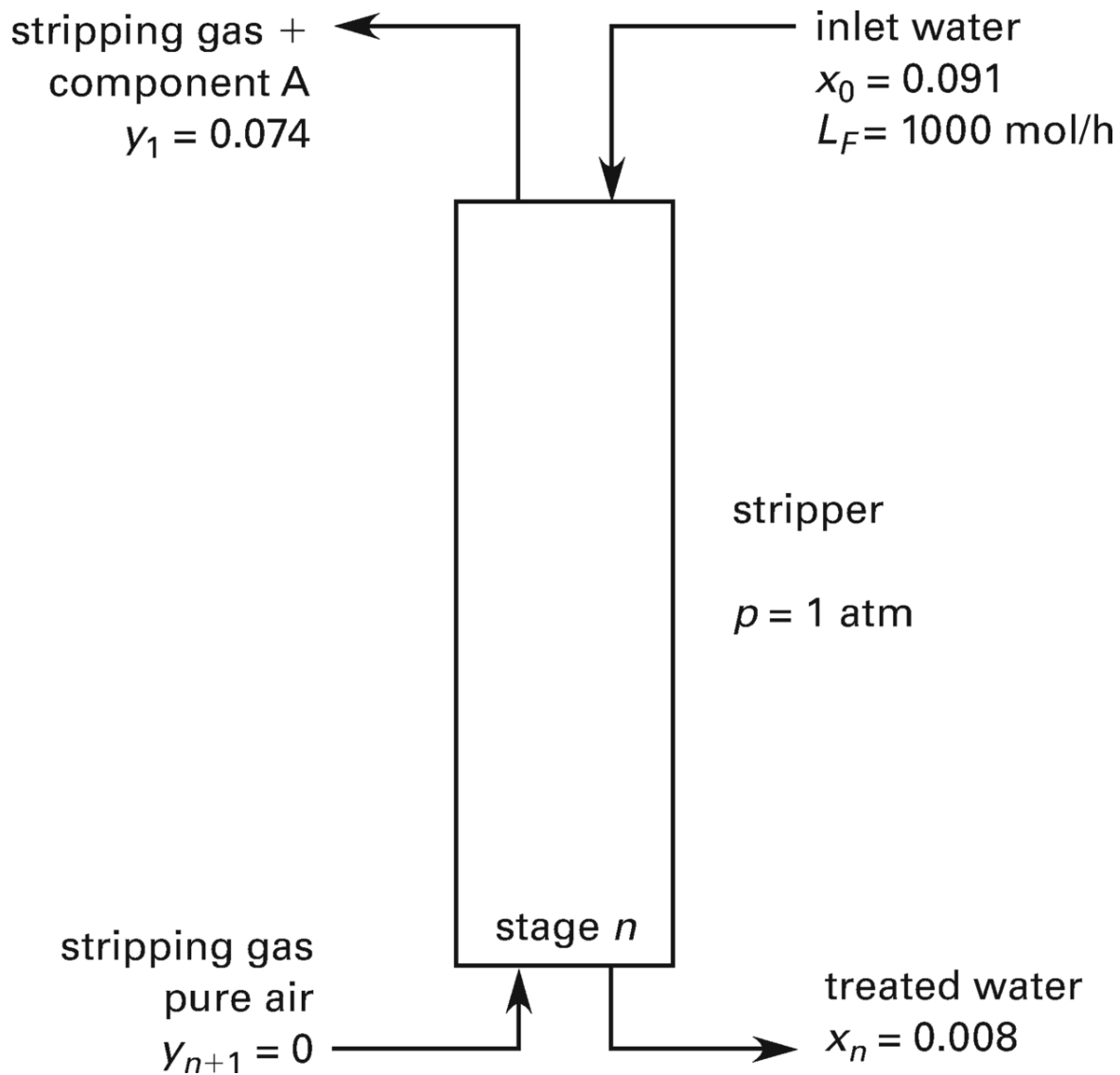
2.3 psi

(D)

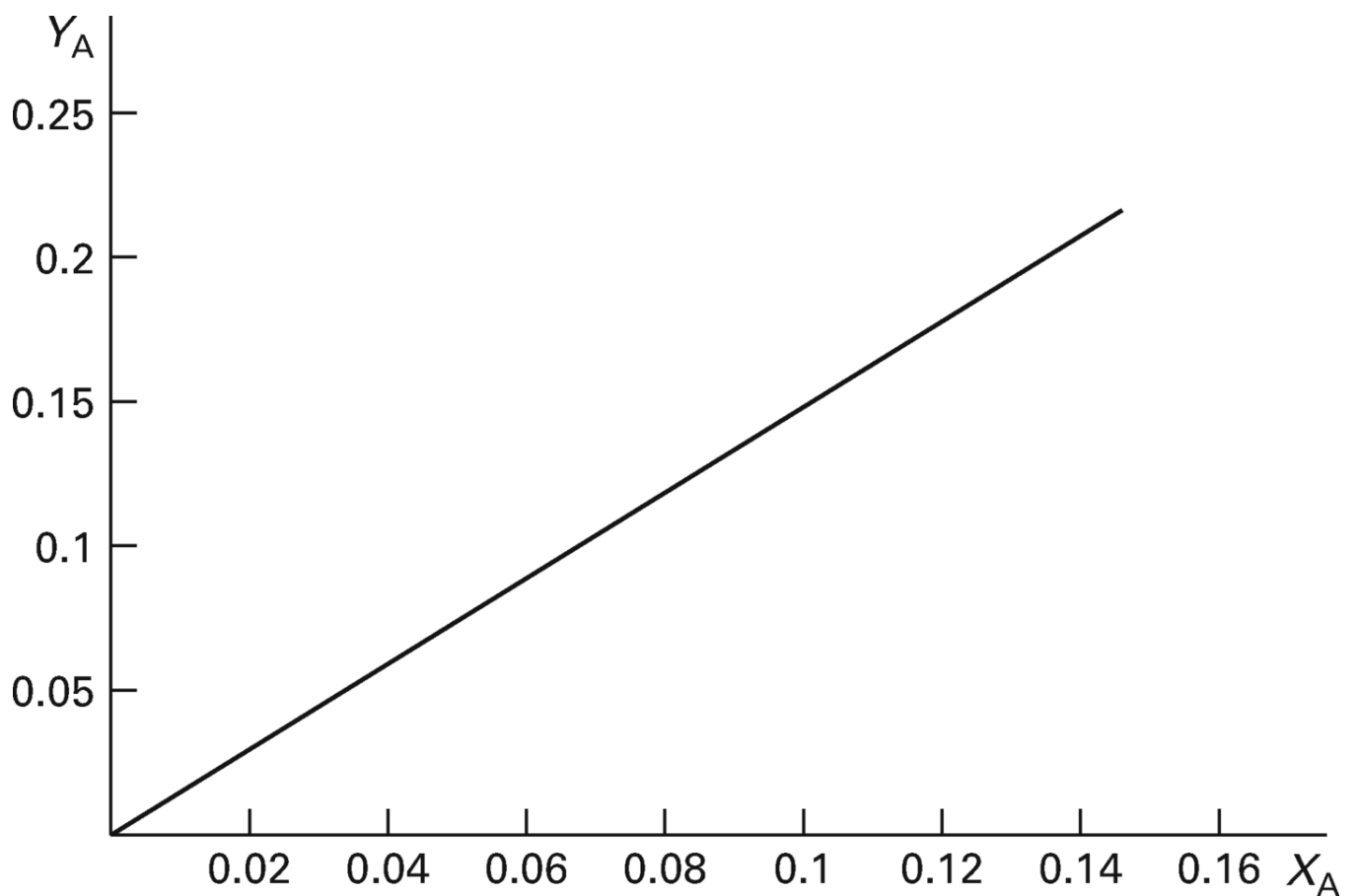
3.4 psi

[10.](#)

A gas stripper uses air to remove component A from a water stream. The tower operates at 1 atm and 30°C. The water feed rate,  $L_F$ , is 1000 mol/h. The inlet water has 9.1 mol% of component A. The stripper must reduce the mole fraction of component A in the water to 0.008. The mole fraction of component A in the air may be increased to 0.074. The constant molar overflow assumption is valid.



The equilibrium data in terms of mole ratios of component A,  $X$  and  $Y$ , are given in the following diagram.



How many equilibrium stages does this separation require?

- (A)  
4 equilibrium stages
- (B)  
5 equilibrium stages
- (C)  
6 equilibrium stages
- (D)  
7 equilibrium stages

[11.](#)

A stripping column is used to extract carbon dioxide from an aqueous solution. The mole fraction of carbon dioxide in the solution is  $8.2 \times 10^{-6}$ . The solution enters the column at 8962 lbmol/hr. The stripping is done with pure nitrogen that enters the bottom of the column at 6.2 lbmol/hr. The lean carbon dioxide stream leaves the stripping column from the bottom; the mole fraction of carbon dioxide in this stream is  $1.9 \times 10^{-6}$ . The stripping column is kept at 760 mm Hg and 250°F. At these conditions, the straight line for the equilibrium carbon dioxide–water system follows Henry's law with a slope of 3622 and an intercept of 0. Assume steady state. With  $x_1$  the mole fraction of carbon dioxide in the stream entering the column,  $x_2$  the mole fraction of carbon dioxide in the stream leaving the column, and  $x_2^*$  the mole fraction of carbon dioxide (in the aqueous phase) in equilibrium with the mole fraction of carbon dioxide in the gas phase, the number of theoretical stages,  $N$ , is given by the Kremser equation.

$$N = \frac{\ln \left( \left( 1 - \frac{\dot{L}}{m\dot{G}} \right) \left( \frac{x_1 - x_2^*}{x_2 - x_2^*} \right) + \frac{\dot{L}}{m\dot{G}} \right)}{\ln \left( \frac{m\dot{G}}{\dot{L}} \right)}$$

Using the Kremser equation, the required theoretical number of stages is

(A)

0.084

(B)

1.0

(C)

1.2

(D)

2.0

Solutions

[1.](#)

*Feed Line*

Since the feed is a saturated liquid, the feed quality,  $q$ , is 1. Therefore, the feed line is vertical at the feed composition,  $z_F = x_F = 0.5$ .

