2.10 The flowsheet neglected to recycle some of the CO_2 and contained some stylistic errors. Use the revised flowsheet below with the following explanation:

The overall process should agree with the overall reaction; ideally only $CaCO_3$ and $NaCl$ should enter the process and only Na_2CO_3 and $CaCl_2$ should leave the process. However, it is not possible to separate $CaCl_2$ from NH_4Cl; both are soluble in water. So, the $CaCl_2/NH_4Cl$ solution must be discarded or purged. Recycling a portion of the $CaCl_2/NH_4Cl$ solution will consume some of the $CaCl_2$ but will also cause NH_4Cl to build up in the chlorinator/carbonator loop. In either case (partial purge or complete purging of the $CaCl_2/NH_4Cl$ solution) NH_4Cl must be added to the system.
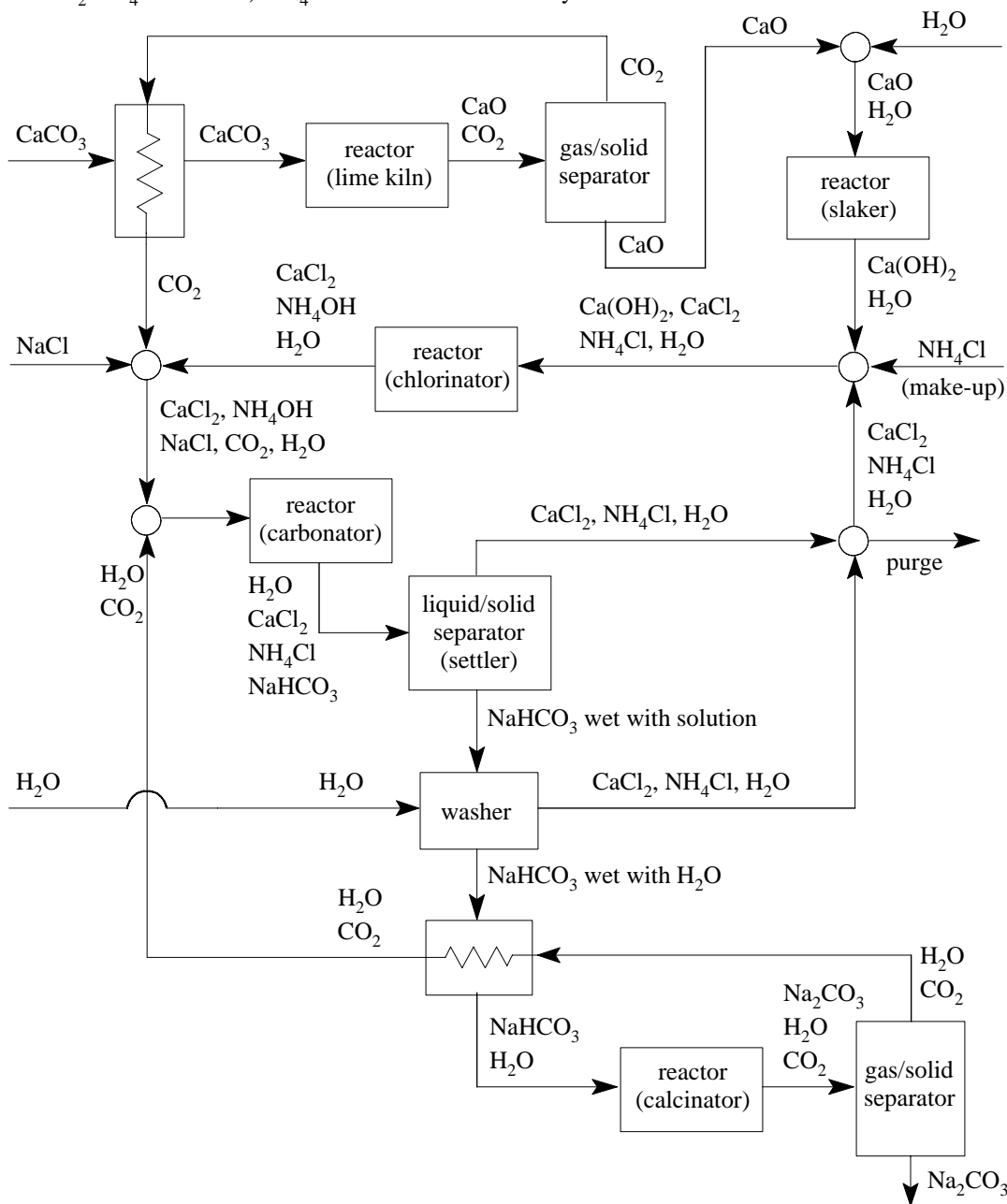
2.15(C) There should not be any SO_3 in the recycle, as shown below.
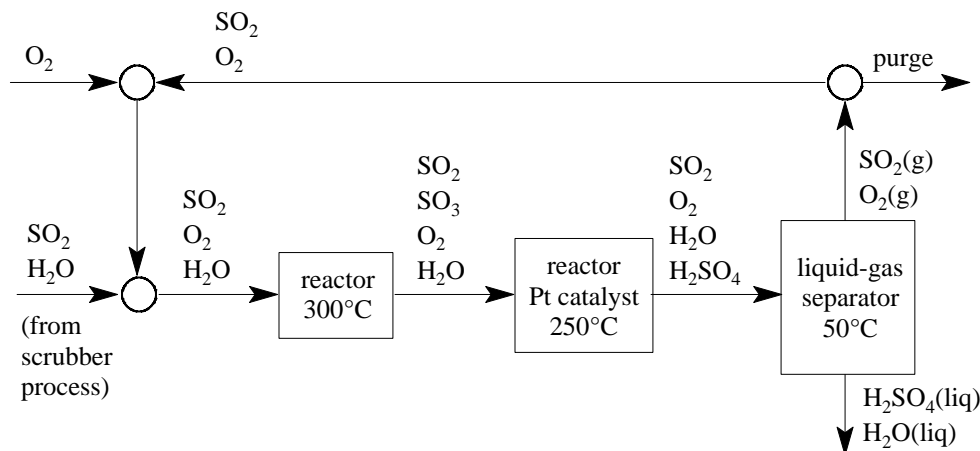
3.13 In the summary of part (B) change stream 6 to stream 8 as follows:

$$F_{T,8} = 92.4 \text{ kg/min}$$

(C) In the summary, change stream 8 to stream 10 as follows:

$$F_{T,10} = 35.6 \text{ kg/min}$$

Summary of stream 10.

