Solutions Manual to Accompany

Basic Principles and Calculations in Chemical Engineering

Seventh Edition

David M. Himmelblau
University of Texas

James B. Riggs
Texas Tech University

PRENTICE HALL
Professional Technical Reference
Upper Saddle River, New Jersey 07458
TYPICAL EXAMS FOR A ONE SEMESTER COURSE
(scheduled in the evening to avoid time constraints on students)

Exam No. 1
(Open Book, 1 1/2 hours)

PROBLEM 1 (5%)

Hydrogen can be separated from natural gas by diffusion through a round tube. The rate of separation is given by

\[ N = 2 \pi D \rho R \]

where

\[ N = \text{rate of transport of } H_2 \text{ from the tube, g moles/(sec)(cm of length of tube)} \]

\[ D = \text{diffusion coefficient} \]

\[ \rho = \text{molar density of } H_2, \text{ g moles/cm}^3 \]

\[ R = \log \text{mean radius of tube, } r_2 - r_1 / n \left( \frac{r_2}{r_1} \right), \text{ with } r \text{ in cm.} \]

What are the units of D?

PROBLEM 2 (10%)

A pallet of boxes weighing 10 tons is dropped from a lift truck from a height of 10 feet. The maximum velocity the pallet attains before hitting the ground is 6 ft/sec. How much kinetic energy does the pallet have in (ft)(lb) at this velocity?

PROBLEM 3 (5%)

The specific gravity of a fuel oil is 0.82. What is the density of the oil in lb/ft³? Show all units.

PROBLEM 4 (10%)

Sulfur trioxide (SO₃) can be absorbed in sulfuric acid solution to form more concentrated sulfuric acid. If the gas to be absorbed contains 55% SO₃, 41% N₂, 3% SO₂, and 1% O₂, how many parts per million of O₂ are there in the gas? (b) What is the composition of the gas on a N₂ free basis?

PROBLEM 5 (15%)

You have 100 kilograms of gas of the following composition:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>30%</td>
</tr>
<tr>
<td>H₂</td>
<td>10%</td>
</tr>
<tr>
<td>N₂</td>
<td>60%</td>
</tr>
</tbody>
</table>

What is the average molecular weight of this gas?

PROBLEM 6 (15%)

If the heat capacity of a substance is 5.32 J/(g)(°C) and its molecular weight is 37.4, what is its heat capacity in

(a) J/(g)(°F)
(b) J/(lb)(°R)
(c) J/(gmoles)(K)

PROBLEM 7 (20%)

A rock containing 100% BaSO₄ is burned with coke (94% C, 6% ash) and the composition of the product is BaSO₄ (11.1%) BaS (72.9%), C(13.9%), ash (2.2%). The reaction is

\[ \text{BaSO}_4 + 4 \text{C} \rightarrow \text{BaS} + 4 \text{CO} \]

Calculate the percent excess reactant, and the degree of completion of the reaction.

PROBLEM 8 (20%)

A gas cylinder to which is attached a Bourden gage appears to be at a pressure of 27.38 in. Hg at 70°F. The barometer reads 101.8 kPa. A student claims that the pressure in the tank is 1.3 psia, but another student points out that this is impossible - the pressure is really 28.2 psia. Can 1.3 psia be correct? Explain and show calculations to back up your explanation.
PROBLEM 1 (25%)

A chemist attempts to prepare some very pure crystals of Na₂SO₄·10H₂O by dissolving 200 g of Na₂SO₄ (Molar Weight = 142.05) in 400 g of boiling water. He then carefully cools the solution slowly until some Na₂SO₄·10H₂O crystallizes out. Calculate the g of Na₂SO₄·10H₂O recovered in the crystals per 100 g of initial solution, if the residual solution after the crystals are removed contains 28% Na₂SO₄.

Right answer but: −10 if answer is in g of Na₂SO₄ and 0 g of Na₂SO₄·10H₂O per 100 g of initial soln

PROBLEM 2 (25%)

Water pollution in the Hudson River has claimed considerable recent attention, especially pollution from sewage outlets and industrial wastes. To determine accurately how much effluent enters the river is quite difficult because to catch and weigh the material is impossible, weirs are hard to construct, etc. One suggestion which had been offered is to add a trace Br⁻ ion to a given sewage stream, let it mix well, and sample the sewage stream after it mixes well.

On one test of the proposal you add ten pounds of NaBr per hour for 24 hours to a sewage stream with essentially no Br⁻ in it. Somewhat downstream of the introduction point a sampling of the sewage stream shows 0.012% NaBr. The sewage density is 60.3 lb/ft³ and river water density is 62.4 lb/ft³.

What is the flow rate of the sewage in lb/min?

−10 if answer based on 0.012 fraction and not 0.00012.

PROBLEM 3 (25%)

In preparing 5.00 moles of a mixture of three gases (SO₂, H₂S, and CS₂), gases from three tanks are combined into a fourth tank. The tanks have the following compositions (mole fractions):

<table>
<thead>
<tr>
<th>Gas</th>
<th>Tank 1</th>
<th>Tank 2</th>
<th>Tank 3</th>
<th>Tank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>0.10</td>
<td>0.20</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.40</td>
<td>0.20</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>CS₂</td>
<td>0.50</td>
<td>0.60</td>
<td>0.50</td>
<td>0.54</td>
</tr>
</tbody>
</table>

How much of Tanks 1, 2, and 3 must be mixed to give a product with composition of Tank 4?

−10 for correct answer but wrong basis

−15 A lot of people said no soln.

They used wrong basis, etc. No soln but correct math balance

(continued)
PROBLEM 4 (25%)

10% a) For the given distillation process, calculate the composition of the bottoms stream.

15% b) If steam leaked into the column at 1000 mole/sec and all else was constant, what would the new bottoms composition be? (should be g-mole). If assumed to k-mole and not stated.

PROBLEM 2 (35%)

Benzene, toluene and other aromatic compounds can be recovered by solvent extraction with sulfur dioxide. As an example, a catalytic reformat steam containing 70% by weight benzene and 30% non-benzene material is passed through the countercurrent extractive recovery scheme shown in the diagram below. One thousand pounds of the reformat steam and 3000 pounds of sulfur dioxide are fed to the system per hour. The benzene product stream (the extract) contains 0.15 pound of sulfur dioxide per pound of benzene. The raffinate stream contains all the initially charged non-benzene material as well as 0.25 pound of benzene per pound of the non-benzene material. The remaining component in the raffinate stream is the sulfur dioxide.

(a) How many pounds of benzene are extracted per hour, i.e. are in the extract?

(b) If 800 pounds of benzene containing in addition 0.25 pound of the non-benzene material per pound of benzene are flowing per hour at point A and 700 pounds of benzene containing 0.07 pound of the non-benzene material per pound of benzene are flowing at point B, how many pounds (exclusive of the sulfur dioxide) are flowing at points C and D?

PROBLEM 1 (35%)

A company burns an intermediate product gas having the composition 4.3% CO₂, 27% CO, 10% H₂, 1.0% CH₄, and the residual N₂ together with a waste oil having the composition 87% C, 13% H₂. Analysis of the stack gas gives an Orsat analysis of 14.6% CO₂, 0.76% CO, and 7.65 O₂ and the rest N₂. Calculate the fraction of the total carbon burned that comes from the product gas.
Reactant A is polymerized as shown in the figure. It is mixed with fresh catalyst and recycled catalyst. Conversion of A is 40% on one pass through the reactor. Fresh catalyst (G) enters at the rate of 0.40 lb G per lb of A in stream H. The separator removes 90% of the catalyst and recycles it as well as recycling unreacted A. Nevertheless, the product stream P contains 15% of the unreacted A and 10% of the catalyst exiting in stream K as well as the polymer product. Determine the ratio of stream R to G.

Note: catalyst does not react in the process!

Exam No. 4
(Open Book, 2 hours)

PROBLEM 1 (25%)

In the vapor-compression evaporator (not insulated) shown in the figure below, the vapors produced on evaporation are compressed to a higher pressure and passed through the heating coil to provide the energy for evaporation. The steam entering the compressor is 98% quality at 10 psia, the steam leaving the compressor is at 50 psia and 400°F, and 6 Btu of heat are lost from the compressor per pound of steam throughput. The condensate leaving the heating coil is at 50 psia, 200°F. The replacement liquid is at the temperature of the liquid inside the evaporator.

Computer:

(a) the work in Btu needed for compression per pound of H_2O going through the compressor.

(b) the Btu of heat transferred from the heating coil to the liquid in the evaporator per pound of H_2O through the coil.

PROBLEM 2 (25%)

An insulated, sealed tank that is 2 ft³ in volume holds 8 lb of water at 100°F. A 1/4 hp stirrer mixes the water for 1 hour. What is the fraction vapor at the end of the hour? Assume all the energy from the motor enters the tank.

For this problem you do not have to get a numerical solution. Instead list the following in this order:

1. State what the system you select is.
2. Specify open or closed.
3. Draw a picture.
4. Put all the known or calculated data on the picture in the proper place.
5. Write down the energy balance (use the symbols in the text) and simplify it as much as possible. List each assumption in so doing.
6. Calculate W.
7. Lists the equations with data introduced that you would use to solve the problem.
8. Explain step by step how to solve the problem (but do not do so).

PROBLEM 3 (15%)

What is the enthalpy change in Btu when 1 pound mole of air is cooled from 600°F to 100°F at atmospheric pressure.

Compute your answer by two ways:
1) Use the tables of the combustion gases
2) Use the heat capacity equation for air.
PROBLEM 4 (10%)  
Answer the following questions by placing T for true and F for false on your answer page. Grading: +2 if correct, 0 if blank, -1 if wrong.

(a) Heat and thermal energy are synonymous terms used to express one type of energy.  
(b) You can find the enthalpy change at constant pressure of a substance such as CO₂ from the solid to the gaseous state by integrating  
   \[ \int_{T_1}^{T_2} C_p \, dT \]  
   from \( T_1 \) (solid temperature) to \( T_2 \) (gas temperature) for a constant pressure path.  
(c) The enthalpy change of a substance can never be negative.  
(d) Heat and work are the only methods of energy transfer in a non-flow process.  
(e) Both \( Q \) and \( \Delta H \) can be classed as state functions (variables).

PROBLEM 5 (25%)  
Hot reaction products (assume they have the same properties as air) at 1000°F leave a reactor. In order to prevent further reaction, the process is designed to reduce the temperature of the products to 400°F by immediately spraying liquid water into the gas stream. How many lb of water at 70°F are required per 100 lb of products leaving at 400°F?

\[ \text{H}_2\text{O at 70°F} \]  
\[ \text{Reactor} \]  
\[ \text{Products} \]  
\[ \text{1000°F} \]  
\[ \rightarrow 400°F \]

For this problem you do not have to get a numerical solution. Instead list the following in this order.