*Top (Rectifying Section) Operating Line*

From equation CHRM44035 (also *NCEES Handbook: Column Material Balance*), the operating equation for the rectifying section is

$$y = \left( \frac{L}{V} \right) x_n + \frac{x_{DD}}{V} = \left( \frac{L}{V} \right) x_n + \left( 1 - \frac{L}{V} \right) x_D$$

$\frac{L}{V}$  [slope]  
 $\left( 1 - \frac{L}{V} \right) x_D$  [y-intercept]

Using equation CHRM44036 (also *NCEES Handbook: Column Material Balance*) to calculate the internal reflux ratio,  $L/V$ , from the external reflux ratio,  $R$ ,

$$\frac{L}{V} = \frac{R}{1 + R} = \frac{2}{1 + 2} = \frac{2}{3} \quad [\text{slope}]$$

The y-intercept is

$$\left( 1 - \frac{L}{V} \right) x_D = \left( 1 - \frac{2}{3} \right) (0.95)$$

= 0.317

The top operating line can be plotted on the equilibrium diagram using the slope and y-intercept.

*Bottom (Stripping Section) Operating Line*

The operating equation for the stripping section is found from equation CHRM44037 (also *NCEES Handbook: Column Material Balance*).

$$y = \left( \frac{L'}{V'} \right) x_n + \frac{x_{BB}}{V'} = \left( \frac{L'}{V'} \right) x_n + \left( 1 - \frac{L'}{V'} \right) x_B$$

One point on the line is the intersection of the bottom operating line with the top operating line at the feed line. One additional point is needed to define the bottom operating line. Rather than determine the slope of the bottom operating line,  $\bar{L}/\bar{V}$ , the second point can be found by determining where the bottom operating line intersects the  $y = x$  line. Substitute  $y = x$  into the operating line equation.

$$y = \left(\frac{L'}{V'}\right)x + \left(1 - \frac{L'}{V'}\right)x_B$$

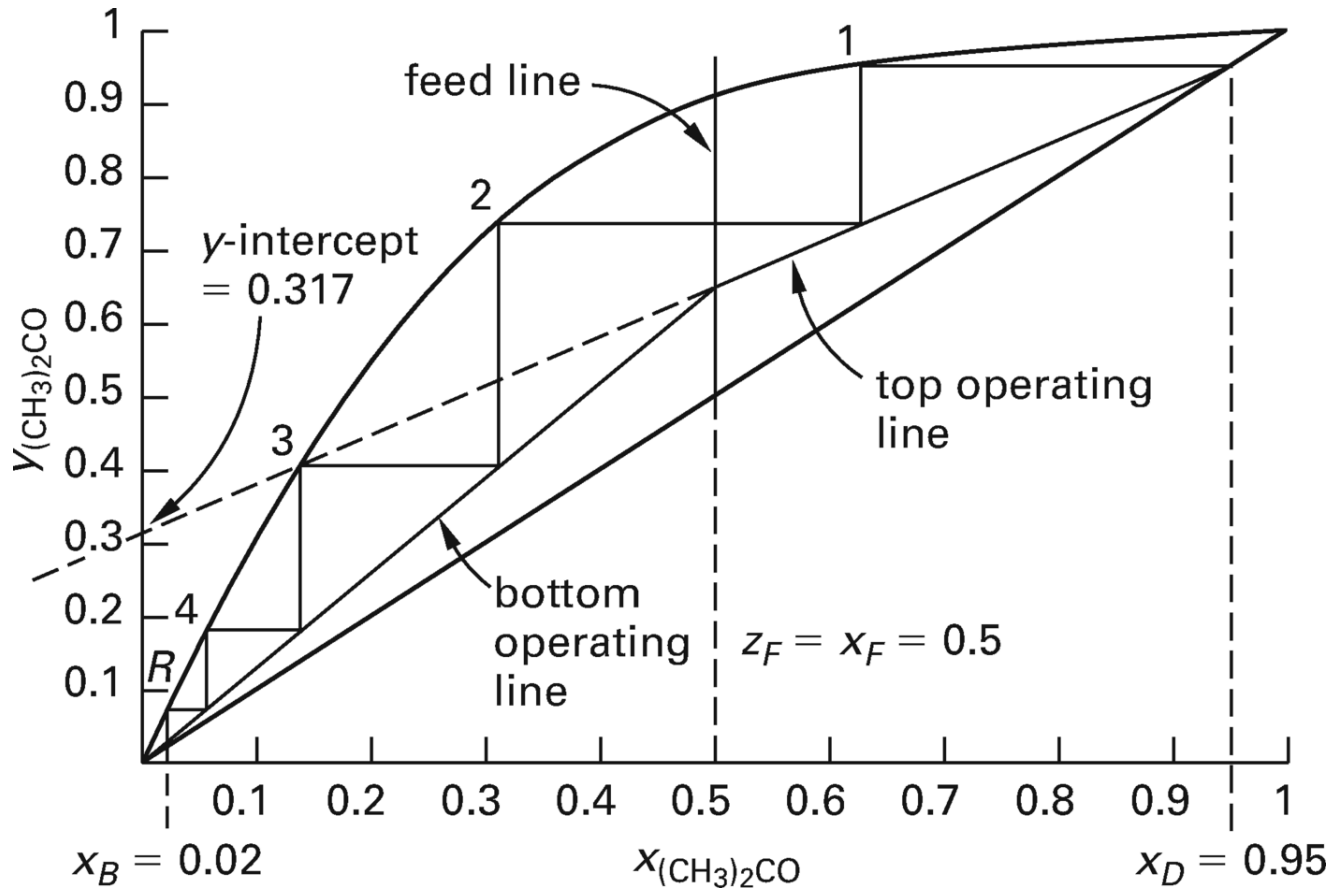
$$x = \left(\frac{L'}{V'}\right)x + \left(1 - \frac{L'}{V'}\right)x_B$$

$$x - \left(\frac{L'}{V'}\right)x = \left(1 - \frac{L'}{V'}\right)x_B$$

$$\left(1 - \frac{L'}{V'}\right)x = \left(1 - \frac{L'}{V'}\right)x_B$$

$$x = x_B = 0.02$$

Refer to the accompanying illustration. The separation requires 4 equilibrium stages and 1 partial reboiler.



The answer is (A).

2.

The distillate,  $D$ , and the bottoms,  $B$ , flow rates can be determined from the overall and ethanol mass balances.

$$F = B + D$$

$$B = F - D$$

$$Fz_F = Bx_B + Dx_D$$

$$Fz_F = (F - D)x_B + Dx_D$$

Rearrange the ethanol mass-balance equation.

$$D = F \left( \frac{z_F - x_B}{x_D - x_B} \right) = \left( 20\,000 \frac{\text{kmol}}{\text{h}} \right) \left( \frac{0.3 - 0.03}{0.85 - 0.03} \right)$$

$$= 6585 \text{ kmol/h}$$

From the overall mass balance, the bottoms flow rate is

$$B = F - D = 20\,000 \frac{\text{kmol}}{\text{h}} - 6585 \frac{\text{kmol}}{\text{h}}$$

$$= 13\,415 \text{ kmol/h}$$

The energy balance is used to determine the condenser heat duty. For the condenser, with equation CHRM44017,

$$\begin{aligned}
 Q_C &= \left(1 + \frac{L_0}{D}\right) \left(\frac{z_F - x_B}{x_D - x_B}\right) F(h_1 - h_D) \\
 &= (1 + 3) \left(\frac{0.3 - 0.03}{0.85 - 0.03}\right) \left(20\,000 \frac{\text{kmol}}{\text{h}}\right) \\
 &\quad \times \left(305 \frac{\text{kcal}}{\text{kmol}} - 55 \frac{\text{kcal}}{\text{kmol}}\right) \\
 &= 6.59 \times 10^6 \text{ kcal/h}
 \end{aligned}$$

The condenser heat duty is positive, indicating that heat is removed from the overhead stream.

For the reboiler, from equation CHRM44013, the heat duty is found from the energy balance.