3.17 Change "and" to "has" in part (A):

(A)   Stream 2 is formed by combining streams 1 and 6. Thus, $F_{Q,2} > F_{Q,1}$ and $F_{Q,2} > F_{Q,6}$. Stream 2 has more Q than stream 3, because Q is converted to Z in the reactor. And stream 5 <u>has</u> the same amount of Q as stream 3.

3.18 Change "the" to "that" in part (B):

(B)   Plan of Attack. The key is to note that the compositions of all air streams are given. The input air, stream 1, is 0.5% water. The recycle, stream 2, is 1.0% water. Streams 3, 4, and 5 have the same composition, 3.0% water. The amount of water that exits via stream 5 is the water <u>that</u> enters with the air in stream 1 plus the water given up by the solids. ...

3.19 The intermediate result on stream 4 should be changed to:

The flow rate of <u>zeolite</u> stream 4 is 6.5 kg/min

3.21 add the following to part (A), second paragraph:

(A)

        A useful approach to analyzing the ratio of product to by-product is to consider the flow rate of HCl into the system. 1 mol/min of HCl is required to convert C_2H_2 to product C_2H_3Cl. The additional HCl in each process converts C_2H_3Cl to by-product $C_2H_4Cl_2$.

Change the wording in part (C):

(C)   Now one must study the internal workings of each scheme. Scheme I has a flow rate into the reactor of 2.2 mol/min. Schemes II and III must have higher flow rates because they have approximately the same flow rate of fresh C_2H_2 and HCl plus the amount recycled. Which scheme recycles the most? Obviously, Scheme II does.

3.30 The published solution uses the incorrect heat capacity for air (42 J/(mol·°C)), which appears incorrectly in the table on p. 138. The correct value is (29 J/(mol·°C).

Substitute flow rates and thermodynamic constants.

$$F_{H2O,3a} = -\frac{100.\,kg}{min}\frac{\left(\dfrac{29\;joules}{(°C)(mol\;air)}\right)\left(\dfrac{1000\;mol\;air}{28.8\;kg\;air}\right)(20-38°C)}{\left(\dfrac{4.1\times10^4\;joules}{mol\;water}\right)\left(\dfrac{1000\;mol\;water}{18\;kg\;water}\right)} = 0.80\;kg\;water\,/\,min$$

By inspection, the flow rate of water through the imaginary water evaporator equals the flow rate of water in stream 2. Thus the weight fraction of water in stream 2 is $(0.80)/(100.+0.80) = 0.0079$.

$$\boxed{\text{Stream 2 is 0.79 wt \% water.}}$$

(B)

Substitute flow rates and thermodynamic constants.

$$\frac{\left(\dfrac{1.46\;kg\;water}{min}\right)\left(\dfrac{4.1\times10^4\;joules}{mol\;water}\right)\left(\dfrac{1000\;mol\;water}{18\;kg\;water}\right)}{\left(\dfrac{100.\,kg\;air}{min}\right)\left(\dfrac{29\;joules}{(°C)(mol\;air)}\right)\left(\dfrac{1000\;mol\;air}{28.8\;kg\;air}\right)} + 20°C = 53°C$$

$$\boxed{\text{The maximum air temperature is 53°C (127°F).}}$$

3.31 The published solution uses the incorrect heat capacity for air (42 J/(mol·°C)), which appears incorrectly in the table on p. 138.   The correct value is (29 J/(mol·°C). In addition, changing the temperature of the water returned to the lake to 55°F from 50°F changes the solution to part (C).

Calculate the rate that energy is removed from the air by cooling.

$$\Delta q_{air} = F_{air}\,C_{P,air}\,(\Delta T)$$

$$= \left(\frac{2\times10^5\;m^3}{min}\right)\left(\frac{1000\;L}{1\,m^3}\right)\left(\frac{1\;mol}{22.4\;L}\right)\left(\frac{29\;joules}{(°C)(mol)}\right)\left(\frac{60\;min}{1\;hr}\right)(68-90\;°F)\left(\frac{1\,°C}{1.8\,°F}\right)$$

$$= -1.90\times10^{11}\;joules\,/\,hr$$

Δq_{air} is negative because the air loses energy when it cools. Calculate the flow rate of chilled water.

$$\Delta q_{air} = -\Delta q_{water} = -F_{water} C_{P,water} (\Delta T)$$

$$F_{water} = \frac{-\Delta q_{air}}{C_{P,water} (\Delta T)}$$

$$= \frac{-(-1.90 \times 10^{11} \text{ joules / hr})}{\left(\dfrac{75 \text{ joules}}{(°C)(\text{mol water})}\right)(60 - 45 °F)\left(\dfrac{1 °C}{1.8 °F}\right)} = \frac{3.04 \times 10^8 \text{ mol water}}{hr}$$

Convert to gal/hr.

$$\left(\frac{3.04 \times 10^8 \text{ mol water}}{hr}\right)\left(\frac{18 \text{ g water}}{1 \text{ mol water}}\right)\left(\frac{1 \text{ mL water}}{1 \text{ g water}}\right)\left(\frac{1 \text{ L}}{1000 \text{ mL}}\right)\left(\frac{1 \text{ gal}}{3.79 \text{ L}}\right) = 1.44 \times 10^6 \text{ gal / hr}$$

> The flow rate of chilled water is 1.4×10^6 gal/hour.