1. State what the system you select is.
2. Specify open or closed.
3. Draw a picture.

Exam No. 5  
(Open Book, 2 hours)

PROBLEM 1 (10%)  
Answer the following questions briefly (no more than 3 sentences);

a. Does the addition of an inert diluent to the reactants entering an exothermic process increase, decrease, or make no change in the heat transfer to or from the process?  
b. If the reaction in a process is incomplete, what is the effect on the value of the standard heat of reaction? Does it go up, down, or remain the same?  
c. How many properties are needed to fix the state of a gas so that all of the other properties can be determined?  
d. Consider the reaction \( \text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(g) \). Is the heat of reaction with the reactants entering and the products leaving at 500K higher, lower, or the same as the standard heat of reaction?

PROBLEM 2 (10%)  
Explain how you would calculate the adiabatic reaction temperature for Problem 5 below if the outlet temperature is not specified. List each step. (You can cite some of the steps listed in Problem 5 if you list them by number in Problem 5.)

PROBLEM 3 (20%)  
A flue gas at 750°F and 1 atm of composition 14.0% \( \text{CO}_2 \), 1.0% \( \text{CO} \), 6.4% \( \text{O}_2 \), and the balance \( \text{N}_2 \) is the product of combustion with excess air at 750°F and 1 atm that is used to burn coke (C). (continued)
PROBLEM 4 (20%)  

Seven pounds of N\textsubscript{2} are stored in a cylinder 0.75 ft\textsuperscript{3} volume at 120°F. Calculate the pressure in the cylinder in atmosphere:

a. Assuming N\textsubscript{2} to be an ideal gas.

b. Assuming N\textsubscript{2} is a real gas and using compressibility factors.

PROBLEM 5 (40%—one half each for the material and energy balances)

Pyrites (FeS\textsubscript{2}) is converted to sulfur dioxide (SO\textsubscript{2}) gas according to the reaction

\[ 4\text{FeS}_2(s) + 11\text{O}_2(g) \rightarrow 2\text{Fe}_2\text{O}_3(s) + 8\text{SO}_2(g) \]

The air which is 35% excess (based on the above reaction) for combustion enters at 27°C, the ore at 18°C, and the products leave at 900K. Because of equipment degradation, unburned FeS\textsubscript{2} exits from the process. In one hour 8000 kg of pyrites are fed to the process, and 2000 kg of Fe\textsubscript{2}O\textsubscript{3} are produced. What is the heat added or removed from the process? Data: For FeS\textsubscript{2}, C\textsubscript{P} = 44.77 + 5.590 × 10\textsuperscript{-2}T where T is in Kelvin and C\textsubscript{P} is in J/(g mol)(K). For Fe\textsubscript{2}O\textsubscript{3}, C\textsubscript{P} = 103.4 + 6.71 × 10\textsuperscript{-2}T with the same units.

Exam No. 6  
(Open Book, 2 hours)

PROBLEM 1 (20%)  

A high pressure line carries natural gas (all methane) at 10,000 kPa and 40°C. How would you calculate the volume of the gas under these conditions that is equivalent to 0.03 m\textsuperscript{3} of CH\textsubscript{4} at standard conditions using an equation of state? Select one equation other than van der Waal's equation, and list it on your solution page. Give a list of steps to complete the calculations. Include all the proper equations, and include a list of data involved, but you do not have to obtain a solution for the volume.

PROBLEM 2 (20%)  

From the following data estimate the vapor pressure of sulfur dioxide at 100°C.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>-10</th>
<th>6.3</th>
<th>32.1</th>
<th>55.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor pressure (atm)</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

PROBLEM 3 (20%)  

Dry atmospheric air at the ambient conditions of 90°F and 29.42 in. Hg absolute passes through a small blower and is bubbled up through water so that the air leaving the water is saturated. The temperature of the water is constant at 80°F, and because of the back pressure in the system, the pressure in the vapor space in the top of the bottle is 2.7 in.

H\textsubscript{2}O greater than atmospheric pressure. The bottle is weighted after the air is blown for 2 hours, 13 minutes, 47 seconds, and the decrease in weight was found to be 8.73 lb. What was the hourly rate of flow of air at ambient conditions in ft\textsuperscript{3}?

PROBLEM 4 (20%)  

A vessel with a volume of 2.83 m\textsuperscript{3} contains a mixture of nitrogen and acetone at 44.0°C and 100.0 kPa. The dew point of the mixture is 20.0°C and the relative saturation of the acetone in the mixture is 58.39%. The vapor pressure of acetone at 44.0°C is 65.35 kPa and it is 24.62 kPa at 20.0°C.

a. What is the partial pressure of acetone vapor in the original mixture, in kPa?

b. How many kg moles of acetone does the original mixture contain?

c. If the nitrogen-acetone mixture is cooled with the volume remaining at 2.83 m\textsuperscript{3} constant so that 27.0 percent of the acetone condenses, what is the final temperature of the mixture in °C?
PROBLEM 5 (20%)

A wet sludge contains 50 percent water by weight. This sludge is first centrifuged, and 0.1 kilograms of water are removed per kilogram of wet sludge feed. The sludge is then dried further using air so that the final product contains 10 percent by weight water. The air for drying is heated, passed into an oven drier, and vented back into the atmosphere. On a day when atmospheric pressure is 760 mm Hg, the temperature is 70°F and the relative humidity is 50%, calculate the cubic meters of wet air required to dry one kilogram of sludge fed to the process. The air vented from the oven drier is at 100°F and 780 mm Hg. It has a dew point of 94°F.
1.1  

a. Basis: 1 m$^3$
\[ 1 \text{ m}^3 = \left( \frac{5280 \text{ ft}}{1 \text{ mi}} \right) \left( \frac{12 \text{ in}}{1 \text{ ft}} \right) \left( \frac{2.54 \text{ cm}}{1 \text{ in}} \right) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right)^3 = 4.17 \times 10^3 \text{ m}^3 \]

b. Basis: 1 ft$^3$/s
\[ 1 \text{ ft}^3 = \frac{60 \text{ s}}{1 \text{ hr}} \times \frac{7.48 \text{ gal}}{1 \text{ ft}^3} = 449 \text{ gal/sec} \]

1.2  

a. Basis: 1 lb$_m$
\[ 1 \text{ lb}_m = \left( \frac{1 \text{ in}^3}{1 \text{ min} \cdot \text{hr}} \right) \left( \frac{1 \text{ ft}^3}{1 \text{ hr}} \cdot \frac{454 \text{ g}}{1 \text{ lb}_m} = 9.14 \left( \frac{\text{lb}_m}{\text{in}^3} \right) \right) \]

\[ 21 \text{ L} = \frac{3600 \text{ s}}{1 \text{ hr}} \cdot \frac{1 \text{ ft}^3}{1 \text{ hr}} \cdot \frac{1 \text{ min}}{1 \text{ hr}} \cdot \frac{454 \text{ g}}{1 \text{ lb}_m} \]  
= \[ 6.1 \times 10^2 \text{ ft}^3 \]

b. 28.32 L
\[ \frac{1 \text{ hr}}{1 \text{ day}} \cdot \frac{1 \text{ min}}{1 \text{ hr}} \cdot \frac{1 \text{ ft}^3}{1 \text{ hr}} \cdot \frac{454 \text{ g}}{1 \text{ lb}_m} \]  
= \[ 6.1 \times 10^2 \text{ ft}^3 \]

c. Basis: 1 lb$_m$/hr
\[ 1 \text{ lb}_m = \left( \frac{1 \text{ in}}{1 \text{ yr}} \right) \left( \frac{1 \text{ ft}^3}{1 \text{ yr}} \right) \left( \frac{1 \text{ in}^2}{1 \text{ ft}^2} \right) \left( \frac{1 \text{ yr}}{366 \text{ days}} \right) \left( \frac{3600 \text{ s}}{24 \text{ hr}} \right) \left( \frac{1 \text{ kg}}{1 \text{ lb}_m} \right) \]  
= \[ 2.2 \text{ lb}_m \]

\[ 1 \text{ ft} = \frac{0.3048 \text{ m}}{1 \text{ in}} \]  
= \[ 1.4 \times 10^{-11} \text{ m} \]

1.3  

The Pascal is a pressure unit, defined as 1 N/m$^2$ and it is not the same as a mass flux unit. The correct equivalent is 3.9 Mg/(hr)(m$^2$). If the "lb" means "lbs," then the conversion is correct. Since the English short ton is not part of SI, "L/ton" is not, either. Correct is "34 gal/ton (142 L/Mg)."

If the ton is a metric ton, then 129 L/ton is correct.

1.4  

a. Basis: 60.0 mile/hr
\[ \frac{60.0 \text{ mile/hr}}{1 \text{ hr}} = \frac{88 \text{ ft}}{3600 \text{ sec}} = \frac{88 \text{ ft}}{1 \text{ mile}} \]

b. Basis: 50.0 lb$_w$/in$^2$
\[ 50.0 \text{ lb}_w = \frac{454 \text{ g}}{1 \text{ kg}} \cdot \frac{1 \text{ kg}}{1 \text{ lb}_w} \cdot \frac{1 \text{ in}^2}{1 \text{ lb}_w} \cdot \frac{100 \text{ cm}^2}{1 \text{ in}^2} \cdot \frac{1 \text{ m}^2}{(2.54 \text{ cm})^2} \cdot \frac{1 \text{ m}^2}{(1 \text{ m})^2} = 3.52 \times 10^4 \text{ kg/m}^2 \]

c. Basis: 6.20 cm/hr$^2$
\[ 6.20 \text{ cm/hr$^2$} = \frac{6.20 \text{ cm}}{1 \text{ m}} \cdot \frac{1 \text{ m}}{10^6 \text{ cm}} \cdot \frac{1 \text{ hr}}{3600 \text{ sec}} = \frac{4.79 \text{ nm}}{1 \text{ sec}} \]

1.5  

(a) N/mm or nm (nanometer)  
(b) °C/M/S  
(c) 100 kPa  
(d) 2.73.15 K  
(e) 1.50 m, 45 kg  
(f) 25°C  
(g) J/s  
(h) 250 N  

1.6  

20 hp = \[ \frac{0.7457 \text{ kW}}{1 \text{ hp}} = 14.91 \text{ kW} \]

No, not enough power even at 100% efficiency; 68 kW = 91.2 hp.
1.7 \[ \frac{1 \text{ hr}}{525 \text{ mile}} \times \frac{2200 \text{ gal}}{1 \text{ hr}} \times \frac{1000 \text{ mile}}{1 \text{ hr}} = 4190.5 \text{ gal} \]

\[ \frac{1 \text{ hr}}{475 \text{ mile}} \times \frac{2000 \text{ gal}}{1 \text{ hr}} \times \frac{1000 \text{ mile}}{1 \text{ hr}} = 4210 \text{ gal} \]

None: 20 gal more are needed.