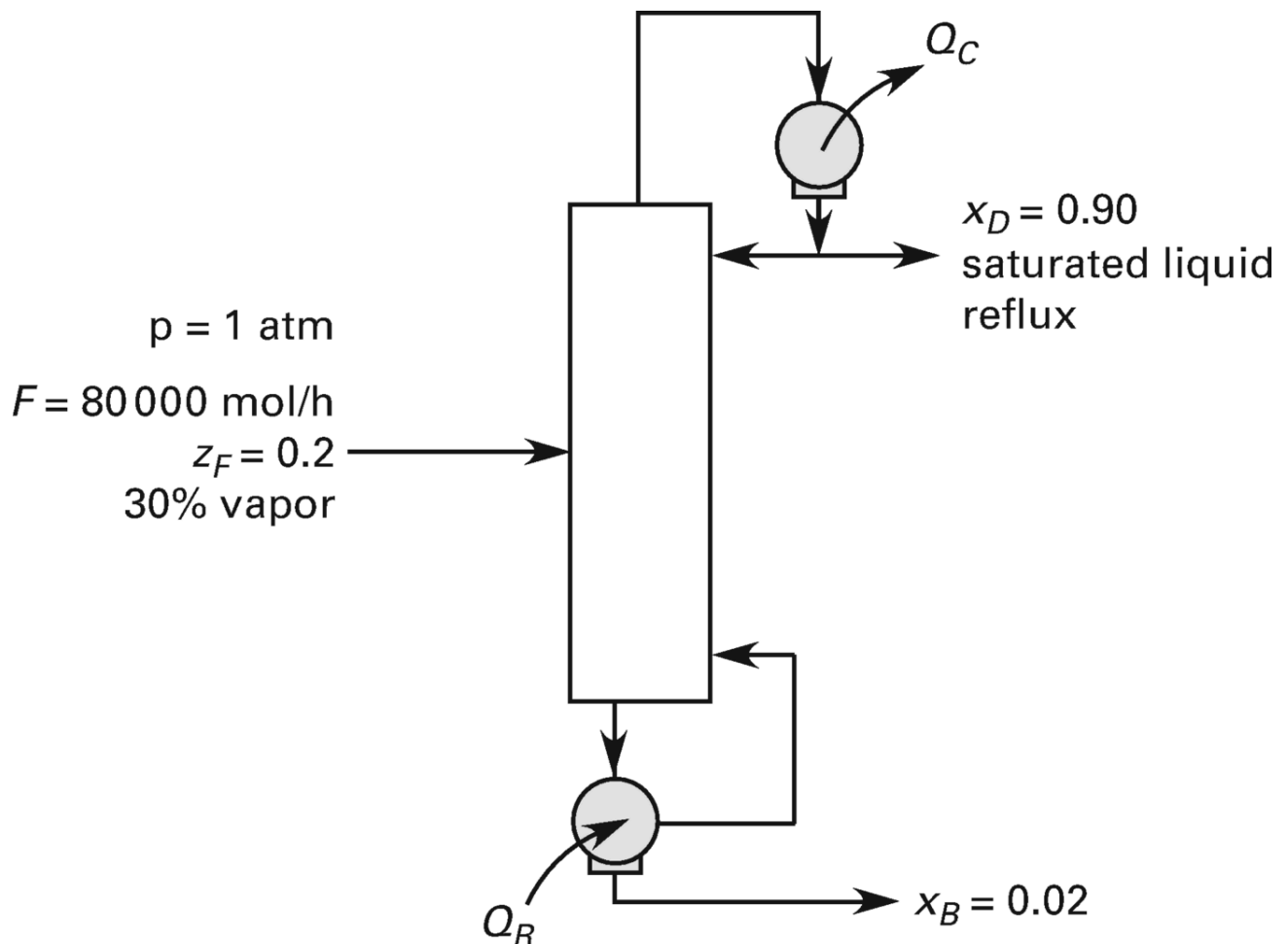
$$\begin{aligned}
 Q_R &= Dh_D + Bh_B - Fh_F + Q_C \\
 &= \left(6585 \frac{\text{kmol}}{\text{h}}\right) \left(55 \frac{\text{kcal}}{\text{kmol}}\right) \\
 &\quad + \left(13\,415 \frac{\text{kmol}}{\text{h}}\right) \left(98 \frac{\text{kcal}}{\text{kmol}}\right) \\
 &\quad - \left(20\,000 \frac{\text{kmol}}{\text{h}}\right) \left(70 \frac{\text{kcal}}{\text{kmol}}\right) + 6.59 \times 10^6 \frac{\text{kcal}}{\text{h}} \\
 &= 6.87 \times 10^6 \text{ kcal/h}
 \end{aligned}$$

The reboiler duty is positive, indicating that heat is added by the reboiler.

The answer is (C).

3.

The bottoms constitute the “water stream.” With a maximum of 2 mol% methanol,  $x_B = 0.02$ . The overhead stream (the distillate) will contain the more volatile, concentrated methanol. With a maximum of 10 mol% water allowed in this stream, the target mole fraction of methanol is  $x_D = 0.90$ .



Feed Line

One point on the feed line is the intersection of the liquid feed composition with the  $y = x$  line, or  $y = x = z_F = 0.2$ . Since the feed is 30% vapor, the feed is 70% liquid. The feed quality,  $q$ , is 0.7. From equation CHRM44044 (also *NCEES Handbook: Graphical Solution for Binary Distillation* (McCabe-Thiele Diagram)), the feed equation is

$$y = \left( \frac{q}{q-1} \right) x + \left( \frac{1}{1-q} \right) z_F$$

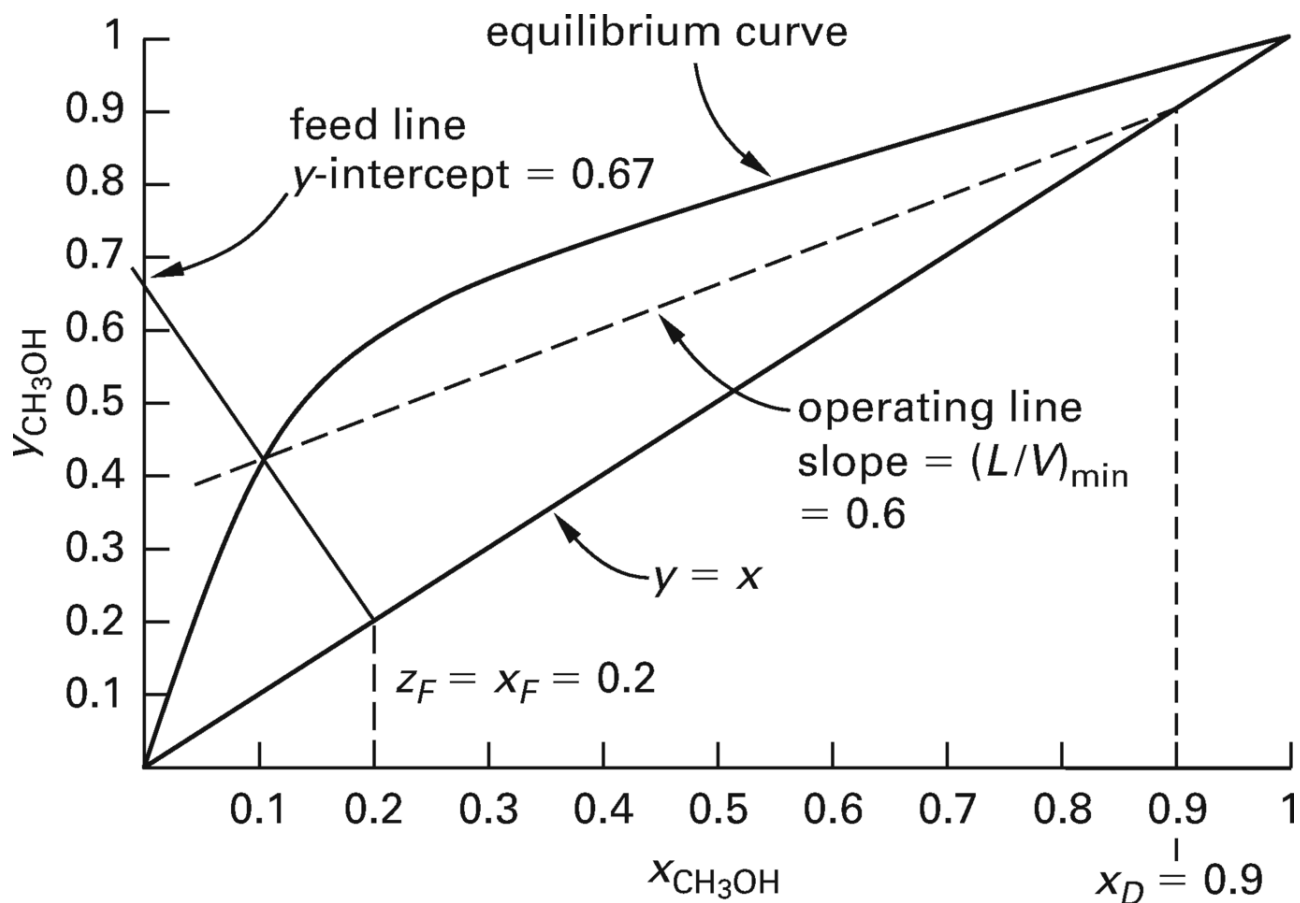
$\frac{q}{q-1}$  [slope]  
 $\left( \frac{1}{1-q} \right) z_F = \left( \frac{1}{1-0.7} \right) (0.2) = 0.67$  [y-intercept]

Using the points (0.2, 0.2) and (0, 0.67), the feed line can be plotted on the equilibrium diagram.