(B)

Calculate the energy released by condensing the water vapor.

$$\Delta q_{condense} = -F_{condense} \Delta H_{vap,water}$$

$$= -\left(\frac{3.29 \times 10^5 \text{ mol water}}{min}\right)\left(\frac{60 \text{ min}}{1 \text{ hr}}\right)\left(\frac{4.1 \times 10^4 \text{ joules}}{1 \text{ mol water}}\right) = -8.08 \times 10^{11} \text{ joules / hr}$$

The energy released by condensing the water vapor is over four times the energy released by cooling the air. Calculate the total energy released by cooling the air and condensing water vapor from the air.

$$\Delta q_{air} = \Delta q_{cool} + \Delta q_{condense}$$

$$= -1.90 \times 10^{11} \text{ joules / hr} + -8.08 \times 10^{11} \text{ joules / hr} = -9.98 \times 10^{11} \text{ joules / hr}$$

The flow rate of chilled water can be calculated from the ratio of the energy released by the air in parts (A) and (B).

$$\text{chilled water}_{part (B)} = \text{chilled water}_{part (A)}\left(\frac{q_{part (B)}}{q_{part (A)}}\right)$$

$$= 1.44 \times 10^6 \text{ gal / hr}\left(\frac{-9.98 \times 10^{11} \text{ joules / hr}}{-1.90 \times 10^{11} \text{ joules / hr}}\right) = 7.56 \times 10^6 \text{ gal / hr}$$

> The flow rate of chilled water is 7.6×10^6 gal/hr.

(C) Apply an energy balance to the lake water - chilled water heat exchanger.

rate energy is adsorbed by lake water = rate energy is removed from chilled water

$$\Delta q_{water} = -\Delta q_{chilled}$$

$$F_{lake} C_{P,water} (\Delta T)_{lake} = -F_{chilled} C_{P,water} (\Delta T)_{chilled}$$

$$F_{lake} = -F_{chilled} \frac{(\Delta T)_{chilled}}{(\Delta T)_{lake}}$$

$$= -7.56 \times 10^6 \text{ gal / hr}\left(\frac{45 - 60°F}{55 - 40°F}\right) = 7.56 \times 10^6 \text{ gal / hr}$$

The flow rate of lake water is 7.6×10^6 gal/hr.

3.40 The published solution uses the incorrect heat capacity for air (42 J/(mol·°C)), which appears incorrectly in the table on p. 138. The solution to (C) incorrectly uses the density of air at $-5°C$ (1.3 kg/m^3), contrary to the exercise statement. In (D), change q_{heater} to q_{evap} and change q_{evap} to q_{heater}.

(C)

$$q_{heater} = \left[\frac{740 \text{ kJ}}{(°C)(hr)} + \left(\frac{0.1 \text{ m}^3}{\text{sec}} \right)\left(\frac{60 \text{ sec}}{1 \text{ min}} \right)\left(\frac{60 \text{ min}}{1 \text{ hr}} \right)\left(\frac{29 \text{ J}}{(°C)(mol)} \right)\left(\frac{1.44 \text{ kg}}{1 \text{ m}^3} \right)\left(\frac{1000 \text{ mol}}{28.8 \text{ kg}} \right)\left(\frac{1 \text{ kJ}}{1000 \text{ J}} \right) \right](20 - (-5))$$

$$= \left[\frac{740 \text{ kJ}}{(°C)(hr)} + \frac{522 \text{ kJ}}{(°C)(hr)} \right](25°C) = 3.16 \times 10^4 \text{ kJ/hr}$$

$q_{heater} = 3.2 \times 10^4$ kJ / hr

(D)

$$q_{evap} = \left(\frac{0.1 \text{ m}^3}{\text{sec}} \right)\left(\frac{60 \text{ sec}}{1 \text{ min}} \right)\left(\frac{60 \text{ min}}{1 \text{ hr}} \right)\left(\frac{9.0 \text{ g water}}{1 \text{ m}^3 \text{ air}} \right)\left(\frac{4.1 \times 10^4 \text{ J}}{\text{mol water}} \right)\left(\frac{1 \text{ mol water}}{18 \text{ g}} \right)\left(\frac{1 \text{ kJ}}{1000 \text{ J}} \right)$$

$$= 7.38 \times 10^3 \text{ kJ / hr}$$

The total heating rate is thus

$$q_{heater} = (3.16 \times 10^4 + 7.38 \times 10^3) \text{ kJ / hr} = 3.9 \times 10^4 \text{ kJ / hr}$$

3.47 This revised solution corresponds to the revised exercise statement (see errata). The published exercise statement leads students to compare ROI's for the two options, and ROI's for services are confusing - beyond the intent of this textbook.

Option 1   operating cost = electricity cost + depreciation

$$= 1.9 \times 10^6 \text{ \$/ year} + \frac{20 \times 10^6 \$}{30 \text{ years}} = 2.6 \times 10^6 \text{ \$/ year}$$

Option 2   operating cost = electricity cost + depreciation

$$= 1.9 \times 10^6 \text{ \$/ year} - 1.5 \times 10^6 \text{ \$/ year} + \frac{50 \times 10^6 \$}{75 \text{ years}} = 1.1 \times 10^6 \text{ \$/ year}$$

Option 2 has the lower operating cost

3.54 (C) The solution incorrectly uses the boule diameter instead of the radius. The corrections are underline below.