1.8 Let \( t_1 \) be the time for A to paint one house; \( t_2 \) for B. A does a house in 5 hours, or 1 house/5 hr. B does one house in 3 hours, or 1 house/3 hr.

\[ \frac{1 \text{ house}}{5 \text{ hr}} + \frac{1 \text{ house}}{3 \text{ hr}} = \frac{t_1 + t_2}{3 \text{ hr}} = 1 \text{ house} \]

Also \( t_1 = t_2 \) so that

\[ \frac{3}{15} t_1 + \frac{5}{15} t_2 = 1 \text{ or } \frac{8}{15} t_1 = 1 \]

\[ t_1 = \frac{\frac{15}{8}}{\frac{15}{8}} \text{ or } t_1 = 1.875 \text{ hr or } 112.5 \text{ min} \]

1.9 (a) mass, because masses exerted on the mass pushes a spring

(b) weight, because the force exerted on the mass pushes a spring

1.10

\[ \begin{array}{cccccc}
20.0 \text{ gal} & 1 \text{ lb}_m & 0.3048 \text{ m} & 3600 \text{ s} & 1 \text{ lb}_m \times (\text{ft}^2) \times (\text{lb}_m)(\text{ft}) & 1 \text{ hr} \times (\text{lb}_m)(\text{ft}) \\
(\text{m})(\text{s}) & 453.6 \text{ g} & 1 \text{ ft} & 1 \text{ hr} & 32.174 & (3600)^2 s^2 \\
\end{array} \]

\[ = 116 \times 10^{-2} \text{ lb}_m(\text{lb}_m)(\text{ft}) = \frac{1.16 \times 10^{-2} \text{ lb}_m}{\text{ft}^2} \]

Solutions Chapter 1

1.11

\[
\begin{array}{cccc}
1.0 \text{ Btu} & 24 \text{ hrs} & 1 \text{ ft}^2 & 1 \text{ in}^2 & 100 \text{ cm}^2 & 1.8^\circ \text{F} & 2.54 \text{ cm} \\
\text{hr}(\text{ft})^2 \times \frac{6^\circ \text{F}}{\text{ft}} & 1 \text{ day} & (12 \text{ in})^2 & (2.54 \text{ cm})^2 & 1 \text{ m}^2 & 1^\circ \text{C} & \text{in} \\
\end{array}
\]

\[ 252 \text{ cal} \times \frac{12 \text{ in}}{1 \text{ ft}} = 4.184 J \times \frac{1 \text{ cal}}{1 \text{ kJ}} = 1.49 \times 10^4 \frac{\text{kJ}}{\text{day}} \times \frac{1 \text{ ft}^2}{\text{m}^2} \times \frac{10^\circ \text{C}}{\text{cm}} \]

1.12 Basis: 1 lb H$_2$O

a. \[ fE = \frac{1}{2} \text{ mv}^2 = \frac{1}{2} \text{ lb}_m \left( \frac{3 \text{ ft}}{s} \right)^2 \left( \frac{32.174 \text{ ft}}{\text{lb}_m} \right) = 0.14(\text{ft})(\text{lb}_m) \]

b. Let \( A = \text{ area of the pipe and } v = \text{ water velocity} \). The flow rate is

\[ q = Av = \left( \frac{\pi D^2}{4} \right) (v) \]

\[ = \pi \left( \frac{2 \text{ in}^2}{1 \text{ ft}^2} \right) \left( \frac{1 \text{ ft}}{12 \text{ in}} \right) \frac{3 \text{ ft}}{60 \text{ s}} \frac{1 \text{ gal}}{1 \text{ ft}^2} = 29.37 \text{ gal/min} \]

1.13 Not really – but people do not usually distinguish between mass and weight.

1.14 The object has a mass of 21.3 kg (within a precision of \( \pm 0.1 \) kg). The weight is the force used to support the mass.
1.15  In American Engineering System

Power = \( \frac{FV}{\text{min}} \)

\[
= \frac{800 \text{ lb}}{\text{min}} \times 300 \text{ ft} = \frac{2.4 \times 10^3 \text{ lb} \cdot \text{ft} \cdot \text{min}}{\text{min}} = 7.27 \text{ hp}
\]

In SI

\[
\text{Power} = \frac{4000 \text{ N} \cdot 1.5 \text{ m}}{1 \text{ s} \cdot 1(\text{N})(\text{m})} = 6000 \text{ watts}
\]

1.16

\[
\text{KE} = \frac{1}{2} \text{ m} \cdot \text{v}^2
\]

\[
= \frac{\left( 12300 \text{ kg} \cdot \frac{1 \text{ lbm}}{2 \text{ kg}} \cdot \frac{10.0 \text{ ft}}{32.2 \text{ lbm} \cdot \frac{\text{ft}}{\text{sec}} \cdot \frac{\text{sec}^2}{\text{ft}}} \right)^2}{778.2(\text{ft}^2) \text{lb}} = 10.11 \text{ Btu}
\]

1.17  Basis: 10 tons at 6 ft/s

\[
\text{KE} = \frac{1}{2} \text{ m} \cdot \text{v}^2 = \frac{1}{2} \left( \frac{20000 \text{ lb}}{\text{s}} \right)^2 \frac{6 \text{ ft}}{32.2(\text{ft})(\text{lb})} = \frac{11200(\text{ft})(\text{lb})}{\text{lb}}
\]

1.18  \( \eta = \frac{\text{numerator}}{\text{denominator}} \)

Numerator = \( Y_{rev} \gamma_b \Delta H_{rev} \)

\[
= \left( \frac{\text{mol cell C}}{\text{mole substrate C}} \right) \left( \frac{\text{e}^- \text{equiv.}}{\text{mol cell C}} \right) \left( \frac{\text{energy}}{\text{mol e}^- \text{equiv.}} \right)
\]

\[
= \frac{\text{energy}}{\text{mol substrate C}}
\]

Denominator = \( \Delta H_{\text{re}} \)

\[
= \frac{\text{energy}}{\text{mol substrate C}}
\]

\[
\eta = \frac{(1)}{(2)} = \frac{\text{energy}}{\text{energy}}
\]

There is no missing conversion factor.
What the author claimed about the units is correct.
Solutions Chapter 1

1.19

\[ Q = 0.61S \sqrt{(2\Delta p)/\rho} \]

Assume hole is open to atmosphere

\[ \Delta p = \frac{144 \text{ in}^2}{1 \text{ ft}^2} \left[ \frac{23 \text{ lb}}{\text{ in}^2} + \frac{73 \text{ in gas}}{1 \text{ gas}} \times \frac{0.703 \text{ H}_2\text{O}}{1 \text{ ft}} \times \frac{14.7 \text{ lb}}{\text{ in}^2} \right] \]

\[ = 3.579 \text{ lb} \text{/ft}^2 \]

\[ \rho = \frac{0.703 \text{ lb}}{1 \text{ ft}^3} \times \frac{62.4 \text{ lb H}_2\text{O}}{1 \text{ ft}^3} = 43.87 \text{ lb/ft}^3 \]

\[ S = \pi \left( \frac{1}{12} \right)^2 = 3.41 \times 10^{-4} \text{ ft}^2 \]

\[ Q = (3600)(0.61)(3.41 \times 10^{-4}) \sqrt{(2)(3579)} \times 43.87 = 0.61 \text{ ft}^3/\text{hr} \]

1.20

\[ q = 0.6(2 \text{ m}^3) \left[ \frac{(2)}{9.81 \text{ m/s}^2} \right] \left[ 10^3 \text{ kg/m}^3 \left( \frac{50 \times 10^6 \text{ kg/m}}{(s^3)(m^3)} \right) \left( \frac{1}{1 - (2/2)} \right) \right] \]

The net units on the right hand side of the equation are

\[ m^3 \left[ \frac{m^2}{s^3} \right] \left[ \frac{m^2}{s^2} \right] = \frac{m^3}{s^4} \]

Consequently, the formula will not yield 80.8 m/s, presumably in the formula the \( g \) should be \( g \) for use in the AE system.
Solutions Chapter 1

1.22

a. \[ Z = 1 + \rho B + \rho^2 C + \rho^3 D \]

Units

B \quad \text{cm}^3 / \text{g mol}

C \quad (\text{cm}^3 / \text{g mol})^2

D \quad (\text{cm}^3 / \text{g mol})^3

b. \[ Z = 1 + \rho^* B^* + (\rho^*)^2 C^* + (\rho^*)^3 D^* \]

Units

B^* \quad \text{ft}^3 / \text{lb}_m

C^* \quad (\text{ft}^3 / \text{lb}_m)^2

D^* \quad (\text{ft}^3 / \text{lb}_m)^3

If B is the original coefficient, B^* is obtained by multiplying B by conversion factors. Let MW is the molecular weight of the compound.

\[ B^* = \frac{B \times \frac{1 \text{ ft}^3}{1 \text{ lb}_m} \times \frac{\frac{1 \text{ g mol}}{1 \text{ lb}_m}}{\frac{454 \text{ g}}{1 \text{ lb}_m}} \times \frac{\frac{1 \text{ ft}}{30.48 \text{ cm}}}{\frac{1 \text{ gal}}{1 \text{ lb}_m}}}{\frac{\text{cm}}{MW}} = \frac{0.016 \text{ cm}}{\text{g mol}} \]

\[ C^* = \frac{C \times \frac{1 \text{ ft}^3}{1 \text{ lb}_m} \times \frac{\frac{1 \text{ g mol}}{1 \text{ lb}_m}}{\frac{454 \text{ g}}{1 \text{ lb}_m}} \times \frac{\frac{1 \text{ ft}}{30.48 \text{ cm}}}{\frac{1 \text{ gal}}{1 \text{ lb}_m}}}{\frac{\text{cm}^3}{MW}} = \frac{2.27 \times 10^{-6} \text{ cm}^3}{MW^2} \]

\[ D^* = \frac{D \times \frac{1 \text{ ft}^3}{1 \text{ lb}_m} \times \frac{\frac{1 \text{ g mol}}{1 \text{ lb}_m}}{\frac{454 \text{ g}}{1 \text{ lb}_m}} \times \frac{\frac{1 \text{ ft}}{30.48 \text{ cm}}}{\frac{1 \text{ gal}}{1 \text{ lb}_m}}}{\frac{\text{cm}^3}{MW}} = \frac{4.696 \times 10^{-4} \text{ cm}^3}{MW^2} \]

Solutions Chapter 1

1.23

\[ u \left[ \frac{m}{s} \right] = k \left[ \frac{m}{s} \right] \left( \frac{\tau}{\rho} \right)^{1/2} \left( \frac{N}{m^2} \right)^{1/4} \left( \frac{m}{kg} \right)^{1/4} \]

To get \( u \) in \( \text{ft} / \text{s} \), substitute for \( \tau \) and for \( \rho \), and multiply both sides of the equation by \( 3.281 \text{ ft} / \text{m} \) (k is dimensionless).

\[ r \left[ \frac{N}{m^2} \right] = \frac{r \text{ lb}_f}{\text{ft}^2} \left( \frac{3.281 \text{ ft}}{1 \text{ m}} \right)^{1/2} \left( \frac{1 \text{ N}}{0.2248 \text{ lb}_f} \right)^{1/4} \left( \frac{1 \text{ kg}}{0.454 \text{ lb}_m} \right)^{1/4} \]
Solutions Chapter 1

For a travel distance of 125 ft, the time required for the flow is

\[
(125 \text{ft}) \left( \frac{30.38 \text{cm}}{54.67 \text{cm/s}} \right) = 69.69 \text{ seconds}
\]

Including the 5-sec instrument delay, about 75 sec will be required for sampling. A delay time of 75 sec may be acceptable for low leak rates, but faster detection would be desired for dangerous concentrations of toxic gases.

b) To reduce sampling time:
1) Increase the flow rate for same diameter tubing,
2) Decrease the tubing diameter for same flow rate,
3) Reduce the tubing length.