### Top (Rectifying Section) Operating Line

The intersection of the top operating line with the feed line at the equilibrium data creates a pinch point, which corresponds to the minimum internal reflux. The top operating line for the rectifying section at the minimum reflux ratio can be plotted on the equilibrium diagram by connecting the distillate composition ( $y = x = x_D = 0.9$ ) to the intersection of the feed line at the equilibrium data curve (at (0.1, 0.42)). The slope of this line is 0.6.

$$\left( \frac{L}{V} \right)_{\min} = \frac{\Delta y}{\Delta x} = \frac{0.9 - 0.42}{0.9 - 0.1} = 0.6$$



The problem statement specifies an internal reflux ratio 50% greater than the minimum internal reflux ratio.

$$\frac{L}{V} = 1.5 \left( \frac{L}{V} \right)_{\min} = (1.5) (0.6) = 0.9$$

With one point ( $y = x = x_D = 0.9$ ) and the operating line slope ( $L/V = 0.9$ ), the top operating line can be plotted on the equilibrium diagram. To check the operating line, calculate the y-intercept. As in *NCEES Handbook: Column Material Balance*, the top operating equation is



$$y = \left(\frac{L}{V}\right) x_n + \frac{x_D D}{V} = \left(\frac{L}{V}\right) x_n + \left(1 - \frac{L}{V}\right) x_D$$

$$\frac{L}{V} = 0.9 \quad [\text{slope}]$$

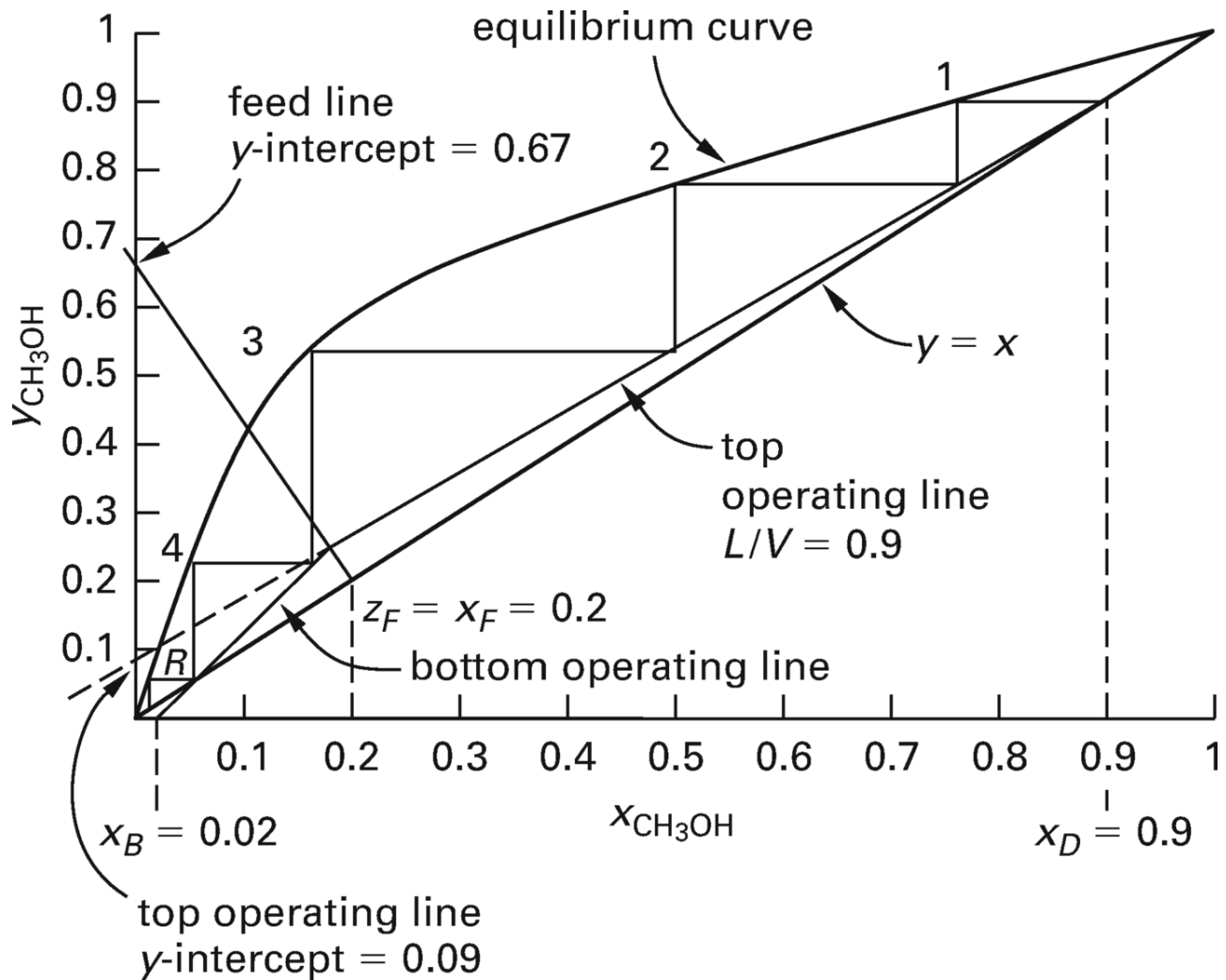
$$\left(1 - \frac{L}{V}\right) x_D = (1 - 0.9)(0.9) = 0.09 \quad [y\text{-intercept}]$$

### Bottom (Stripping Section) Operating Line

The bottom operating line intersects the top operating line at the feed line. The bottom operating line also intersects the  $y = x$  line at  $x_B = 0.02$ . Using these two points, the bottom operating line can be plotted on the equilibrium diagram.

Starting at the distillate and stepping off stages shows that this separation requires 4 equilibrium stages and a partial reboiler to achieve a bottoms composition of just under 2 mol%.

From the illustration, the optimum feed location is at stage 3, since the stages were stepped off to minimize the total number of stages.



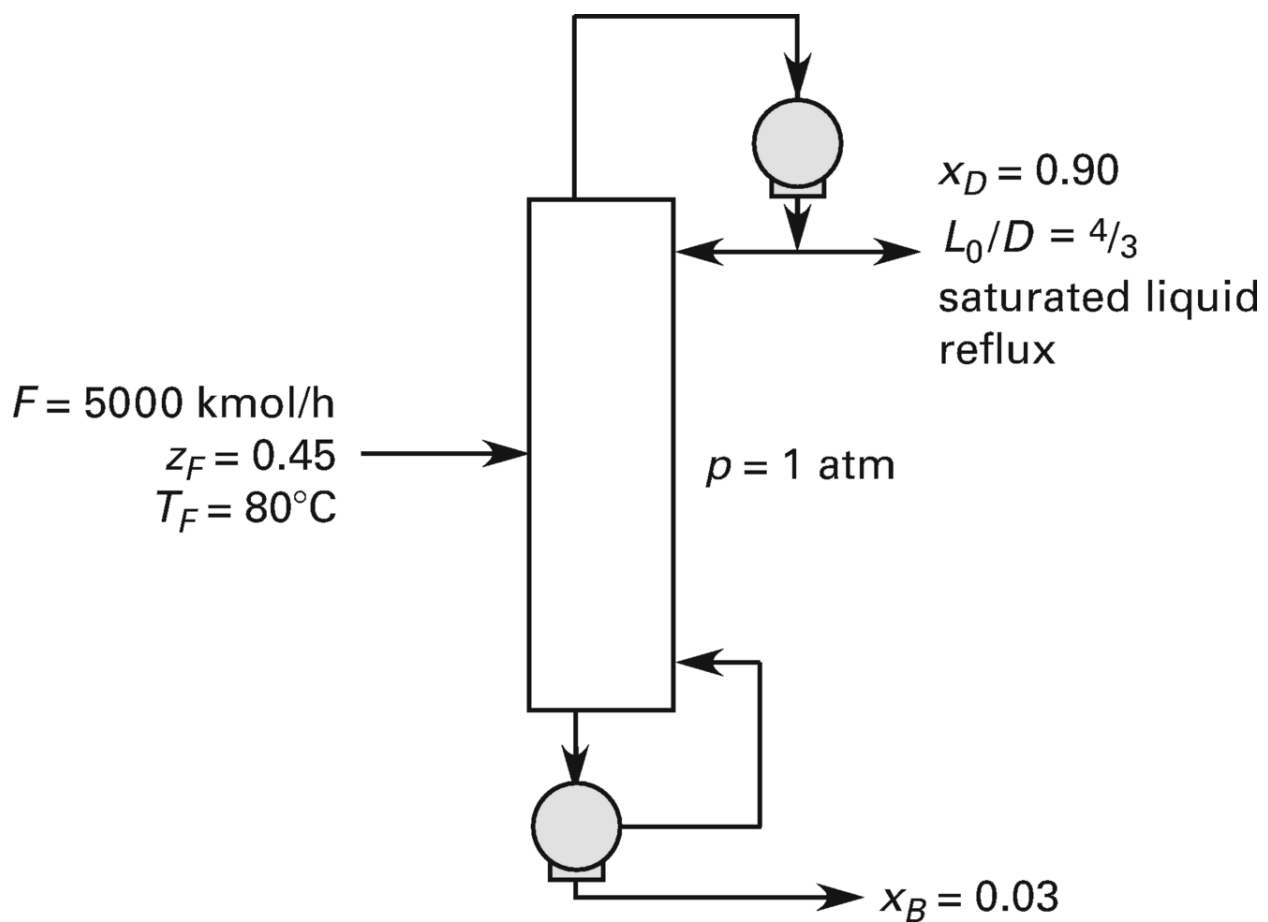
The answer is (C).

4.