The density is thus a factor of $0.393/0.433 = 0.91$ less than the boule. Again apply conservation of mass.

$$\text{mass of silica fiber} \;=\; \text{mass of silica boule}$$

$$(\text{volume of fiber})(\text{density of fiber}) \;=\; (\text{volume of boule})(\text{density of boule})$$

$$\text{volume of fiber} \;=\; (\text{volume of boule})\frac{(\text{density of boule})}{(\text{density of fiber})}$$

$$=\; \pi\,(\text{radius of boule})^2(\text{length of boule})\frac{(\text{density of boule})}{(\text{density of fiber})}$$

$$=\; \pi\,\underline{(1.25\ \text{cm})^2(1.0\ \text{m})}\left(\frac{1\ \text{m}}{100\ \text{cm}}\right)^2\frac{1}{0.91}$$

$$=\; \underline{5.4\times10^{-4}\ \text{m}^3}$$

The volume of the fiber on the spool is the volume of a cylinder which encloses the entire spool minus the volume of a cylinder for the empty spool.

$$\text{volume of fiber} \;=\; (\text{volume of filled spool}) \;-\; (\text{volume of empty spool})$$

$$=\; \pi\,(\text{radius of filled spool})^2(\text{ht of spool}) \;-\; \pi\,(\text{radius of empty spool})^2(\text{ht of spool})$$

$$\text{radius of filled spool} \;=\; \left[\frac{\text{volume of fiber}}{\pi\,(\text{ht of filled spool})} + (\text{radius of empty spool})^2\right]^{1/2}$$

$$=\; \left[\frac{5.4\times10^{-4}\ \text{m}^3}{\pi\,(10\ \text{cm})}\left(\frac{100\ \text{cm}}{1\ \text{m}}\right)^3 + (10\ \text{cm})^2\right]^{1/2} \;=\; \underline{10.8\ \text{cm}}$$

4.4 Replace the last line in the solution with the following text and replace the figure with the figure shown below.

… The path moves downward to 1 torr and a partial molar volume that is 90% liquid and 10% vapor. Because the vapor/liquid region is about four decades wide at 1 torr - from liquid at 0.1 L/(mol benzene) to vapor at about $22.4 \times (760\ \text{torr}/1\ \text{torr}) = 17{,}000$ L/(mol benzene) - the point is about one-quarter the width of the two-phase region. The condensed liquid is drained, which corresponds to moving to the border between vapor and the two-phase region. Finally the temperature is returned to 26°C.
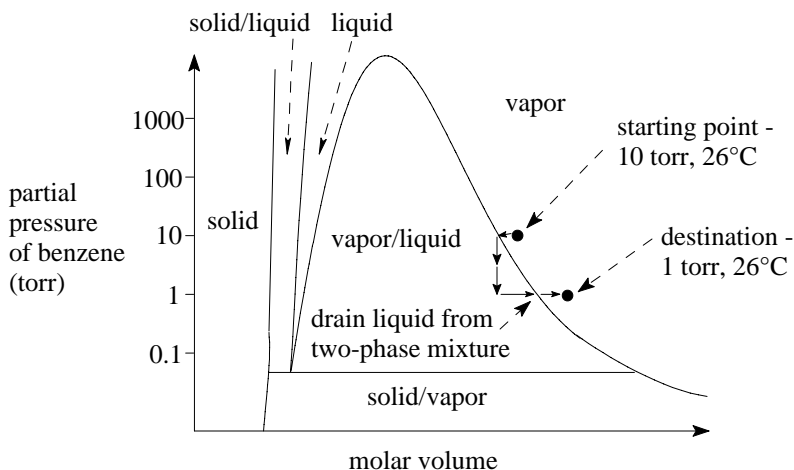
4.5   Replace the entire solution with the following:

Because the process is at constant volume, it is perhaps easier to start with the *P-V* phase map. Until we reach the two-phase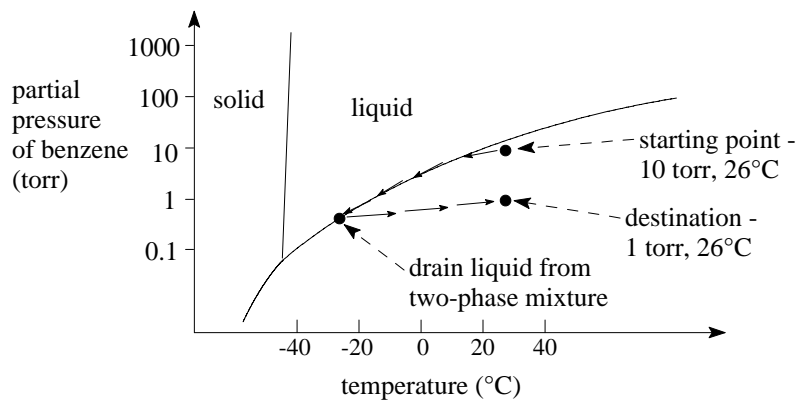 border (at the dew point) the system is still entirely vapor so the path is vertically downward. After we reach the border to the vapor/liquid region, the benzene begins to condense, which decreases the partial pressure of benzene. Condensing 90% of the benzene vapor results in a molar volume of benzene (which is the weighted average of the molar volume of benzene liquid and benzene vapor) that is about one decade from the two-phase border. Because the two-phase region is over 4 decades wide at this pressure (see solution to 4.4) the molar volume is about one-quarter width of the two phase region. The condensed liquid is drained, which corresponds to moving to the two-phase/vapor border. Finally the system is returned to a total pressure of 1 atm and 26°C.