1.26 Place units for the symbols in the given equation, and equate the units on the left and right hand sides of the equation by assigning appropriate units to the coefficient 0.943.

\[
\frac{\text{Btu}}{\text{hr}/(\text{ft}^2 \Delta T)} = \left( \frac{\text{Btu}}{\text{hr} \cdot (\text{ft} \cdot \text{lb}_m)} \right)^2 \left( \frac{\text{ft}}{\text{lb}_m \cdot \text{ft} \cdot \text{lb}_m} \right) \left( \frac{(\text{hr})(0)}{\text{lb}_m \cdot \text{ft}} \right) \gamma^2
\]

The units are the same on the right and left so that 0.943 has no units associated with it.

1.27 Introduce the units. The net units are the same on both sides of the equation.

\[
\frac{(\text{ft})(\text{hr})^{1.5} \left( \frac{\text{ft}^2}{\text{s}^2} \right)}{\text{s}^2} = \frac{\text{ft}^3}{\text{s}}
\]

1.28 Basis: Dow -

1. \[ \frac{2 \text{ in} \cdot 10 \text{ ft} \cdot 62.4 \text{ lb}_m}{\text{s} \cdot \text{hr} \cdot (\text{ft}^2) \cdot 3600 \text{ s}} \times \frac{1 \text{ ft}}{12 \text{ in}} = 1.248 \times 10^3 \]

2. \[ \frac{20 \text{ ft} \cdot 10 \text{ mi} \cdot \text{lb}_m}{\text{hr} \cdot \text{hr} \cdot (\text{ft}^2) \cdot 5280 \text{ ft} \cdot 1 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ s}} = 2 \times 10^7 \]

3. \[ \frac{1 \text{ ft} \cdot 1 \text{ m} \cdot 12.5 \text{ kg}}{\text{s} \cdot \text{m} \cdot (2 \times 10^{10} \text{ cp}) \cdot 1 \text{ p} \cdot 100 \text{ cm} \cdot 100 \text{ cm} \cdot 1 \text{ kg} \cdot 1 \text{ ft}} \times \frac{1 \text{ p}}{1 \text{ (g)(cm)(s)}} = 4.81 \times 10^7 \]

4. \[ \frac{2 \text{ mm} \cdot 3 \text{ cm} \cdot 25 \text{ lb}_m}{\text{s} \cdot \text{ft} \cdot (1 \times 10^{16} \text{ cp}) \cdot 1 \text{ p} \cdot \text{lb}_m \cdot 10 \text{ mm} \cdot (30.48)^2 \text{ cm}^2} \times \frac{1 \text{ p}}{1 \text{ (g)(cm)(s)}} = 2.38 \times 10^9 \]

1.29 \[ \frac{\text{ton}}{\text{min}} = \frac{Q \text{ gal}}{\text{min}} \left( \frac{0.1337 \text{ ft}^3}{1 \text{ gal}} \right) \left( \frac{1 \text{ ton}}{2000 \text{ lb}_m} \right) \left( \frac{60 \text{ min}}{1 \text{ hr}} \right) \]

\[ = Q \left( \frac{(4.011 \times 10^{-1}) \left( \frac{\text{ft}^3}{\text{ton} \cdot \text{min}} \right)}{(\text{gal})(\text{lb}_m \cdot \text{hr})} \right) \]

1.30 Two because any numbers added to the right hand side of the decimal point in 10 are irrelevant.
### Solutions Chapter 1

| 1.31 | The sum is 1287.1430. Because 1234 has only 4 significant figures to the left of an implied decimal point, the answer should be 1287 (no decimal point). |
| 1.32 | The number of significant figures to the right of the decimal point is 1 (from 210.0 m), hence the sum of 215.110 m should be rounded to 215.1 m. |
| 1.33 | A calculator gives 569.8269 000, but you should truncate to 4 significant figures, or 569.8 cm$^3$. |
| 1.34 | Two significant figures (based on 6.3). Use $4.8 \times 10^3$. |

| 1.35 | Step 1: The product 1.3824 is rounded off to 1.4  
Step 2: Calculate errors.  
For absolute error, the product 1.4 means $1.4 \pm 0.05$  
Thus $0.05 \div 100\% = 3.6\%$ error  
Similarly 3.84 has $0.005 \div 100\% = 0.13\%$ error  
and 0.36 has $0.005 \div 100\% = 1.4\%$ error  
Total 2.7% error |
Solutions Chapter 2

2.1 The first paragraph of the letter is ok. In the second paragraph, the author is wrong. The molecular weight, even in SI, is the ratio of mass to moles (or the mass per a fixed number of molecules) and is not dimensionless.

2.2 Yes

2.3 A mole is a number of molecules. Molecular weight is the mass per mole.

2.4 All of the answers are wrong. A mole is a number of molecules.
   a) It is not a number of molecules in a volume
   b) It is not a weight
   c) It is not a number of molecules in a gram
   d) It is not an atomic weight or sum thereof
   e) It is not a molecular weight

2.5 The statement is partially correct. A mole is a number of entities, not a quantity of material. "Quantity" usually is not considered to be enumerated.

2.6 a) mol\(^{-1}\) means the inverse of the unit "mol."
   b) Yes

2.7 1. (d) 2. (c)

2.8 \(893.51 \text{ g C} \div \text{1 g mol C}\) from adding elemental masses

2.9
   a. Basis: 120 lb mole NaCl: \(\frac{120 \text{ lb}}{\text{lb mol}} \times \frac{454 \text{ g}}{\text{lb}} = 3.18 \times 10^4 \text{ g/mol}
   
   b. Basis: 120 gm mole NaCl: \(\frac{120 \text{ lb}}{\text{g mol}} \times \frac{454 \text{ g}}{\text{lb}} = 15.4 \text{ lb}
   
   c. Basis: 120 lb NaCl: \(\frac{120 \text{ lb}}{\text{lb mol}} \times \frac{454 \text{ g}}{58.45 \text{ g}} = 932 \text{ g mol}
   
   d. Basis: 120 gm NaCl: \(\frac{120 \text{ lb}}{\text{454 g}} \times \frac{58.45 \text{ lb}}{\text{lb mol}} = 4.52 \times 10^5 \text{ lb mol}

2.10 (a) \(\text{MW} = 40.08 \text{ g/mol} + 12.01 \text{ g/mol} + 2(16.00) \text{ g/mol} = 100.9 \text{ g/mol CaCO}_3\)
   
   b) \(\frac{10 \text{ g CaCO}_3}{100.09 \text{ g CaCO}_3} = 0.0999 \text{ g mol}\)
   
   c) \(\frac{20 \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} = 0.200 \text{ lb mol CaCO}_3\)
   
   d) \(\frac{454 \text{ g CaCO}_3}{1 \text{ lb mol CaCO}_3} = 90.880 \text{ g CaCO}_3\)
Solutions Chapter 2

2.11. (a) \[
\frac{4 \text{ g mol } \text{ MgCl}_2}{g \text{ mol } \text{ MgCl}_2} \times (95.23) \text{ g } \text{ MgCl}_2 = 380.9 \text{ g}
\]

(b) \[
\frac{2 \text{ lb mol } \text{ C}_6\text{H}_6}{\text{lb mol } \text{ C}_6\text{H}_6} \times (44.09) \text{ lb } \text{ C}_6\text{H}_6 = 4 \times 10^4 \text{ g } \text{ C}_6\text{H}_6
\]

(c) \[
\frac{16 \text{ g } \text{ N}_2}{(28.02) \text{ g } \text{ N}_2} \times \frac{1 \text{ lb mol } \text{ N}_2}{454 \text{ g mol } \text{ N}_2} = 1.26 \times 10^{-3} \text{ lb mol } \text{ N}_2
\]

(d) \[
\frac{3 \text{ lb } \text{ C}_2\text{H}_6\text{O}}{(46.07) \text{ lb } \text{ C}_2\text{H}_6\text{O}} \times \frac{1 \text{ lb mol } \text{ C}_2\text{H}_6\text{O}}{454 \text{ g mol } \text{ C}_2\text{H}_6\text{O}} = 29.56 \text{ g mol } \text{ C}_2\text{H}_6\text{O}
\]

2.12. (a) \[
\frac{16.1 \text{ lb mol } \text{ HCl}}{1 \text{ lb mol HCl}} = 585 \text{ lb HCl}
\]

(b) \[
\frac{19.4 \text{ lb mol } \text{ KCl}}{1 \text{ lb mol KCl}} = 466 \text{ lb KCl}
\]

(c) \[
\frac{11.9 \text{ g mol } \text{ NaNO}_3}{1 \text{ g mol } \text{ NaNO}_3} \times \frac{85 \text{ g } \text{ NaNO}_3}{2.20 \times 10^3 \text{ lb }} = 2.23 \text{ lb } \text{ NaNO}_3
\]

(d) \[
\frac{164 \text{ g mol } \text{ SiO}_2}{1 \text{ g mol } \text{ SiO}_2} \times \frac{60.1 \text{ g } \text{ SiO}_2}{2.20 \times 10^3 \text{ lb }} = 21.7 \text{ lb } \text{ SiO}_2
\]

2.13 Basis: 100 g of the compound

<table>
<thead>
<tr>
<th>comp.</th>
<th>g</th>
<th>MW</th>
<th>g mol</th>
<th>Ratio of Atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>42.11</td>
<td>12</td>
<td>3.51</td>
<td>1.09</td>
</tr>
<tr>
<td>O</td>
<td>51.46</td>
<td>16</td>
<td>3.22</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>6.43</td>
<td>1.08</td>
<td>6.38</td>
<td>2</td>
</tr>
</tbody>
</table>

Multiply by 11 to convert the ratios into integers
The formula becomes C_{12}O_{31}H_{17}
Checking MW: 12(12) + 11(16) + 22(1.008) = 342 (close enough)
2.14 Vitamin A, C<sub>20</sub>O<sub>H</sub><sub>30</sub> Mol Wt.: 286
Vitamin C, C<sub>6</sub>H<sub>8</sub>O<sub>6</sub>, mol. wt: 176