Calculate the feed quality,  $q$ , from NCEES Handbook: Feed Conditions.

$$\begin{aligned} q &= 1 + \frac{c_{pL}(T_b - T_F)}{\Delta h_{\text{vap}}} = \frac{h_V - h_F}{h_V - h_L} \\ &= \frac{900 \frac{\text{kcal}}{\text{kmol}} - 45 \frac{\text{kcal}}{\text{kmol}}}{900 \frac{\text{kcal}}{\text{kmol}} - 175 \frac{\text{kcal}}{\text{kmol}}} \\ &= 1.18 \end{aligned}$$

The feed is subcooled, which is evident from  $H_F < H_L$ .



#### Feed Line

The slope of feed line can be calculated using equation CHRM44044.

$$\frac{q}{q-1} = \frac{1.18}{1.18-1} = 6.56$$

Since the process stream is 55 mol% water, the mole fraction of water in the feed,  $z_{\text{H}_2\text{O}}$ , is 0.55. The mole fraction of ARBC<sup>3</sup> in the feed,  $z_F$ , is

$$1 = z_{\text{H}_2\text{O}} + z_F$$

$$z_F = 1 - z_{\text{H}_2\text{O}} = 1 - 0.55 = 0.45$$

The feed line intersects the  $y = x$  line at the feed composition,  $z_F$ , providing (0.45, 0.45) as one point on the feed line. With this point and the slope, the feed line can be plotted on the equilibrium diagram. Alternatively, a second feed line point can be obtained by calculating the y-intercept of the feed line from the feed equation, equation CHRM44044.

$$\left(\frac{1}{1-q}\right) z_F = \left(\frac{1}{1-1.18}\right) (0.45) = -2.5$$

These two points,  $x = y = z_F$  (0.45, 0.45) and the y-intercept (0, -2.5), can also be used to plot the feed line.

#### Top (Rectifying Section) Operating Line

The slope of the top operating line is calculated from equation CHRM44036, using the given external reflux ratio.

$$\frac{L}{V} = \frac{\frac{L_0}{D}}{1 + \frac{L_0}{D}} = \frac{\frac{4}{3}}{1 + \frac{4}{3}} = 0.57$$

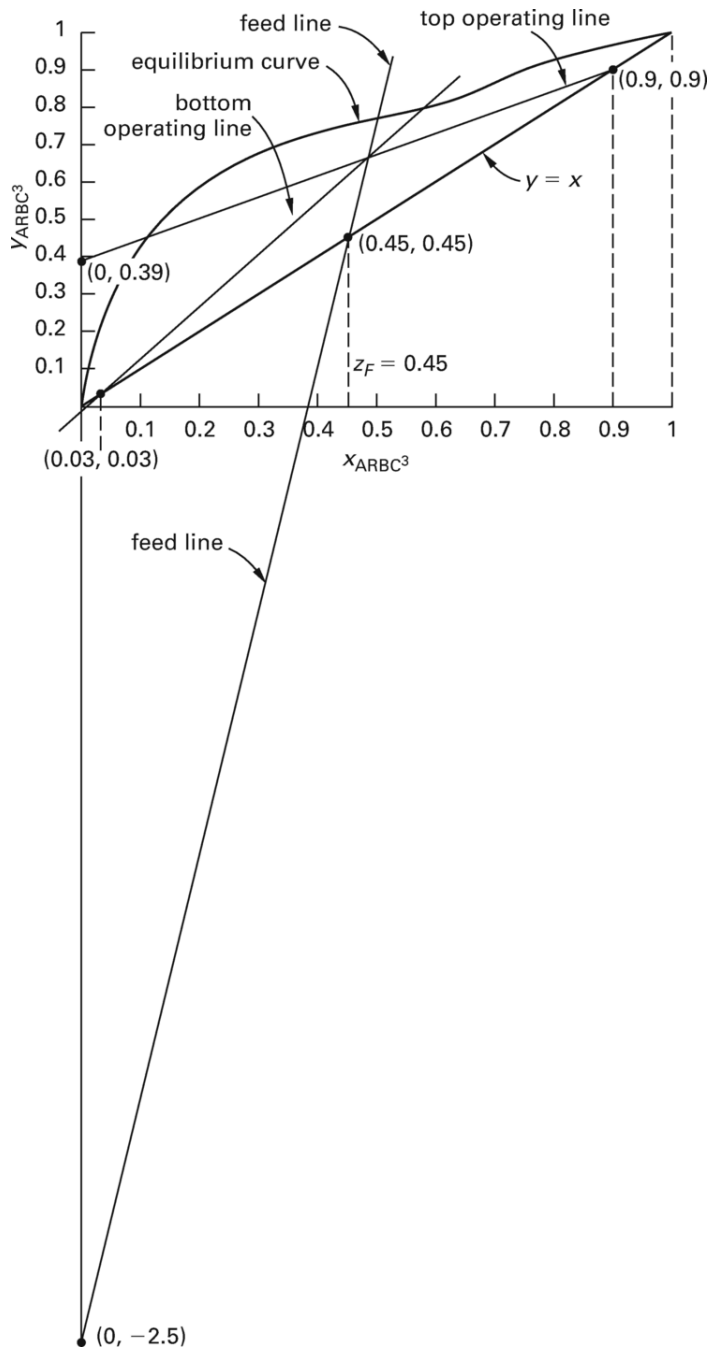
The y-intercept can be obtained from equation CHRM44035.

$$\frac{x_D}{R+1} = \left(1 - \frac{L}{V}\right) x_D = (1 - 0.57) (0.9) = 0.39$$

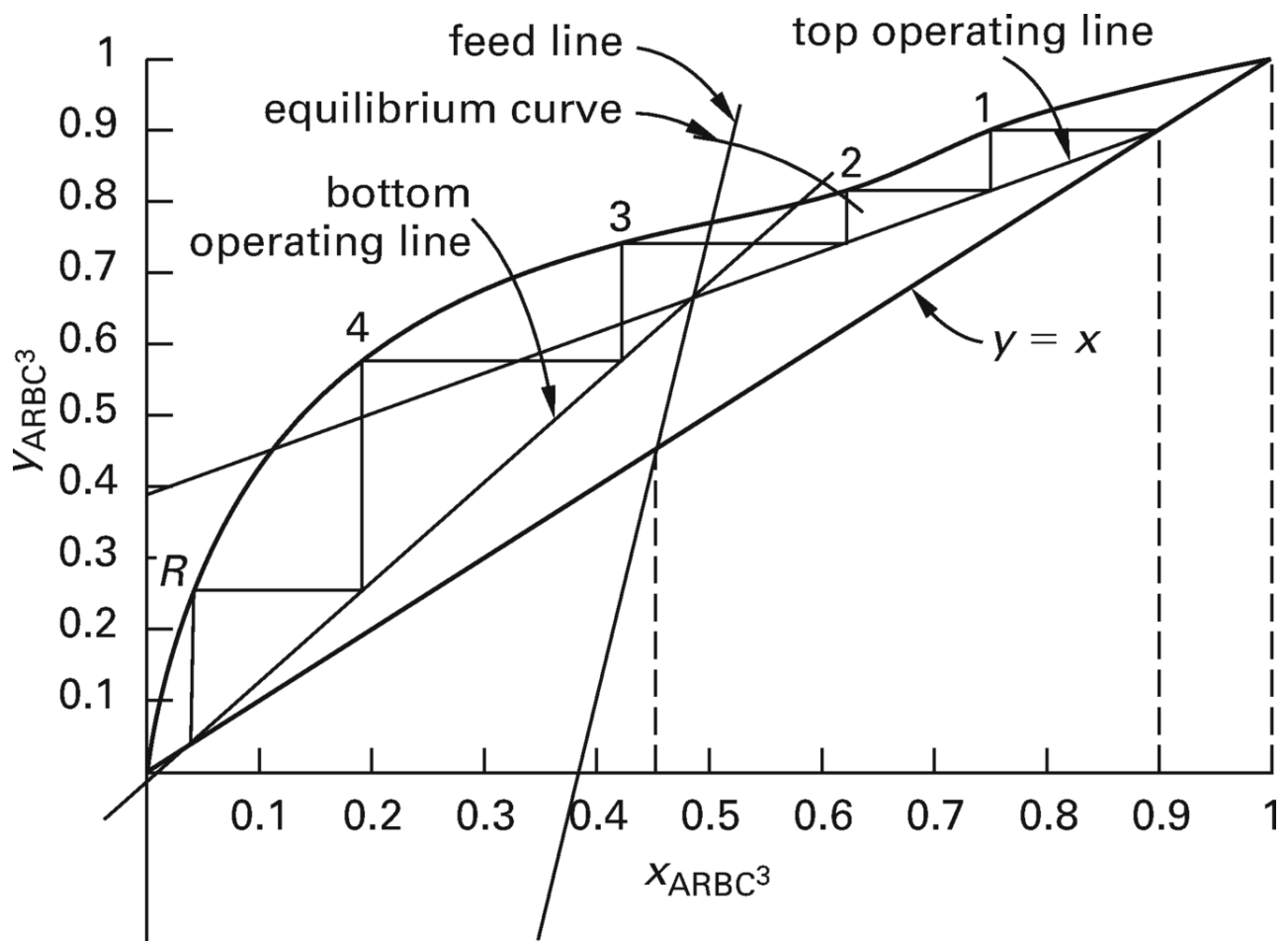
Alternatively, the top operating line can be plotted using two points, the intersection of the operating line with the  $y = x$  line at  $x_D$  (0.9, 0.9) and the  $y$ -intercept (0, 0.39).