We now map the path on the *P-V* map to the *P-T* map. Pressure and temperature both decrease as we cross the vapor region to the vapor/liquid two-phase line. Because the system remains two-phase, we are obliged to follow the vapor/liquid line downward, until the partial pressure of benzene decreases by a factor of ten. We then drain the condensed liquid from the system, which does not change our position on the *P-T* phase map. We then return the total pressure to 1 atm and the temperature to 26°C.

partial pressure of benzene (torr)

1000

100 — solid   liquid

10 — starting point - 10 torr, 26°C

1 — destination - 1 torr, 26°C

0.1 — drain liquid from two-phase mixture

-40 -20   0   20   40

temperature (°C)
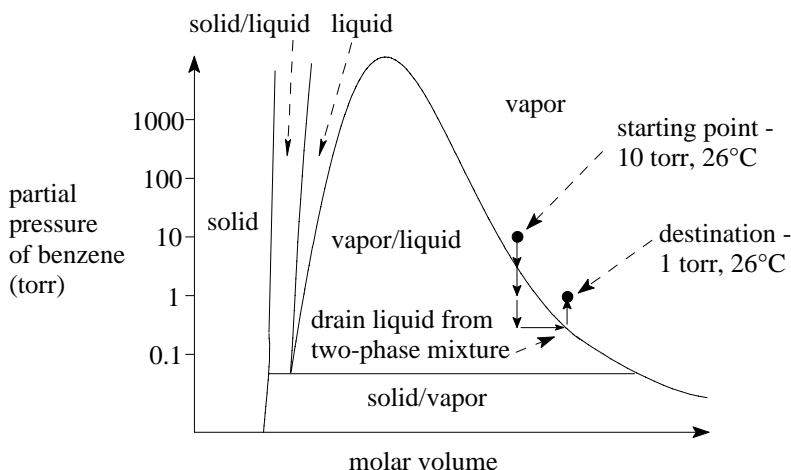
4.6 Part (E) second paragraph …

The gulf air at 100% humidity has a water partial pressure of 0.026 atm, so 95% humidity is a water partial pressure of (0.95)(0.026) = 0.025 atm. The gulf air is 0.025 mol fraction water vapor. After mixing, the mol fraction is 0.012.

The mixture is at 6°C and contains 1.2 mol% H_2O vapor.

4.10 Part (C) Last paragraph on the page …

A point on the operating line is the pair of streams that leave the bottom of the upper portion of the absorber, $x = K/\text{oil} = 0.068/8.5 = 0.008$ and $y = K/\text{air} = 0.0032$ (from the graph).

4.13 The flowsheet is missing an arrowhead on the oil recycle

chemical process

water

E
X
water

oil

oil

liquid / liquid absorber
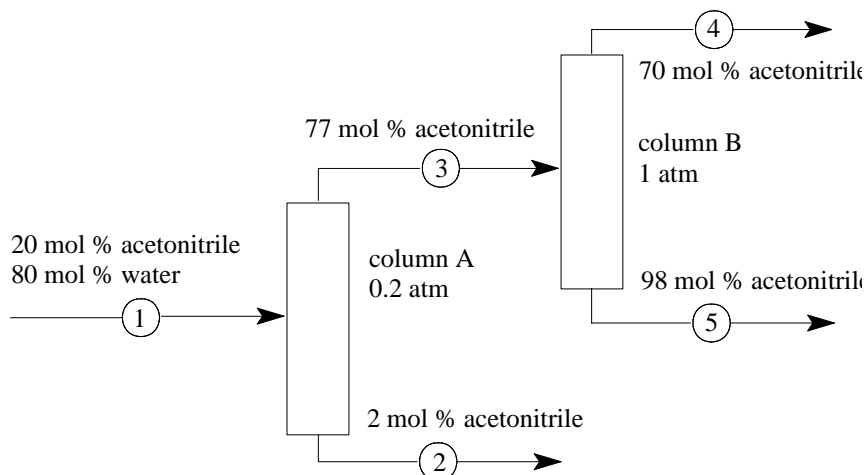
E, X, oil

E

X, N$_2$

N$_2$

purge

N$_2$

gas/liquid separator −50°C

X

oil (make-up for purge)

gas/liquid separator 150°C

gas / liquid stripper

E
oil

N$_2$

N$_2$

N$_2$
(make-up for purge)

oil

purge
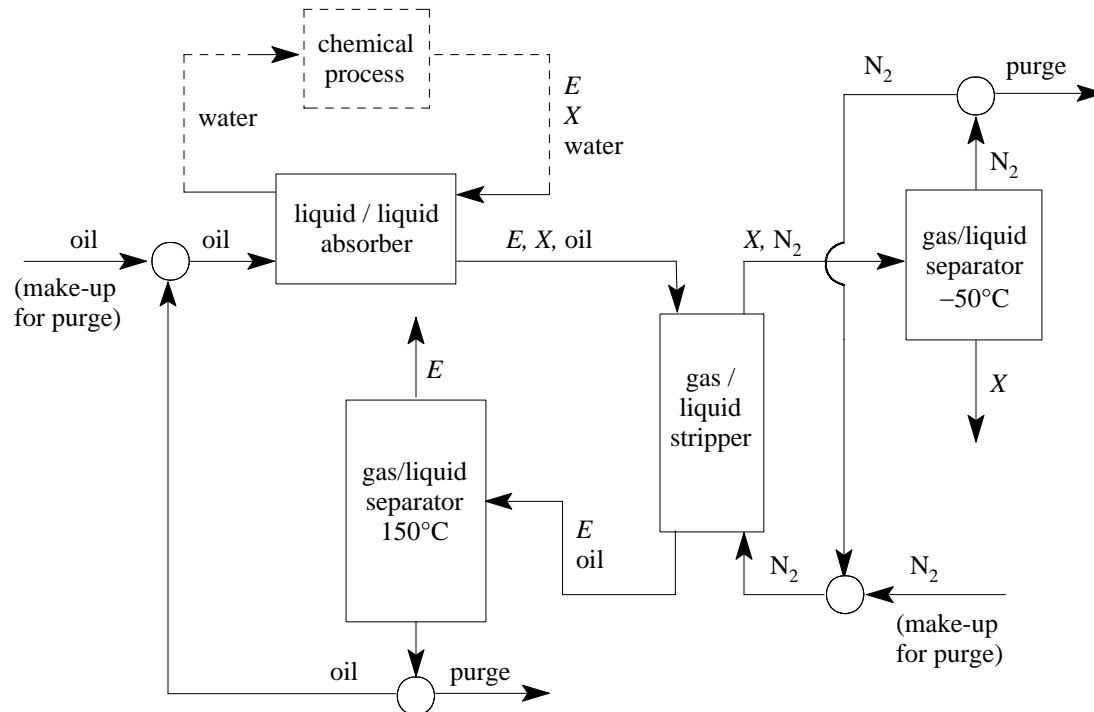
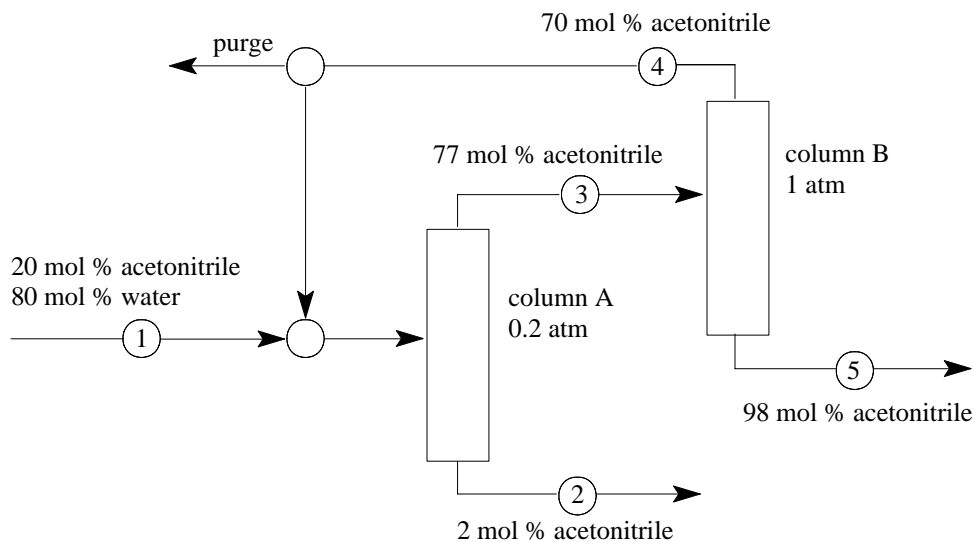**4.26** There is an error in the fifth bullet item:

- the feed needs to be <u>heated</u> before it enters the feed stage, which decreases x_{DCE} and y_{DCE}.

4.31 The compositions of streams 4 and 5 were switched. The correct solution is shown below.

The key is that the composition of the azeotrope changes with pressure. The azeotrope at 0.2 atm contains more acetonitrile than the azeotrope at 1 atm. At 0.2 atm, one can distill to above 68 mol %, the azeotrope at 1 atm. Distillation at 1 atm begins above the azeotrope and can reach 98 mol % acetonitrile. One possible process is shown below, with the McCabe-Thiele analyses on the following pages. Note that above the azeotrope, water is more volatile than acetonitrile (see temperature-composition diagram on page 208) and thus the 98 mol % acetonitrile is the bottoms of the distillation column B.

4

70 mol % acetonitrile

77 mol % acetonitrile

3

column B 1 atm

20 mol % acetonitrile
80 mol % water

column A 0.2 atm

98 mol % acetonitrile

1

5

2 mol % acetonitrile

2

An even better process would recycle stream 4. Stream 4 could be combined with stream 1 and fed to the first column at the second stage. Or stream 4 could be fed into the third stage of the first column.
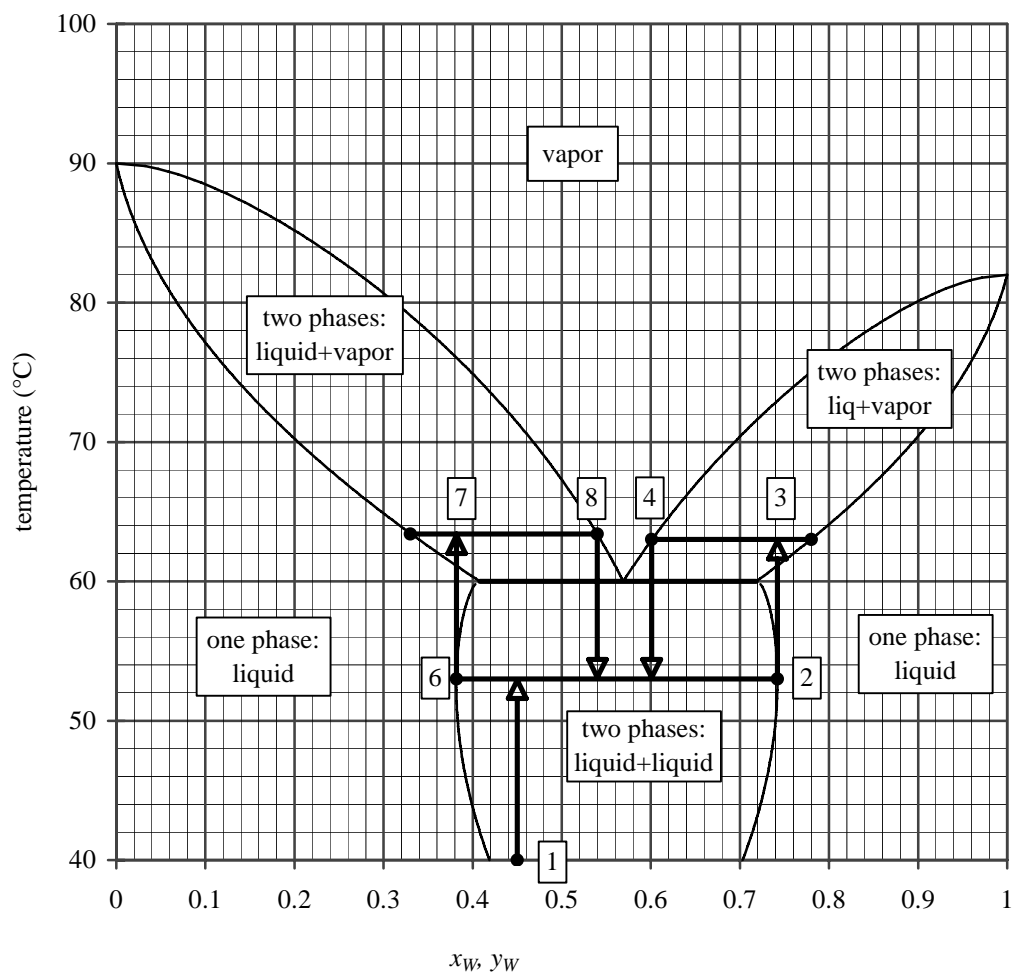
70 mol % acetonitrile