Vitamin A:

a. Vitamin A = \( \frac{2.00 \text{ g mol}}{1 \text{ lb mol}} \cdot \frac{286 \text{ g}}{454 \text{ g}} \cdot \frac{1 \text{ lb}}{1 \text{ g mol}} = 1.26 \text{ lb} \)

\( \frac{16 \text{ g}}{454 \text{ g}} = 0.0352 \text{ lb} \)

Vitamin C = \( \frac{2.00 \text{ g mol}}{1 \text{ lb mol}} \cdot \frac{176 \text{ g}}{454 \text{ g}} \cdot \frac{1 \text{ lb}}{1 \text{ g mol}} = 0.775 \text{ lb} \)

\( \frac{16 \text{ g}}{454 \text{ g}} = 0.0352 \text{ lb} \)

b. Vitamin A = \( \frac{1.00 \text{ lb mol}}{1 \text{ lb mol}} \cdot \frac{286 \text{ g}}{454 \text{ g}} \cdot \frac{1 \text{ lb}}{1 \text{ lb mol}} = 130,000 \text{ g} \)

Vitamin C = \( \frac{1.00 \text{ lb mol}}{1 \text{ lb mol}} \cdot \frac{176 \text{ g}}{454 \text{ g}} \cdot \frac{1 \text{ lb}}{1 \text{ lb mol}} = 79,900 \text{ g} \)

For both \( \frac{12 \text{ lb}}{1 \text{ lb}} \cdot \frac{454 \text{ g}}{1 \text{ lb}} = 5450 \text{ g} \)

2.15 Basis: 1000 lb oil

\[ \frac{0.926 \text{ lb oil}}{\text{ft}^3} \cdot \frac{62.4 \text{ lb H}_2\text{O}}{\text{ft}^3} = \frac{57.78 \text{ lb oil}}{\text{ft}^3} \]

\[ \frac{1000 \text{ lb oil}}{1 \text{ ft}^3} = 129.5 \text{ gal} \]

2.16 Basis: 10,010 lb

\[ \frac{10,010 \text{ lb}}{8.80 \text{ lb gal}} = 152 \text{ ft}^3 \]

2.17 Basis: 1 g mol each compound

\begin{align*}
g & \quad \text{g mol} & \quad \text{mw} & \quad \rho \text{ (g/cm)}^3 & \quad V \text{ (cm)}^3 \\
Pb & 1 & 207.21 & 207.21 & 11.33 & 18.3 \\
Zn & 1 & 65.38 & 65.38 & 7.14 & 9.16 \\
C & 1 & 12.01 & 12.01 & 2.26 & 5.31 \\
\end{align*}

\( \dot{V} = \frac{\text{mass} (\text{g})}{\text{density} (\text{g/cm}^3)} \)

Set 2 is the correct one

2.18 Basis: 10,000 SiC crystals

volume of 10^4 crystals: \[ \frac{(0.5 \times 10^6 \text{ m}^3)(\pi/4)(20 \times 10^4 \text{ m})(10^4)}{3.93 \times 10^{14} \text{ m}^3} = 1.25 \times 10^7 \text{ g} \]

grams SiC = \( (3.93 \times 10^{14} \text{ m}^3)(3.17 \text{ g/cm}^3)(100 \text{ cm}^3/1 \text{ m}^3) = 1.25 \times 10^7 \text{ g} \)
2.19 (a) Volume cylinder = \pi r^2 h = \pi (0.0125\text{m})^2 (1.0\text{m}) = 4.9 \times 10^{-4}

Volume cylinder = Volume fiber

4.9 \times 10^{-4}\text{m}^3 = \pi (6.25 \times 10^{-4}\text{m})^2 h

h = 40,000 \text{m of fiber}

Mass = (density)(volume) = (2.25 \times 10^4\text{g/m}^3)(4.9 \times 10^{-4}\text{m}^3) = 1.100\text{g}

(b) \rho_{\text{water}} = \frac{0.125 \times 10^{-3}\text{m}}{2} + 5 \times 10^{-4}\text{m} = 1.1 \times 10^{-4}

V_{\text{water}} = \frac{0.125 \times 10^{-3}\text{m}}{2} = 6.25 \times 10^{-4}

\Delta V_{\text{water}} = \Delta V_{\text{mass}} = (40,000\text{m})(1.1 \times 10^{-4}\text{m}^3 - (6.25 \times 10^{-4}\text{m}^3)\text{x}) = 1.1 \times 10^{-3}\text{m}^3

\frac{1.740 \text{ kg}}{\text{m}^3} = 1.9 \text{ kg/polymer}

2.20 The backfill must contain 1000 gal of liquid that will occupy the voids, or 1000/0.2 = 5000 gal of backfill. The empty space must be at least 10,000 gal for the tank plus 5000 gal for the backfill, or 15,000 gal equivalent to 2005 ft^3.

\frac{2005 \text{ ft}^3}{3.281 \text{ ft}} \times \frac{1 \text{ cm}}{1 \text{ cm}} \times \frac{2.2 \text{ g}}{1 \text{ kg}} = 1.25 \times 10^6 \text{kg}

2.21 \frac{1 \text{ kg}}{1160 \text{ m}^3} = 223.1 \text{ kg/kg mol}

2.22 Basis: 5000 bbl of 28° API oil + 20,000 bbl 15° API oil \rightarrow calculate \rho_{\text{mix}} \text{ in lbm/gal, lbm/ft}^3

(assume volumes are additive); 1 bbl = 42 gal

\frac{\text{lbm}_{28° \text{ API oil}} + \text{lbm}_{15° \text{ API oil}}}{\text{total vol}} = \frac{\text{lbm}_{28° \text{ API oil}} + \text{lbm}_{15° \text{ oil}}}{5000 + 20,000 \text{ bbl}}

\text{SG}_{28°} = \frac{141.5}{28 + 131.5} = 0.887 \quad \rho_{28°} = (0.887)(62.4) = 55.36 \text{ lbm/ft}^3

\text{SG}_{15°} = \frac{141.5}{15 + 131.5} = 0.966 \quad \rho_{15°} = (0.966)(62.4) = 60.27 \text{ lbm/ft}^3

V_{28°} = (5000 \text{ bbl})(42 \text{ gal/bbl})(\text{ft}^3/7.481 \text{ gal}) = 2.807 \times 10^6 \text{ft}^3

V_{15°} = (20,000)(42 \text{ gal/bbl})(\text{ft}^3/7.481 \text{ gal}) = 1.123 \times 10^6 \text{ft}^3

\rho_{\text{mix}} = \frac{(55.36 \text{ lbm}_{28°} / \text{ft}^3)(2.807 \times 10^6 \text{ft}^3) + (60.27 \text{ lbm}_{15°} / \text{ft}^3)(1.123 \times 10^6 \text{ft}^3)}{2.807 \times 10^6 + 1.123 \times 10^6 \text{ft}^3}

= 59.29 \text{ lbm/ft}^3 = 7.93 \text{ lbm/gal}

2.23 Yes

\text{Sp. gr.} 60°F = \frac{141.5}{60°F - 60°F \times API + 131.5} = \frac{141.5}{45.38 + 131.5} = 0.80

\text{Sp. gr.} 60°F = \text{Density}
2.24
\[
\frac{1.049 \text{ g/cm}^3 \text{ HAc}}{1.00 \text{ g/cm}^3 \text{ H}_2\text{O}} \frac{100 \text{ lb_m}}{453.6 \text{ g}} \left( \frac{1 \text{ m}}{3.2808 \text{ ft}} \right)^3 \left( \frac{100 \text{ cm}^3}{1 \text{ m}^3} \right) = \frac{65.43 \text{ lbm/ft}^3}{100 \text{ lb_m}}
\]
or
\[
\frac{1.049 \text{ lb/ft}^3 \text{ HAc}}{62.4 \text{ lb/ft}^3 \text{ H}_2\text{O}} = \frac{65.46 \text{ lbm/ft}^3}{100 \text{ lb_m}}
\]

2.25
\[
\rho_{\text{oil}} = \frac{(0.82) \text{ lb oil/ft}^3 \text{ oil}}{1 \text{ lb H}_2\text{O/ft}^3} = 51 \text{ lb/ft}^3 \text{ for the oil}
\]

2.26
The density of water at 25°C is 0.997 g/cm³ and at 4°C is 1.000 g/cm³. Ignore any change in density of the Ag₂O.
\[
\frac{0.997 \text{ g H}_2\text{O/cm}^3}{7.30; \text{ g Ag}_2\text{O/cm}^3} = 7.278 \text{ g Ag}_2\text{O/cm}^3
\]

2.27
Sp.gr. = 1.2185 for 30% H₂SO₄ soln
\[
\rho = 1.2185 \text{ g/cm}^3
\]
\[
0.30 (1.2185) = 0.3656 \text{ g/cm}^3 \text{ of H}_2\text{SO}_4 \text{ in the solution}
\]
\[
\frac{0.3656 \text{ g}}{1000 \text{ cm}^3} \times \frac{1 \text{ L}}{1 \text{ L}} = 365.6 \text{ g H}_2\text{SO}_4/\text{L}
\]
Answer: yes

2.28
Basis: 1 Day
\[
\frac{200 \text{ mg HgCl}_2}{10^3 \text{ gal}} \times \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \times \frac{1 \text{ lb}}{62.4 \text{ lb} \cdot 454 \text{ g}} = 271.52 \text{ g HgCl}_2/1 \text{ gmol HgCl}_2
\]
\[
\frac{1 \text{ g mol Hg}}{10^3 \text{ mg Hg}} \times \frac{1 \text{ gmol HgCl}_2}{1 \text{ gmol Hg}} = 3.90 \times 10^{-4} \text{ ppm}
\]
This discharge for 1 analysis is just below the prescribed limit. If more than one analysis is made per day, a violation occurs.
2.29 Basis: 1 L of 0.10 molar H₂SO₄ solution = 1 L soln  
\[ \text{MW H₂SO₄} = 98.08 \]
\[ \rho_{\text{soln}} = 1.858 \text{ g 96\% soln/cm}^3 \text{ 96\% soln, since sp. gr. = 1.858} \]

(a) \[
\frac{0.10 \text{ g mol H₂SO₄}}{1 \text{ L soln}} = \frac{98.08 \text{ g H₂SO₄}}{1 \text{ g mol H₂SO₄}} \times \frac{1.00 \text{ g 96\% soln}}{0.96 \text{ g H₂SO₄}} = \frac{10.22 \text{ g 96\% soln}}{1 \text{ L soln}}
\]

(b) \[
\frac{1 \text{ cm}^3 \text{ 96\% soln}}{1.858 \text{ g 96\% soln}} = \frac{10.22 \text{ g 96\% soln}}{1 \text{ L soln}} = 5.50 \text{ cm}^3 \text{ 96\% soln/L soln}
\]

(c) Assume no volume change on mixing for such a dilute solution

96\% H₂SO₄ soln  \[ \begin{array}{c|c}
\text{g} & \text{cm}^3 \\
10.22 & 5.50 \\
\hline
\text{H₂O} & 994.5 \\
994.5 & 1004.7 \\
\hline
& 1000
\end{array} \]

\[ \rho_{\text{soln}} = \frac{1004.7}{1000} = 1.0047 \text{ g/cm}^3 \]

2.30 \[ \rho_{\text{ice}} = 0.917 \text{ g/cm}^3 \text{ Density of ice} \]
\[ \rho_{\text{H₂O}} = 1.00 \text{ g/cm}^3 \text{ Density of H₂O(l)} \]
\[ \rho_{\text{alcohol}} = 0.791 \text{ g/cm}^3 \text{ Density of pure alcohol} \]

If the rum is 97 proof (48.5\% EtOH), the density is 0.917 g/cm³. As the proof rises, the density of the solutions decreases below that of ice, causing the ice to sink.

