2.10 The flowsheet neglected to recycle some of the CO₂ 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 CaCO₃ and NaCl should enter the process and only Na₂CO₃ and CaCl₂ should leave the process. However, it is not possible to separate CaCl₂ from NH₄Cl; both are soluble in water. So, the CaCl₂/NH₄Cl solution must be discarded or purged. Recycling a portion of the CaCl₂/NH₄Cl solution will consume some of the CaCl₂ but will also cause NH₄Cl to build up in the chlorinator/carbonator loop. In either case (partial purge or complete purging of the CaCl₂/NH₄Cl solution) NH₄Cl must be added to the system.
2.15 (C) There should not be any SO$_3$ in the recycle, as shown below.

![Chemical reaction diagram]

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 has 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 that 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 zeolite 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$_2$H$_2$ to product C$_2$H$_3$Cl. The additional HCl in each process converts C$_2$H$_3$Cl to by-product C$_2$H$_4$Cl$_2$. 
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 \( \text{C}_2\text{H}_2 \text{ and HCl } \) plus the amount recycled. Which scheme recycles the most? Obviously, Scheme II does.

\[ \text{3.30} \] 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.

\[
F_{\text{H}_2\text{O},3a} = \frac{100. \text{ kg}}{\text{min}} \left( \frac{29 \text{ joules}}{(\text{°C})(\text{mol air})} \right) \left( \frac{1000 \text{ mol air}}{28.8 \text{ kg air}} \right) (20 - 38^\circ \text{C}) = 0.80 \text{ kg water / min}
\]

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. \]

\[ \text{Stream 2 is 0.79 wt % water.} \]

(B)

Substitute flow rates and thermodynamic constants.

\[
\left( \frac{1.46 \text{ kg water}}{\text{min}} \right) \left( \frac{4.1 \times 10^4 \text{ joules}}{\text{mol water}} \right) \left( \frac{1000 \text{ mol water}}{18 \text{ kg water}} \right) + \frac{100. \text{ kg air}}{\text{min}} \left( \frac{29 \text{ joules}}{(\text{°C})(\text{mol air})} \right) \left( \frac{1000 \text{ mol air}}{28.8 \text{ kg air}} \right) = 53^\circ \text{C}
\]

\[ \text{The maximum air temperature is } 53^\circ \text{C (127°F).} \]

\[ \text{3.31} \] 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.

\[
\Delta q_{\text{air}} = F_{\text{air}} C_{p,\text{air}} (\Delta T)
\]

\[
= \left( \frac{2 \times 10^5 \text{ } \text{m}^3}{\text{min}} \right) \left( \frac{1000 \text{ L}}{1 \text{ m}^3} \right) \left( \frac{1 \text{ mol}}{22.4 \text{ L}} \right) \left( \frac{29 \text{ joules}}{(°C)(\text{mol})} \right) \left( \frac{60 \text{ min}}{1 \text{ hr}} \right) \left( \frac{68 - 90 ^\circ \text{F}}{1.8 ^\circ \text{F}} \right) \left( \frac{1 ^\circ \text{C}}{1 ^\circ \text{F}} \right)
\]

\[ = -1.90 \times 10^{11} \text{ joules / hr} \]

\( \Delta q_{\text{air}} \) is negative because the air loses energy when it cools. Calculate the flow rate of chilled water.
\[ \Delta q_{\text{air}} = -\Delta q_{\text{water}} = -F_{\text{water}} C_{P,\text{water}} (\Delta T) \]

\[
F_{\text{water}} = \frac{-\Delta q_{\text{air}}}{C_{P,\text{water}} (\Delta T)} = \frac{-(-1.9 \times 10^{11} \text{ joules/hr})}{75 \text{ joules/}(1^\circ\text{C})(\text{mol water}) \left(60 - 45 \text{ }^\circ\text{F}\right) \left(1^\circ\text{C}/1.8 \text{ }^\circ\text{F}\right)} = 3.04 \times 10^8 \text{ mol water/hr} \]

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 \times 10^6 \text{ gal/hour.}

(B) Calculate the energy released by condensing the water vapor.

\[ \Delta q_{\text{condense}} = -F_{\text{condense}} \Delta H_{\text{vap,water}} \]

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

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.

\[
\Delta q_{\text{air}} = \Delta q_{\text{cool}} + \Delta q_{\text{condense}} = -1.9 \times 10^{11} \text{ joules/hr} + -8.08 \times 10^{11} \text{ joules/hr} = -9.98 \times 10^{11} \text{ joules/hr} \]

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

\[
\text{chilled water}_{\text{part (B)}} = \frac{\text{chilled water}_{\text{part (A)}} \left(\frac{\Delta q_{\text{part (B)}}}{\Delta q_{\text{part (A)}}}\right)}{\text{chilled water}_{\text{part (A)}}} = 1.44 \times 10^6 \text{ gal/hr} \left(\frac{-9.98 \times 10^{11} \text{ joules/hr}}{-1.90 \times 10^{11} \text{ joules/hr}}\right) = 7.56 \times 10^6 \text{ gal/hr} \]

The flow rate of chilled water is 7.6 \times 10^6 \text{ 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

\[
\Delta q_{\text{water}} = -\Delta q_{\text{chilled}} \]

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

\[
F_{\text{lake}} = -\frac{(\Delta T)_{\text{chilled}}}{(\Delta T)_{\text{lake}}} = -\frac{45 - 60 \text{ }^\circ\text{F}}{55 - 40 \text{ }^\circ\text{F}} \text{ gal/hr} = 7.56 \times 10^6 \text{ gal/hr} \]
The flow rate of lake water is $7.6 \times 10^6$ gal/hr.

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

(C)

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

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

\[
q_{\text{heater}} = 3.2 \times 10^4 \text{ kJ/hr}
\]

(D)

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

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

The total heating rate is thus

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

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.
mass of silica fiber = mass of silica boule

(volume of fiber)(density of fiber) = (volume of boule)(density of boule)

volume of fiber = (volume of boule)(density of boule)

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

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

= \( 5.4 \times 10^{-4} \text{ m}^3 \)

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.

\[
\text{volume of fiber} = (\text{volume of filled spool}) - (\text{volume of empty spool})
\]

\[
\pi (\text{radius of filled spool})^2 (\text{ht of spool}) - \pi (\text{radius of empty spool})^2 (\text{ht of spool})
\]

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

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

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 \( 22.4 \times 760 \text{ torr/1 torr} = 17,000 \text{ L/(mol benzene)} \) - 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.
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% H₂O 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, $x = K/oil = 0.068/8.5 = 0.008$ and $y = K/air = 0.0032$ (from the graph).

4.13 The flowsheet is missing an arrowhead on the oil recycle
4.26 There is an error in the fifth bullet item:
• the feed needs to be heated 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.
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.

20 mol % acetonitrile  
80 mol % water

98 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 \( x_{y_W}y_W \) 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 \( x_{y_W}y_W \) 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
two phases: liquid+vapor

two phases: liquid+liquid

one phase: liquid

vapor

two phases: liq+vapor

x_W, y_W
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:
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.

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

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

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

\[
v = \frac{\text{Re}}{900}
\]

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

\[
v = \left( \frac{1.1}{F} \right)^{1/2}
\]
As in part (a) we solve the two simultaneous equations for $v$ to obtain $v = 1.6 \text{ m/s at } Re = 1500$ and $F = 0.4$. The (untruncated) velocity of the hot air is 14 m/s. Thus the upward velocity of the popped corn is $14 - 1.6 = 12.4 \text{ m/s}$. Truncating to two significant figures,

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.