purge

77 mol % acetonitrile

column B
1 atm

column A
0.2 atm

20 mol % acetonitrile
80 mol % water

98 mol % acetonitrile

2 mol % acetonitrile

4.33 An improved solution is given below. The previous solution was correct, but not as clean.

(A)   The optimal liquid-liquid separation is at the widest portion of the liquid+liquid region, 53°C.
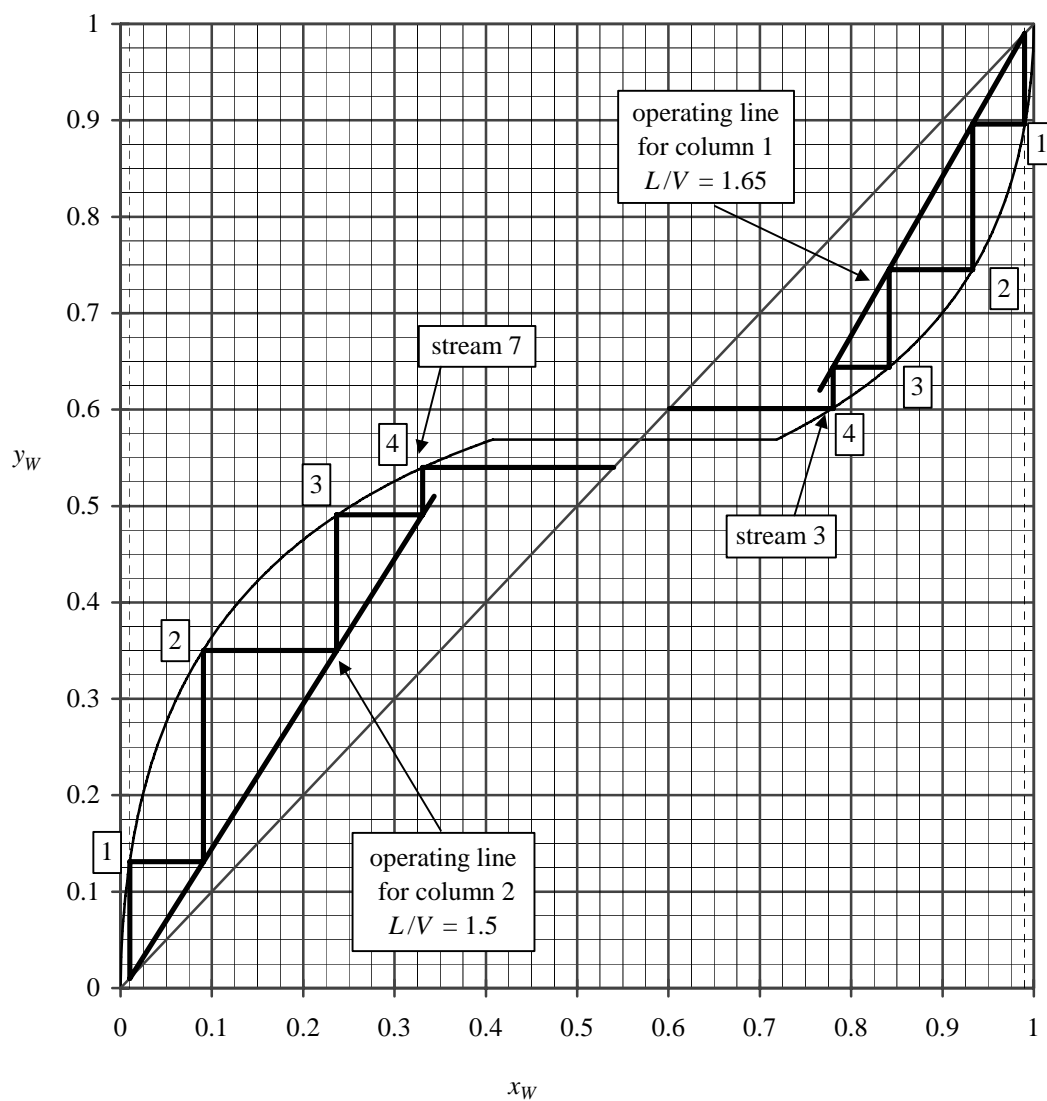
(B)   See phase diagram below.

There are many valid designs for distillation columns 1 and 2. One design is given on the diagrams.

(C)   Heater 2 is arbitrarily operated at 63°C. Any temperature between about 62°C and 76°C is valid, although not necessarily optimal. From the McCabe-Thiele analysis on the x_W-y_W liquid-vapor equilibrium diagram, column 1 has 4 stages and an L/V ratio of about 1.65.