2.31 \[ \rho_{\text{water}} \text{ at } 60^\circ\text{F} = 0.99905 \text{ g/mL} \]

\[ \frac{60^\circ\text{F}}{0.879} = \frac{0.99905 \text{ g/cm}^3}{0.879} \]

Sp. gr. of benzene at 60°F = 0.99905 / 0.879

2.32

\[
\begin{array}{c|c|c}
\text{a.} & \frac{0.90 \text{ kg liq.}}{\text{m}^3} & 10^3 \text{ kg H₂O} \\
& \text{kg m}^{-3} & \text{m}^3 \\
& = & 900 \text{ kg liq. m}^{-3} \\
\hline
\text{b.} & \frac{1 \text{ m}^3}{900 \text{ kg liq. m}^{-3} \times 3.2808 \text{ ft}^{-3}} & 0.454 \text{ kg} \\
& \text{m}^3 & \text{lb}_m \\
& = & 0.0178 \text{ lb}_m \\
\hline
\text{c.} & \frac{0.9(1000 \text{ g})}{1.5 \text{ liter} + 232 \text{ g}} & 1582 \text{ g} \\
& \text{liter} & \text{g}
\end{array}
\]

2.33 Basis: 1.704 kg HNO₃  
1 kg H₂O

a. Comp. Kg mass fraction weight percent

<table>
<thead>
<tr>
<th>HNO₃</th>
<th>1.704</th>
<th>0.63</th>
<th>63</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>1</td>
<td>0.37</td>
<td>37</td>
</tr>
<tr>
<td>Total</td>
<td>2.704</td>
<td>1.00</td>
<td>37</td>
</tr>
</tbody>
</table>

b. Ignore the change of density of water with temperature

\[
\frac{1.382 \text{ lb soln}}{0.63 \text{ lb HNO₃}} = \frac{1.05 \text{ lb H₂O}}{1 \text{ ft}^3 \text{ H₂O}} \times \frac{62.4 \text{ lb H₂O}}{\text{ft}^3 \text{ soln}} = 54.3 \text{ lb HNO₃} \text{ so ln}
\]

\[ \frac{1 \text{ lb soln}}{1.05 \text{ lb H₂O}} \times \frac{62.4 \text{ lb H₂O}}{\text{ft}^3 \text{ so ln}} = \frac{54.3 \text{ lb HNO₃}}{\text{ft}^3 \text{ soln}} \]
Solutions Chapter 2

2.34
Density of acetaldehyde

\[ \frac{kg}{m^3} = \frac{783}{m^3} \]

Volume of acetaldehyde

\[ \frac{113.0 \text{ kg}}{783 \text{ kg acetaldehyde}} = 0.144 \text{ m}^3 \]

Maximum required volume

\[ = 0.144 \text{ cm}^3 \]

Volume of vessel = max. required volume

\[ = \frac{4}{3} \pi r^3 \]

\[ r = \frac{3}{4\pi} \times 0.144 \text{ m}^3 \]

\[ = 0.33 \text{ m} \]

A spherical vessel with a radius of 0.33 m could be used to store the liquid.

2.35
Specific gravity = 0.792 \( \left( \frac{g}{cm^3} \right) \)

\[ \frac{0.500 \text{ L}}{1 \text{ L}} \times \frac{0.792 \text{ g MeOH}}{1 \text{ lb}} \times \frac{1 \text{ lb}}{16 \text{ Oz}} \times \frac{454 \text{ g}}{1 \text{ lb}} = \frac{13.96 \text{ Oz}}{1 \text{ L}} \]

Yes

2.36
\[ Q = \frac{V_A}{s} = \frac{56.7 \text{ ft}}{4} \times \frac{\pi (6 \text{ in})^2}{144 \text{ in}^2} \times \frac{0.3048 \text{ m}^3}{1 \text{ ft}^3} = 0.316 \text{ m}^3/s \]

2.37
Basis: 40,000 lb fuel

\[ \frac{40,000 \text{ lb fuel}}{0.91 \text{ lb fuel}} \times \frac{1 \text{ fuel}}{62.4 \text{ lb H}_2\text{O}} \times \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \times \frac{1 \text{ min}}{40 \text{ gal}} = 132 \text{ min} \]

2.38
Basis: 100 g of compound

<table>
<thead>
<tr>
<th>C</th>
<th>H</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.9</td>
<td>2.2</td>
<td>70.9</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>26.9 / 12</td>
<td>2.2 / 1</td>
<td>70.9 / 16</td>
</tr>
<tr>
<td>( \frac{2.24}{12} )</td>
<td>( \frac{2.20}{1} )</td>
<td>4.43</td>
</tr>
<tr>
<td>( \frac{2.24}{2.20} )</td>
<td>( \frac{2.20}{2.20} )</td>
<td>4.43 / 2.20</td>
</tr>
<tr>
<td>( \frac{1.02}{1.00} )</td>
<td>( \frac{1.00}{1} )</td>
<td>2.01</td>
</tr>
</tbody>
</table>

Simplest ratio

1 1 2

The empirical formula of this organic compound is \( C_{10}H_{16}O_{7} \).
1. Basis: 100 g sample: 49.5 g C; 5.2 g H; 28.8 g N; 16.5 g O

2. Divide each mass number by the molar mass:
   (49.5 g C/12.011 g/mol C) = 4.121 mol C
   (5.2 g H/1.008 g/mol H) = 5.159 mol H
   (28.8 g N/14.007 g/mol N) = 2.056 mol N
   (16.5 g O/15.999 g/mol O) = 1.031 mol O

3. Divide each molar amount by the smallest molar amount
   (4.121 mol C/1.031 mol O) = (4 mol C/mol O)
   (5.159 mol H/1.031 mol O) = (5 mol H/mol O)
   (2.056 mol N/1.031 mol O) = (2 mol N/mol O)
   (1.031 mol O/1.031 mol O) = (1 mol O/mol O)

4. Empirical Formula is then \( \text{C}_4\text{H}_5\text{N}_2\text{O} \)

2.41 Basis: 1 gal of solution.

Mass of solution:

\[
\frac{1.0824 \text{ lb soln}}{7.481 \text{ gal}} = \frac{1.00 \text{ lb H}_2\text{O}}{\text{ft}^3\text{H}_2\text{O}} = \frac{62.4 \text{ lb H}_2\text{O}}{\text{ft}^3\text{H}_2\text{O}}
\]

Mass fraction KOH = \( \frac{0.813 \text{ lb}}{9.03 \text{ lb}} = 0.09\)

Mass fraction H\(_2\)O = \( 1 - 0.09 = \frac{0.91}{1.00} \) Total

2.42 Mass fraction to mole fraction:

\[
x_i = \frac{\omega_i}{\frac{\omega_i}{MW_i} + \frac{(1-\omega_i)}{MW_2}}
\]

Mole fraction to mass fraction

\[
\omega_i = \frac{x_i MW_2}{(x_i MW_1) + (1-x_i) MW_2}
\]
### 2.43 Basis: 100 kg mol gas

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Mol % x mol</th>
<th>MW</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>30</td>
<td>16</td>
<td>480</td>
</tr>
<tr>
<td>H₂</td>
<td>10</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>N₂</td>
<td>60</td>
<td>28</td>
<td>1680</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td></td>
<td><strong>2180</strong></td>
</tr>
</tbody>
</table>

\[
\frac{21.8 \text{ kg}}{	ext{kg mol}}
\]

### 2.44 Basis: 100 g mol gas

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol = %</th>
<th>MW</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>19.3</td>
<td>44</td>
<td>849.2</td>
</tr>
<tr>
<td>N₂</td>
<td>72.1</td>
<td>28</td>
<td>2018.8</td>
</tr>
<tr>
<td>O₂</td>
<td>6.5</td>
<td>32</td>
<td>208.0</td>
</tr>
<tr>
<td>H₂O</td>
<td>2.1</td>
<td>18</td>
<td>37.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0</strong></td>
<td></td>
<td><strong>3113.8</strong></td>
</tr>
</tbody>
</table>

\[
\text{Avg. mol. wt} = \frac{3113.8}{100.0} = 31.138
\]

### 2.45 Basis: 100 lb mol

<table>
<thead>
<tr>
<th>Comp.</th>
<th>% x mol</th>
<th>MW</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>16</td>
<td>44</td>
<td>2640</td>
</tr>
<tr>
<td>CO</td>
<td>10</td>
<td>28</td>
<td>280</td>
</tr>
<tr>
<td>N₂</td>
<td>30</td>
<td>28</td>
<td>840</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td></td>
<td><strong>3760</strong></td>
</tr>
</tbody>
</table>

\[
\text{Avg. MW} = \frac{37.6 \text{ lb/lb mol}}{}
\]
2.49 Basis: 190,000 ppm

\[ \frac{190,000 \text{ g PCB}}{10^6} \times 100 = 19\% \]

2.50 Yes. Bases are first entries.

\[
\begin{align*}
4800 \text{ g mol CCl}_4 &\quad 10^3 \text{ g mol air} &\quad 154 \text{ g CCl}_4 &\quad 103 \text{ mg CCl}_4 \\
10^9 \text{ g mol air} &\quad \text{kg mol air} &\quad 22.8 \text{ m}^3 &\quad \text{g mol CCl}_4 &\quad \text{g CCl}_4 \\
32.4 \text{ mg CCl}_4/\text{m}^3 &\quad \text{which exceeds the NIOSH standards}
\end{align*}
\]

2.51

<table>
<thead>
<tr>
<th>25,600 ton</th>
<th>25,600 ton</th>
<th>( \frac{2.6 \text{ yr}}{1 \text{ gal}} \times 1 \text{ gal} )</th>
<th>2000 lb</th>
<th>454 g</th>
<th>10^4 \mu g</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>P</td>
<td>[ 1.2 \times 10^{14} \text{gal} \times 3.785 \text{ L} ]</td>
<td>1 ton</td>
<td>1 lb</td>
<td>1 g</td>
</tr>
</tbody>
</table>

\[ = 133.1 \mu g/\text{L} \]

b. \[ \frac{19,090 \text{ lb}(P_{\text{municipal}})}{30,100 \text{ lb}(P_{\text{total}})} = 63.4\% \]

c. \[ \frac{19,090 \text{ lb}(P_{\text{municipal}})}{30,100 \text{ lb}(P_{\text{total}})} \times 0.70 \text{ lb}(P_{\text{det}}) = 100 \text{ lb}(P_{\text{det}}) = 44.4\% \]