### Bottom (Stripping Section) Operating Line

Knowing that the bottom operating line intersects the top operating line at the feed line provides one point on the line. A second point needed to plot the line can be identified as the intersection of the bottom operating line with the  $y = x$  line, at  $x_B$  (0.03, 0.03). The feed line and the operating lines are plotted on the equilibrium diagram as shown.



Stepping off stages shows that the total number of equilibrium stages required is approximately 4 plus a reboiler.



The optimum feed location is where the operating lines intersect the feed line, at stage 3.

The answer is (A)

[5.](#)

Distillation occurs when a liquid converts to a vapor by vaporization. The feed stream undergoes distillation when it converts to a vapor within the flash chamber. Option A is correct.

Leaching occurs when a liquid washes away part of a solid. Filtration occurs when a fluid component is partially or completely blocked by a filter. Sublimation occurs when a solid converts to a vapor.

The answer is (A).

[6.](#)

Take an overall material balance, and solve for the liquid flow rate.

$$F = L + V$$

$$L = F - V$$

$$= 100 \frac{\text{mol}}{\text{min}} - 55 \frac{\text{mol}}{\text{min}}$$

$$= 45 \text{ mol/min}$$

The vapor-liquid equilibrium constant is

$$k = \frac{y}{x} = 1.25$$

Therefore,  $x = y/1.25$ . Take a material balance for component A, and solve for the vapor composition of component A.

$$\begin{aligned}
 0.30F &= xL + yV \\
 &= \left(\frac{y}{1.25}\right)L + yV \\
 y &= \frac{0.30F}{\frac{L}{1.25} + V} = \frac{(0.30)\left(100 \frac{\text{mol}}{\text{min}}\right)}{\frac{45 \frac{\text{mol}}{\text{min}}}{1.25} + 55 \frac{\text{mol}}{\text{min}}} \\
 &= 0.3297 \quad (0.33)
 \end{aligned}$$

The answer is (B).

7.

The inlet gas and exit (treated) gas compositions in terms of mole ratios,  $Y_i$ , and the air flow rate,  $G$ , are needed to plot the operating line. The inlet gas stream has 4.5 mol% ammonia. From equation CHRM44053 (also *NCEES Handbook: Absorption and Stripping*), the mole ratio of the inlet gas,  $Y_{n+1}$ , is

$$Y_{n+1} = \frac{y_{\text{NH}_3}}{1 - y_{\text{NH}_3}} = \frac{0.045}{1 - 0.045} = 0.047$$

The amount of ammonia in the feed is

$$\begin{aligned}
 G_{\text{NH}_3, \text{in}} &= y_{n+1} G_F = (0.045) \left(15\,000 \frac{\text{mol}}{\text{h}}\right) \\
 &= 675 \text{ mol/h}
 \end{aligned}$$

The absorber removes 95.75% of the ammonia from the inlet air stream, leaving 4.25% of the inlet ammonia remaining in the gas.

$$\begin{aligned}
 G_{\text{NH}_3, \text{out}} &= (4.25\%) G_{\text{NH}_3, \text{in}} = (0.0425) \left(675 \frac{\text{mol}}{\text{h}}\right) \\
 &= 28.7 \text{ mol/h}
 \end{aligned}$$

The airflow rate is

$$\begin{aligned}
 G_{\text{air}} &= G_F - G_{\text{NH}_3, \text{in}} = 15\,000 \frac{\text{mol}}{\text{h}} - 675 \frac{\text{mol}}{\text{h}} \\
 &= 14\,325 \text{ mol/h}
 \end{aligned}$$

From equation CHRM44053 (also *NCEES Handbook: Absorption and Stripping*), the mole ratio of ammonia in the treated gas stream is

$$\begin{aligned}
 Y_1 &= \frac{G_{\text{NH}_3, \text{out}}}{G} = \frac{28.7 \frac{\text{mol NH}_3}{\text{h}}}{14\,325 \frac{\text{mol air}}{\text{h}}} \\
 &= 0.002 \text{ mol NH}_3/\text{mol air}
 \end{aligned}$$

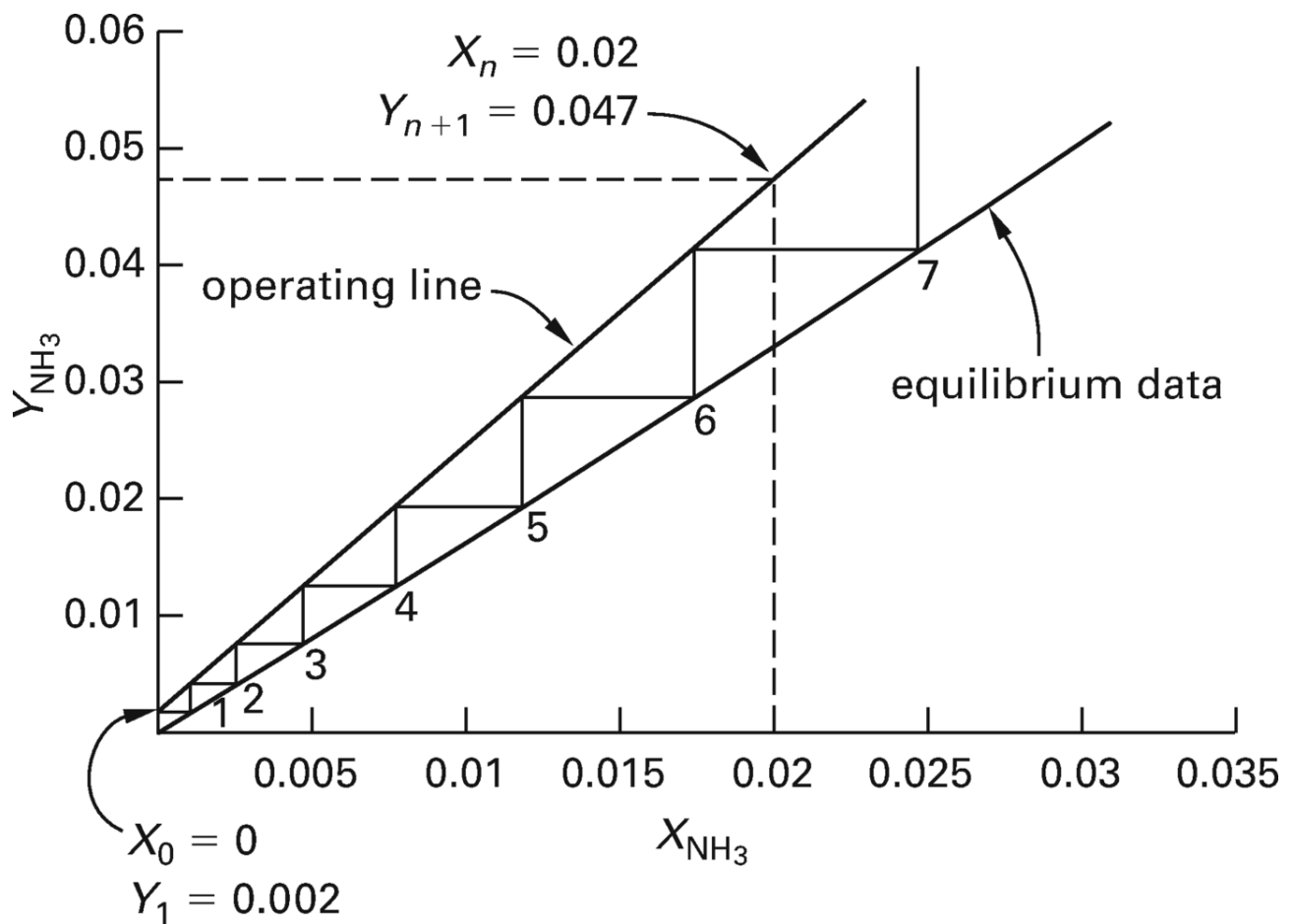
The operating equation, from equation CHRM44057 (also *NCEES Handbook: Absorption and Stripping*), is

$$Y_{j+1} = \left(\frac{L}{G}\right) X_j + \left(Y_1 - \left(\frac{L}{G}\right) X_0\right)$$

Since  $L/G = 2.25$ , the y-intercept is

$$Y_1 - \left(\frac{L}{G}\right) X_0 = 0.002 - (2.25)(0) = 0.002$$

Plot the operating line on the equilibrium diagram and step off stages. This separation requires approximately 7 equilibrium stages.



The answer is (B).

8.