(D)   Heater 3 is arbitrarily operated at 63.5°C. Any temperature between about 62°C and 72°C is valid, although not necessarily optimal. From the McCabe-Thiele analysis on the x_W-y_W liquid-vapor equilibrium diagram, column 2 has 4 stages and an L/V ratio of about 1.5.

phase diagram for *W-R* mixtures at 1 atm

Phase diagram: temperature (°C) versus x_W, y_W. Vapor region at top; two phases: liquid+vapor regions; one phase: liquid regions on left and right; two phases: liquid+liquid region in the center. Labeled points 1 through 8.

x-y diagram for liquid+vapor systems of *W* - *R* mixtures at 1 atm

4.40 The process flowsheet had a typographical error; the composition of the aniline-rich product should be < 2% MCH. Also, the heptane recycle needed a purge. Here is a corrected flowsheet:

100.% heptane

100.% heptane

5

purge

83% heptane
9% MCH
8% aniline

distillation
column

2

6 100.% heptane
150. kg/min

100.% heptane

88% MCH
12% aniline

distillation
column

liquid-liquid
separator

53% MCH
47% aniline

liquid-liquid
separator

3

4

16.% MCH
84.% aniline

16.% MCH
84.% aniline

16.% MCH
84.% aniline

aniline-rich
liquid

MCH (< 2%)
aniline

1

100. kg/min
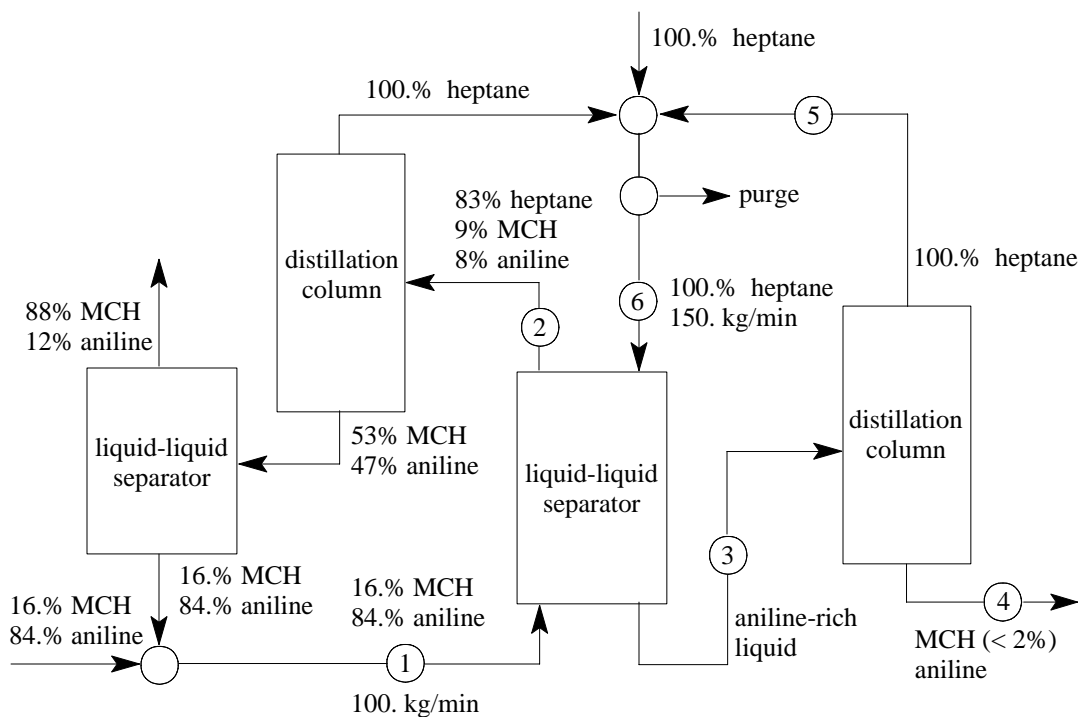
5.18 The solution to part (b) is omitted from the solution manual.

(B) We seek the upward velocity of the popped corn, which is the upward velocity of the hot air, minus the terminal velocity of the popped corn. We repeat the calculation of part (a), but with the parameters for popped corn.

$$\text{volume} = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi\left(\frac{30 \text{ mm}}{2}\frac{1 \text{ m}}{1000 \text{ mm}}\right)^3 = 1.42 \times 10^{-5} \text{ m}^3$$

$$\text{density} = \rho = \frac{\text{mass}}{\text{volume}} = \frac{(0.05 \text{ g})(1 \text{ kg}/1000 \text{ g})}{1.42 \times 10^{-5} \text{ m}^3} = 3.5 \text{ kg}/\text{m}^3$$

$$\text{Re} = \frac{d\,v\rho_{\text{fluid}}}{\mu} = \frac{(30 \text{ mm})(1 \text{ m}/1000 \text{ mm})v(0.9 \text{ kg}/\text{m}^3)}{3 \times 10^{-5} \text{ Pa} \cdot \text{s}} = 900v$$

$$\boxed{v = \frac{\text{Re}}{900}}$$

$$\text{F} = \frac{4}{3}\frac{g\,d(\rho_{\text{sphere}} - \rho_{\text{fluid}})}{v^2 \rho_{\text{fluid}}} = \frac{4}{3}\frac{(9/8 \text{ m}/\text{s}^2)(30 \text{ mm})(1 \text{ m}/1000 \text{ mm})(3.5 - 0.9 \text{ kg}/\text{m}^3)}{v^2(0.9 \text{ kg}/\text{m}^3)} = \frac{1.1}{v^2}$$

$$\boxed{v = \left(\frac{1.1}{\text{F}}\right)^{1/2}}$$

As in part (a) we solve the two simultaneous equations for v to obtain $v = 1.6$ m/s at Re = 1500 and F = 0.4. The (untruncated) velocity of the hot air is 14 m/s. Thus the upward velocity of the popped corn is 14 - 1.6 = 12.4 m/s. Truncating to two significant figures,

$$\boxed{\text{The velocity of the popped corn is 12 m/s.}}$$

6.2   Add the following to (C).

(C)   Thus the equilibrium concentration of X depends on the rate of decomposition of X, as expected. Also, the rate that the concentration reaches equilibrium depends on the rate of decomposition of X as shown qualitatively in the plot below. Also shown is the predicted result for no decomposition (part B) in which the concentration of X increases linearly.