For d. and e. assume that (P) outflow remains unchanged.

d. \[ P_{\text{retained/yr}} = 2,240 + 6,740 + 0.7 \times 19,090 - 4,500 = 17,843 \text{ ton/yr}. \]

\[ P_{\text{conc. in ppb}} = \]

\[ \frac{17,843 \text{ ton}}{2.6 \text{ yr}} \times \frac{1}{2000 \text{ lb}} \times \frac{1 \text{ g}}{1 \text{ cm}^3} = 92.6 \text{ ppb} \]

This is greater than 10 ppb. **Eutrophication will not be reduced.**

e. \[ P_{\text{retained/yr}} = 2,240 + 6,740 + 0.3 \times 19,090 - 4,500 = 10,207 \text{ ton/yr} \]

\[ P_{\text{conc. in ppb}} = \]

\[ \frac{10,207 \text{ ton}}{2.6 \text{ yr}} \times \frac{1}{2000 \text{ lb}} \times \frac{1 \text{ g}}{1 \text{ cc}^{cc}} = 53.2 \text{ ppb} \]

This will not help.
Solutions Chapter 2

2.52  Basis: 10⁶ g mol gas

\[
\begin{align*}
350 \text{ g mol H}_2\text{S} & | 1 \text{ g mol gas} & | 34g \text{ H}_2\text{S} & | 1 \text{ g mol CO}_2 \\
10^6 \text{ g mol gas} & | 1 \text{ g mol CO}_2 & | 1 \text{ g mol H}_2\text{O} & 44 \text{ g CO}_2
\end{align*}
\]

\[
\frac{270}{10^6} \text{ g H}_2\text{S} = \frac{270}{10^6} \text{ g total liquid}
\]

mass fraction H₂S = \(2.70 \times 10^{-4}\)

2.53  (a) \(\frac{1 \text{ mol O}_2}{100 \text{ mol gas}} = 10^6 \text{ mol O}_2/10^5 \text{ mol gas} \text{ or } 10^4 \text{ ppm}\)

(b) Basis: 100 mol gas

<table>
<thead>
<tr>
<th>Comp.</th>
<th>% = mol</th>
<th>mol fr.</th>
<th>or mol %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>55</td>
<td>0.932</td>
<td>92.2</td>
</tr>
<tr>
<td>SO₃</td>
<td>3</td>
<td>0.051</td>
<td>5.1</td>
</tr>
<tr>
<td>O₂</td>
<td>1</td>
<td>0.017</td>
<td>1.7</td>
</tr>
<tr>
<td>Total</td>
<td>59</td>
<td>1.000</td>
<td>100.0</td>
</tr>
</tbody>
</table>

2.54  

<table>
<thead>
<tr>
<th>MW</th>
<th>CaCO₃: 100.06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>40.05</td>
</tr>
<tr>
<td>Mg</td>
<td>24.3</td>
</tr>
<tr>
<td>C</td>
<td>12.01</td>
</tr>
<tr>
<td>O</td>
<td>16.00</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
100.06 \text{ g CaCO}_3 & | 1 \text{ g mol CaCO}_3 & | 1 \text{ g mol Ca} \\
\text{g mol Ca CO}_3 & | 1 \text{ g mol Ca} & 40.05 \text{ g Ca}
\end{align*}
\]

= 2.50 \text{ g CaCO}_3/\text{g Ca}

Similarly \(g \text{ CaCO}_3/\text{g Mg} = 4.118 \text{ g CaCO}_3/\text{g Mg}\)

Total alkalinity = 2.50 (56.4) + 4.118 (8.8) = 177 \text{ mg CaCO}_3/L

2.55  Total dosage = 27lb/0.75 ml gal = 36lb/mil gal = 36lb/mil gal \times \frac{1 \text{ mg/L}}{8.34lb/mil gal} = 4.3 \text{ mg/L}

Residual Cl₂ = 4.3 \text{ mg/L} - 2.6 \text{ mg/L} = 1.7 \text{ mg/L}

2.56  No. 1 molecule in 10⁻³ or more is not 13-20 ppb

2.57  On a mol basis, the carbon dioxide concentration in air is about 350 parts per million (ppm), while that of oxygen is about 209,500 ppm. If the atmospheric concentration of carbon dioxide is increasing at about 1% per year (i.e., from 350 ppm this year to 353.5 ppm next year), and not to 1%, the 3.5-ppm change in dioxide concentration causes the oxygen concentration to fall from 209,500 to about 209,497 ppm, which is less than a 0.002% decrease. So, there is no need to worry about an oxygen deficit at present.
Solutions Chapter 2

2.58

Basis: 100 g of the sample

The biomass sample is

\[ g = \% \text{ dry weight of cells} \]

\[
\begin{array}{c|c}
\text{C} & 50.2 \\
\text{O} & 20.1 \\
\text{N} & 14.0 \\
\text{H} & 8.2 \\
\text{P} & 3.0 \\
\text{other} & 95.5 \\
\text{Total} & 100.0 \\
\end{array}
\]

10.5 g cells | 50.2 g C | 1 g mol C | 12 g C
---|---|---|---

\[
g = \frac{0.439 \text{ g mol C/g mol ATP}}{100 \text{ g cells}}
\]

2.59

\[ \text{MM}(s) \rightarrow \text{NN}(s) + 3\text{CO}_2(g) \]

\[ \begin{array}{c|c|c|c|c}
\text{a.} & 2 \times 10^6 \text{ disintegrations/min} & 1 \text{ curie} & 10^4 \text{ \mu curie} & 11 \text{ \mu curie} \\
& 60 & 3 \times 10^8 \text{ disintegrations/s} & 1 \text{ curie} \\
\end{array} \]

\[ \begin{array}{c|c|c}
\text{b.} & 2 \times 10^7 \text{ disintegrations/min} & 0.80 \\
& & [1.6 \times 10^7 \text{ cpm}] \\
\end{array} \]

Solutions Chapter 2

2.60

The relation to use is

\[ t_{1/2} = \frac{\ln(2)}{(k)(\text{OH}^-)} \]

with \( (\text{OH}^-) = 1.5 \times 10^4 \)

\[
\begin{array}{|c|c|c|}
\hline
\text{Methanol} & 0.15 \times 10^{-12} & 30.8 \times 10^4 \\
\text{Ethanol} & 1 \times 10^{-12} & 4.6 \times 10^4 \\
\text{MTBE} & 0.60 \times 10^{-12} & 7.7 \times 10^4 \\
\hline
\end{array}
\]

The order is in increasing persistence ethanol, MTBE, and methanol.
### Solutions Chapter 3

<table>
<thead>
<tr>
<th>3.1</th>
<th>A gas requires a convenient basis of 1 or 100 g moles or kg moles (if use SI units).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(b) A gas requires a convenient basis of 1 or 100 lb moles (if use AE units).</td>
</tr>
<tr>
<td></td>
<td>(c) Use 1 or 100 kg of coal, or 1 or 100 lb of coal because the coal is a solid and mass is a convenient basis.</td>
</tr>
<tr>
<td></td>
<td>(d) Use 1 or 100 moles (SI or AE) as a convenient basis as you have a gas.</td>
</tr>
<tr>
<td></td>
<td>(e) Same answer as (e).</td>
</tr>
</tbody>
</table>

| 3.2     | Since the mixture is a gas, use 1 or 100 moles (SI or AE) as the basis.             |

<table>
<thead>
<tr>
<th>3.3</th>
<th>Pick one day as a basis which is equivalent to what is given — two numbers:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a) 134.2 lb Cl       (b) 10.7 \times 10^6 gal water.</td>
</tr>
</tbody>
</table>
4.1 \[ T_K = -10 + 273 = 263K \]
\[ T_{\text{ff}} = -10 \times (1.8) + 32 = 14^\circ F \]
\[ T_{\text{R}} = 14 + 460 = 474^\circ R \]

4.2 Yes, if the temperature scale is a linear relative one (°C, °F), or a logarithmic scale (ln 1° is zero). No, if the scale is absolute, but read J. Wisnias, J. Chem. Educ., 77, 518-522 (2000) for a different conclusion.

4.3 \[ C_p = 8.41 + \frac{2.4346 \times 10^7 T_K}{(2.4346 + 10^{-3} \frac{J}{\text{g/mol}K^2} T_K)} \]

Substitute \( 1.8 \, T_K = T_R \)
\[ C_p = 8.41 + 2.4346 \times 10^{-5} \frac{J}{\text{g/mol}K^2} \frac{T_R}{1.8} \]
\[ = 8.41 + 1.353 \times 10^{-2} T_R \]

4.4 \[
\begin{align*}
\frac{10^\circ C}{1.0^\circ C} &+ 32 = 50^\circ F \\
\frac{10^\circ C}{1.0^\circ C} &+ 32 + 460^\circ R = 510^\circ R \\
\frac{-25^\circ F}{1.0^\circ C} &+ 273K = 241.3K \\
\frac{150K}{0.1K} &+ 273K = 270^\circ R
\end{align*}
\]

4.5 First multiply the RHS of the equation so that
\[
\frac{\text{Btu}}{(\text{lb mol}) (^\circ F)} \times \frac{1054.81}{1 \, \text{Btu}} \times \frac{1 \, \text{lb mol}}{454 \, \text{g mol}} \times \frac{1.8^\circ F}{1.0^\circ C} = 4.182 \frac{J}{(\text{g mol})(^\circ K)}
\]
and substitute \( T_{\text{ff}} = 1.8T_c + 32 \)
\[
C_p = \left[ 8.448 + 0.5757 \times 10^{-2} \left( 1.8T_c + 32 \right) - 0.2159 \times 10^{-5} \left( 1.8T_c + 32 \right)^2 \right.
\]
\[ + 0.3059 \times 10^{-6} \left( 1.8T_c + 32 \right)^3 \]
\[ \times 4.182 \frac{J}{(\text{g mol})(^\circ K)} \]

Simplifying,
\[ C_p = 36.05 + 0.04477T_c - 0.2874 \times 10^{-4} T_c^2 + 0.7424 \times 10^{-8} T_c^3 \]

4.6 The instrument does not contain mercury, but must contain a fluid that responds at -76°C and can be calibrated to measure temperature.