The inlet gas stream has a mole fraction of ammonia of 0.03. The molar flow rate of ammonia in the inlet (feed) gas is

$$G_{\text{NH}_3, \text{in}} = y_{n+1} G_F = (0.03) \left( 38\,000 \frac{\text{mol}}{\text{h}} \right) = 1140 \text{ mol/h}$$

The absorber removes 95% of the ammonia from the inlet air stream. The molar flow rate of ammonia in the exit water is

$$L_{\text{NH}_3, \text{out}} = (95\%) G_{\text{NH}_3, \text{in}} = (0.95) \left( 1140 \frac{\text{mol}}{\text{h}} \right) = 1083 \text{ mol/h}$$

The air (carrier gas) flow rate,  $G$ , is

$$\begin{aligned} G_{\text{air}} &= G_F - G_{\text{NH}_3, \text{in}} \\ &= 38\,000 \frac{\text{mol gas}}{\text{h}} - 1140 \frac{\text{mol NH}_3}{\text{h}} \\ &= 36\,860 \text{ mol/h} \end{aligned}$$

Given the ratio  $L/G = 3.25$ , the solvent flow rate,  $L$ , is

$$\begin{aligned} L_{\text{water}} &= 3.25G = (3.25) \left( 36\,860 \frac{\text{mol air}}{\text{h}} \right) \\ &= 119\,800 \text{ mol/h} \end{aligned}$$

The mole ratio of ammonia in the exiting water stream, using equation CHRM44052, is

$$X_n = \frac{L_{\text{NH}_3, \text{out}}}{L} = \frac{1083 \frac{\text{mol NH}_3}{\text{h}}}{119\,800 \frac{\text{mol water}}{\text{h}}} = 0.009 \text{ mol NH}_3/\text{mol air}$$

The operating line can be plotted by identifying the two points  $(X_0, Y_1)$  and  $(X_n, Y_{n+1})$ . From the problem statement, the pure water feed means that  $X_0 = 0$ . Also from the problem statement, the inlet gas stream is 0.03 mole fraction ammonia or

$$y_{n+1} = 0.03$$

The corresponding mole ratio of ammonia in the inlet gas stream,  $Y_{n+1}$ , using equation CHRM44053 (also *NCEES Handbook: Absorption and Stripping*), is

$$Y_{n+1} = \frac{y_{\text{NH}_3}}{1 - y_{\text{NH}_3}} = \frac{0.03}{1 - 0.03} = 0.031$$

One point on the operating line,  $(X_n, Y_{n+1})$ , is  $(0, 0.031)$ .

As previously calculated, the molar flow rate of ammonia in the inlet gas is 1140 mol/h. The absorber removes 95% of the ammonia from the inlet air stream, leaving  $100\% - 95\% = 5\%$  of the ammonia in the treated gas stream.

$$G_{\text{NH}_3, \text{out}} = (5\%) G_{\text{NH}_3, \text{in}} = (0.05) \left( 1140 \frac{\text{mol}}{\text{h}} \right) = 57 \text{ mol/h}$$

As previously calculated, the air (carrier gas) flow rate,  $G$ , is 36 660 mol/h. The mole ratio of ammonia in the treated gas stream, using equation CHRM44053 (also *NCEES Handbook: Absorption and Stripping*), is

$$\begin{aligned} Y_1 &= \frac{G_{\text{NH}_3, \text{out}}}{G} \\ &= \frac{57 \frac{\text{mol NH}_3}{\text{h}}}{36\,660 \frac{\text{mol air}}{\text{h}}} \\ &= 0.0015 \end{aligned}$$

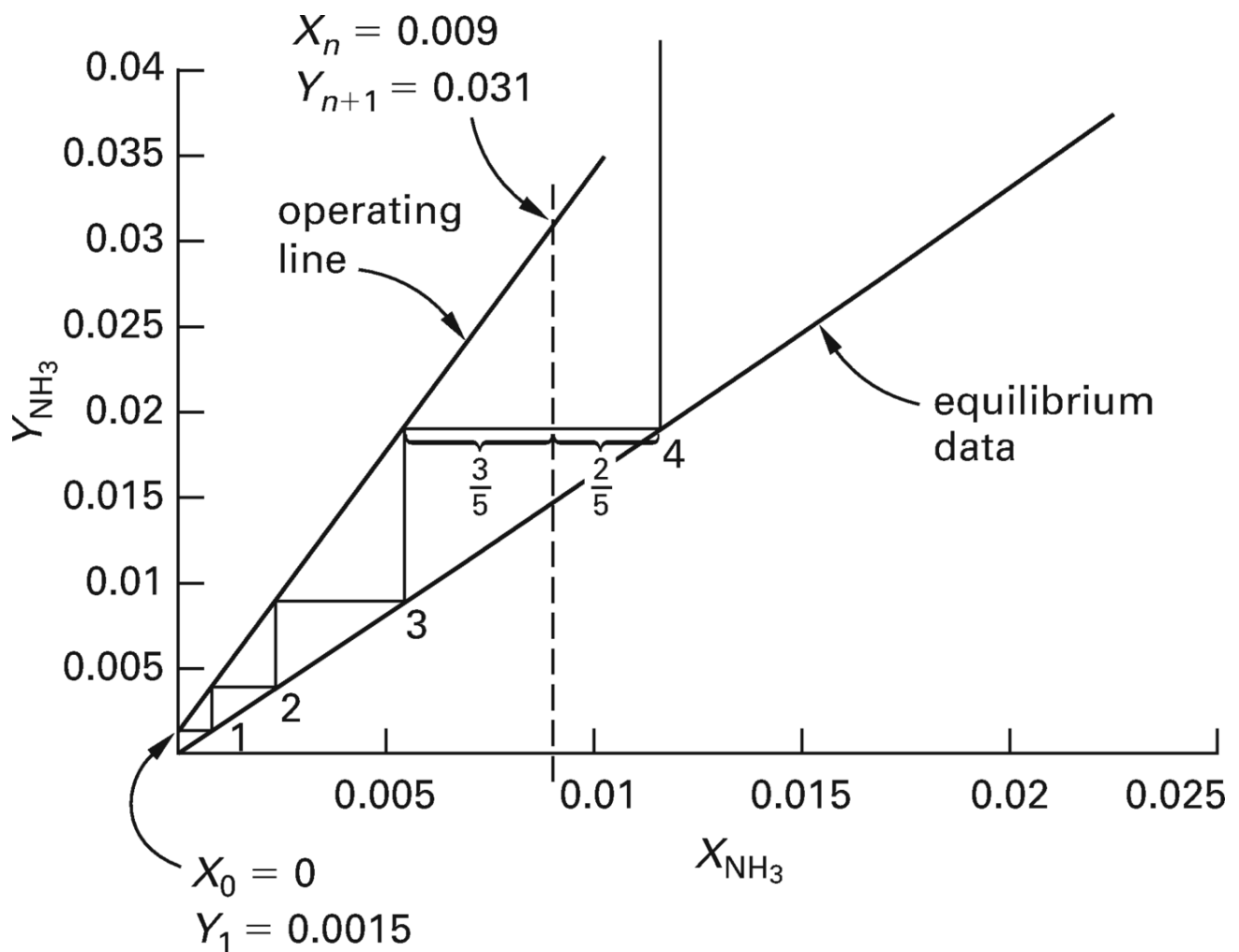
As in *NCEES Handbook: Absorption and Stripping*, the operating equation is

$$\begin{aligned} Y_{\text{out}} &= Y_{\text{in}} - \left( \frac{L_S}{G_S} \right) (X_{\text{out}} - X_{\text{in}}) \\ &= \left( \frac{L_S}{G_S} \right) X_{\text{out}} + \left( Y_{\text{in}} - \left( \frac{L_S}{G_S} \right) X_{\text{in}} \right) \end{aligned}$$

The problem statement specifies that the liquid-to-gas ratio,  $L/G$ , is 3.25, which is the slope of the operating line. The y-intercept of this line is

$$\begin{aligned} Y_{\text{in}} - \left( \frac{L_S}{G_S} \right) X_{\text{in}} &= 0.0015 - (3.25)(0) \\ &= 0.0015 \end{aligned}$$

This separation requires approximately  $3\frac{3}{5}$  equilibrium stages.



The answer is (B).

9.

Use Raoult's law to calculate the pressure of each component.

$$\begin{aligned}
 P_A &= x_A P_A^\circ \\
 &= (0.8) \left( 0.552 \frac{\text{lbf}}{\text{in}^2} \right) \\
 &= 0.441 \text{ lbf/in}^2 \\
 P_B &= x_B P_B^\circ \\
 &= (0.2) \left( 2.848 \frac{\text{lbf}}{\text{in}^2} \right) \\
 &= 0.570 \text{ lbf/in}^2
 \end{aligned}$$

Calculate the total pressure of the system using Dalton's law of partial pressure.

$$\begin{aligned}
 P &= P_A + P_B \\
 &= 0.441 \frac{\text{lbf}}{\text{in}^2} + 0.570 \frac{\text{lbf}}{\text{in}^2} \\
 &= 1.011 \text{ lbf/in}^2 \quad (1.0 \text{ psi})
 \end{aligned}$$

The answer is (B).

10.

The inlet water stream has 9.1 mol% A. The mole ratio of component A in the inlet solvent stream is from *NCEES Handbook: Absorption and Stripping*.

$$X_0 = \frac{x_0}{1 - x_0} = \frac{0.091}{1 - 0.091} = 0.10$$

Given the desired mole fraction of component A of 0.008 in the treated water, the mole ratio of component A needed in this stream is from *NCEES Handbook: Absorption and Stripping*.



$$X_n = \frac{x_n}{1 - x_n} = \frac{0.008}{1 - 0.008} = 0.008$$

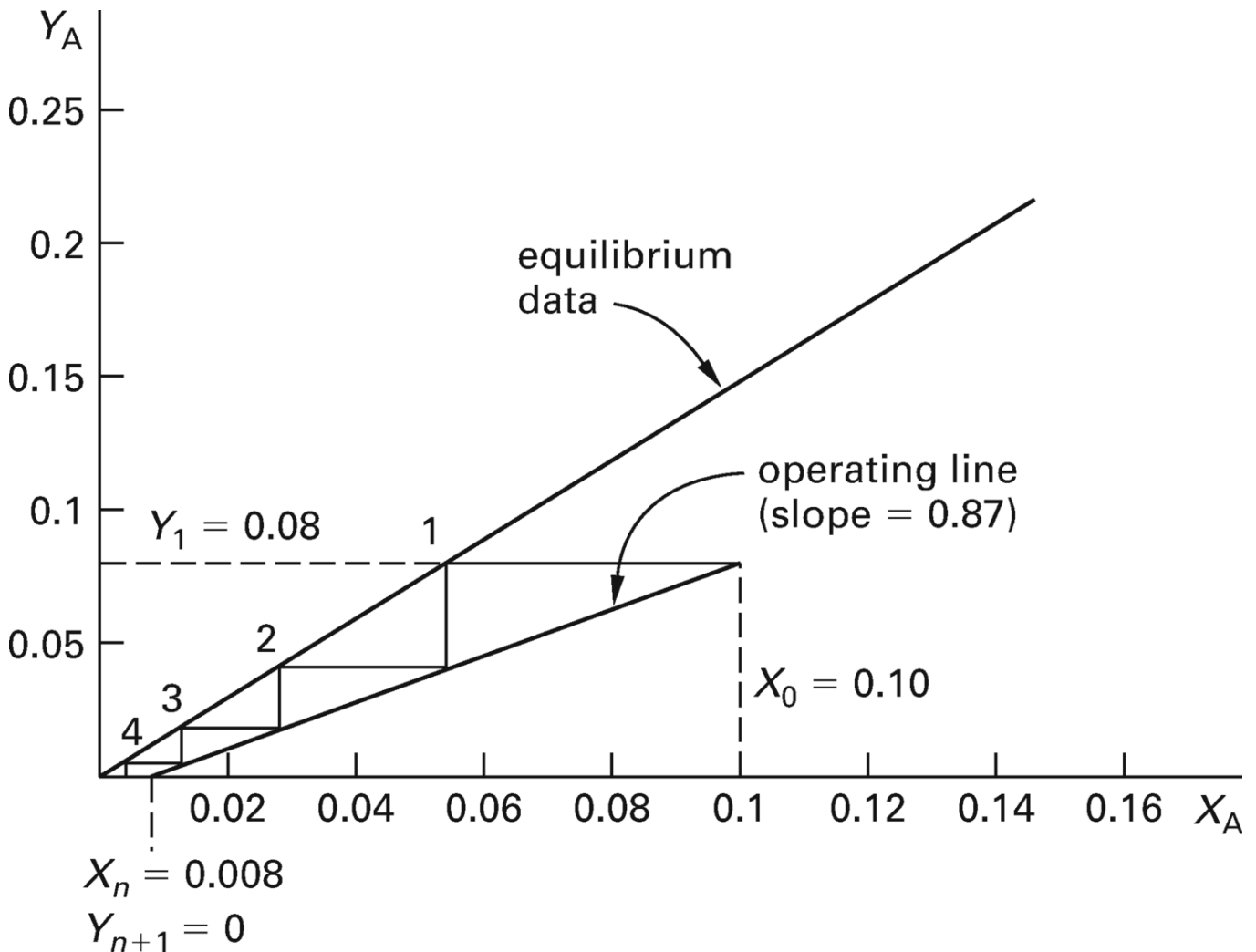
The inlet gas stream is pure air. The mole ratio of solute in the inlet air is

$$Y_{n+1} = 0$$

With a target mole fraction of A in the exit gas stream of 0.074, the corresponding mole ratio of component A in this stream is from *NCEES Handbook: Absorption and Stripping*.

$$Y_1 = \frac{y_1}{1 - y_1} = \frac{0.074}{1 - 0.074} = 0.08$$

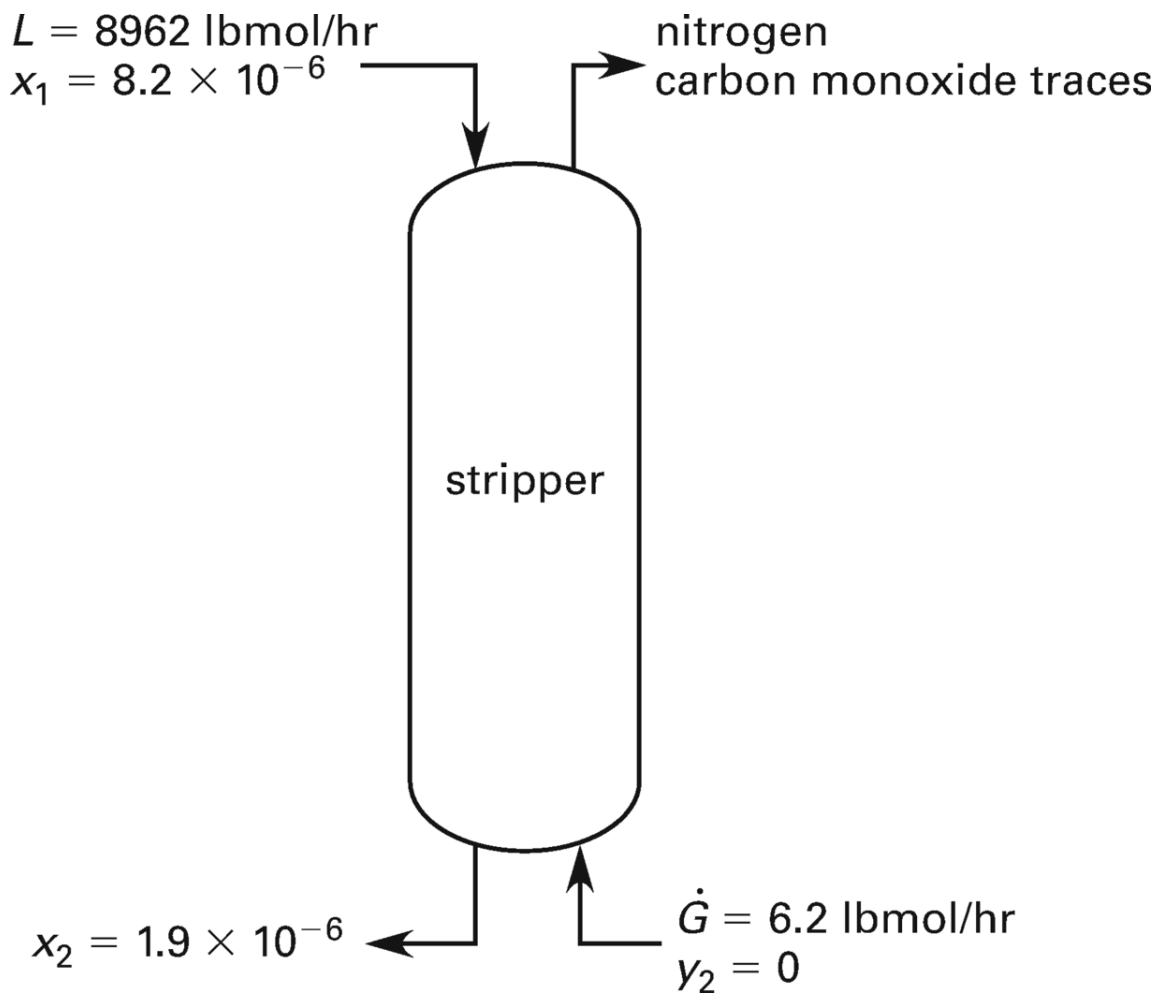
In contrast to absorption processes, the operating line lies below the equilibrium data. The operating line can be plotted using the conditions at the entrance and the exit of the stripping tower; one point is  $(X_n, Y_{n+1})$ , and another point is  $(X_0, Y_1)$ . Plotting the operating line with the equilibrium data and stepping off stages shows that this separation requires approximately 4 (3.5) stages.



The answer is (A).

[11.](#)

Draw the stripping column.



The intercept,  $b$ , of the straight-line equation for the Henry's law is given as 0. The equation of this straight line is

$$y = mx + b$$

Applying the preceding equation at equilibrium gives

$$y_1 = mx_2^* + b$$

Solving for the equilibrium concentration of carbon dioxide in the aqueous phase gives

$$x_2^* = \frac{y_1 - b}{m} = \frac{0 - 0}{m} = 0$$

Using the Kremser equation, the required theoretical number of stages is

$$\begin{aligned}
N &= \frac{\ln \left( \left( 1 - \frac{\dot{L}}{m\dot{G}} \right) \left( \frac{x_1 - x_2^*}{x_2 - x_2^*} \right) + \frac{\dot{L}}{m\dot{G}} \right)}{\ln \left( \frac{m\dot{G}}{\dot{L}} \right)} \\
&= \frac{\ln \left( \left( 1 - \frac{8962 \frac{\text{lbmol}}{\text{hr}}}{(3622) \left( 6.2 \frac{\text{lbmol}}{\text{hr}} \right)} \right) \times \left( \frac{8.2 \times 10^{-6} - 0}{1.9 \times 10^{-6} - 0} \right) + \frac{8962 \frac{\text{lbmol}}{\text{hr}}}{(3622) \left( 6.2 \frac{\text{lbmol}}{\text{hr}} \right)} \right)}{\ln \frac{(3622) \left( 6.2 \frac{\text{lbmol}}{\text{hr}} \right)}{8962 \frac{\text{lbmol}}{\text{hr}}}} \\
&= 1.19 \quad (1.2)
\end{aligned}$$

The answer is (C).