4.7 The first sentence really means that the unit interval \( \Delta ^\circ C = \) the unit interval \( \Delta K \). However, \( ^\circ C \neq K \) as a temperature measure. The second sentence is satisfactory when referred to temperature, but the "only difference" should be omitted. Third sentence: there is no difference in the precision but the reported value of temperature may be rounded off to leave fewer significant figures (unlikely as much as one digit).
### Solutions Chapter 4

#### 4.8 Basis: given temperatures

<table>
<thead>
<tr>
<th></th>
<th>°F</th>
<th>°R</th>
<th>K</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>140*</td>
<td>600</td>
<td>333</td>
<td>60</td>
</tr>
<tr>
<td>b.</td>
<td>77</td>
<td>537</td>
<td>298*</td>
<td>25</td>
</tr>
<tr>
<td>c.</td>
<td>40</td>
<td>500*</td>
<td>277.8</td>
<td>4.5</td>
</tr>
<tr>
<td>d.</td>
<td>-40</td>
<td>420</td>
<td>233</td>
<td>-40*</td>
</tr>
<tr>
<td>e.</td>
<td>1000*</td>
<td>1460</td>
<td>811</td>
<td>538</td>
</tr>
<tr>
<td>f.</td>
<td>540</td>
<td>1000*</td>
<td>555</td>
<td>282</td>
</tr>
<tr>
<td>g.</td>
<td>1340</td>
<td>1800</td>
<td>1000*</td>
<td>727</td>
</tr>
<tr>
<td>h.</td>
<td>1832</td>
<td>2292</td>
<td>1273</td>
<td>1000*</td>
</tr>
</tbody>
</table>

#### 4.9 Basis: 0.171 \times 10^{-8} \text{Btu} \left(\text{ft}^2\text{hr}(\degree\text{R})^4\right)^{-1}

\[
\frac{0.17 \times 10^{-8} \text{Btu}}{\left(\text{ft}^2\text{hr}(\degree\text{R})^4\right)} \times \frac{(\text{hr})^2}{(\text{in})^2} \times \frac{(100 \text{ cm})^2}{(1 \text{ K})^2} \times \frac{1.055 \times 10^3 \text{J}}{1 \text{ Btu}} = \frac{5.67 \times 10^{-5} \text{J}}{(\text{m}^2)(\text{K})^4}
\]

#### 4.10 Yes, if the fluid expansion is linear with temperature.

#### 4.11 You do not get a straight line with \( p \) vs. \( 1/T \), but do so with \( \ln p \) vs. \( 1/T \).

At \( p = 1340 \text{ mm Hg}, \ T = 384 \text{ K}, \ a = 20.36 \) and \( b = -5.12 \times 10^4 \) with the units of K.
5.1

Basis: 15 cm$^3$ water

a. \[ m = \rho V = \frac{1000 \text{ kg}}{\text{m}^3} \times 10 \text{ m} \times 10 \text{ m} \times 0.15 \text{ m} = 15,000 \text{ kg} \]

b. \[ F = m g = \frac{15,000 \text{ kg}}{\text{s}^2} \times 9.8 \text{ m/s}^2 \times 1 \text{ N/} \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \times 1 \text{ Pa} = 1470 \text{ Pa} \]

\[ = \frac{1470 \text{ kPa}}{1 \text{ atm}} \times 14.7 \text{ psi} = 0.21 \text{ psi} \]

or \[ \frac{15 \text{ cm} \text{ H}_2\text{O}}{2.54 \text{ cm} \text{ in}} \times \frac{1 \text{ in}}{1 \text{ ft}} \times \frac{14.696 \text{ psi}}{33.91 \text{ lb} \text{ H}_2\text{O} \text{ ft}} = 0.21 \]

5.2

$\rho_{\text{concrete}} = 2080 \text{ kg/m}^3$

$\rho_{\text{water}} = 1000 \text{ kg/m}^3$

Volume of concrete:

Sides

\[ V_s = \frac{5 \text{ m}}{1000 \text{ mm}} \times 30.2 \text{ m} \times 200 \text{ mm} \times 1 \text{ m} \times 2 \text{ sides} = 60.4 \text{ m}^3 \]

Ends
5.3 The pressure is a gauge pressure.

Basis: 50.0 psig

\[
\begin{align*}
\text{a.} & \quad \frac{50.0 \text{ psig}}{33.91 \text{ ft H}_2\text{O}} = 14.7 \text{ psia} \\
& \text{(difference)} \\
\text{b.} & \quad \text{No. Insufficient height.} \\
\text{Alternate solutions can be applying } \Delta p = \rho \Delta h_g
\end{align*}
\]

5.4 \( p = \rho gh \) so \( h_{Hg} = h_{kero} \frac{\rho_{kero}}{\rho_{Hg}} \); \( \rho_{kero} = \frac{0.82}{1.00} \frac{g}{cm^3} \)

Basis: 5 in kerosine

\[
\begin{align*}
\text{5.0 in } \text{kero} & \quad 25.4 \text{ mm} \quad 0.82 \frac{g}{cm^3} \\
1 \text{ in} & \quad 13.6 \frac{g}{cm^3} = 7.66 \text{ m Hg}
\end{align*}
\]

5.5 \[
\frac{lb.}{in.^2} = \frac{lb.}{in.^2} \text{ in the AE system}
\]

so the procedure is ok, although the unit conversion is ignored.

5.6 The equation is

\[
\Delta p = 4 f \rho \left[ \frac{(v^2/2g)}{(L/D)} \right]
\]

The units on the right hand side (with f dimensionless) in SI are

\[
\frac{\rho \frac{kg}{m^3}}{\frac{m^2}{s^2}} \left( \frac{m^3}{m \frac{kg}{m} \frac{m}{s^2}} \right) \to \frac{1}{m^2}
\]

hence the equation is not dimensionally consistent because \( \Delta p \) has the units of \( N/m^2 \). If \( g \) is replaced with \( g_c \), the units would be correct.
5.7 \( Q = 0.61S\sqrt{2\Delta p}/\rho \) assume hole is open to atmosphere

\[ \Delta p = \frac{144 \text{ in}^2}{1 \text{ ft}^2} \left( \frac{23 \text{ lb}}{1 \text{ in}^2} + \frac{73 \text{ in. gas}}{1 \text{ gas}} \frac{0.703 \text{ H}_2\text{O}}{12 \text{ in}} \frac{14.7}{33.91 \text{ ft H}_2\text{O}} \right) \]

\[ = 3.579 \text{ lb/ft}^2 \]

\[ \rho = \frac{0.701 \text{ lb}}{\text{ft}^3} \cdot \frac{62.4 \text{ lb H}_2\text{O}}{1 \text{ lb H}_2\text{O}} = 43.87 \text{ lb/ft}^3 \]

\[ S = \frac{\pi}{4} \left( \frac{1}{(2\pi)(12)} \right) = 3.409 \times 10^{-4} \]

\[ Q = (3600)(0.61)(3.409 \times 10^{-4})\sqrt{2(3.579)\rho/43.87} = \frac{54.6 \text{ ft}^3}{\text{hr}} \]

5.8 Basis: Dept = 1000 m \( p = p_o + \rho gh \)

\[ p = 1 \text{ atm} + \frac{1000 \text{ m}}{1 \text{ cm}^3} \cdot \frac{1.024 \text{ g/cm}^3}{1 \text{ cm}} \cdot \frac{1 \text{ kg}}{1 \text{ g}} \cdot \frac{100 \text{ cm}}{1 \text{ m}} \cdot \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \cdot \frac{1 \text{ kPa}}{1 \text{ N/m}^2} \]

\[ = 100.1 \text{ atm} + 1.014 \times 10^4 \text{ kPa} \]

Alternative solution:

\[ 101.3 \text{ kPa} + \frac{1000 \text{ m sea H}_2\text{O}}{1 \text{ cm}^3} \cdot \frac{1.024 \text{ g H}_2\text{O}}{1 \text{ m}} \cdot \frac{3.28 \text{ ft}}{1 \text{ m}} \cdot \frac{101.3 \text{ kPa}}{1 \text{ atm}} \cdot \frac{1 \text{ atm}}{0.01 \times 10^4} \]

\[ = 1.013 \times 10^4 \]

5.9 (a) \( P_{\text{Amb}} = P_{\text{inag}} + P_{\text{om}} \)

\[ \left( \frac{22.4 \text{ lb}}{1 \text{ in}^2} \right) + \left( \frac{28.6 \text{ in. Hg}}{1 \text{ in}} \right) \left( \frac{14.7 \text{ psia}}{1 \text{ in. Hg}} \right) \left( \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right) = 5250 \text{ lb/ft}^2 \]

(b) \( \left( \frac{22.4 \text{ psig}}{1 \text{ in. Hg}} \right) + \frac{28.6 \text{ in. Hg}}{14.7 \text{ psia}} = 74.2 \text{ in. Hg} \)

(c) \( \left( \frac{22.4 \text{ psig}}{1 \text{ in. Hg}} \right) + \left( \frac{28.6 \text{ in. Hg}}{1 \text{ in. Hg}} \right) \cdot \left( \frac{28.6 \text{ in. Hg}}{27.92 \text{ in. Hg}} \right) = 2.51 \times 10^3 \text{ N/m}^2 \)

(d) \( \left( \frac{22.4 \text{ psig}}{1 \text{ in. Hg}} \right) + \left( \frac{28.6 \text{ in. Hg}}{1 \text{ in. Hg}} \right) \cdot \left( \frac{33.91 \text{ ft H}_2\text{O}}{29.92 \text{ in. Hg}} \right) = 84.1 \text{ ft H}_2\text{O} \)
Solutions Chapter 5

5.10 Neither John is necessarily right. The pressure at the top of Pikes Peak is continually changing.

5.11 \( \Delta p = \rho gh \)

\[
\begin{align*}
\text{a.} & \quad \frac{1 \text{ g}}{\text{cm}^3} \cdot \frac{9.8 \text{ m}}{\text{s}^2} \cdot \frac{1 \text{ kg}}{1000 \text{ g}} \cdot \frac{1 \text{ Pa}}{1 \text{ kg} \cdot \text{m}^2} \cdot \frac{1 \text{ kPa}}{1000 \text{ Pa}} \\
& \quad = 128.4 \text{ kPa}
\end{align*}
\]

\[
\begin{align*}
\frac{F}{A_{\text{Bottom}}} &= \frac{mg}{A_{\text{Bottom}}} = \rho Vg = \rho (S \cdot A)(gh) \\
\end{align*}
\]

\[
\begin{align*}
A_{\text{Bottom}} &= \frac{\pi}{4} D^2 = \frac{\pi}{4} (30.5 \text{ m})^2 = 730.62 \text{ m}^2 \\
A_{\text{Top}} &= 730.62 \text{ m}^2 \\
A_{\text{Side}} &= \pi Dh = \pi (30.5 \text{ m}) (13.1 \text{ m}) = 1255.2 \text{ m}^2 \\
S \cdot A &= A_{\text{Top}} + A_{\text{Bottom}} + A_{\text{Side}}
\end{align*}
\]

5.12 \( \Delta p = \rho gh \)

\[
\begin{align*}
\frac{\rho (S \cdot A)(gh)}{A} &= \\
\frac{7.86 \text{ g/cm}^3 \cdot (100 \text{ cm})^2}{2.716.46 \text{ m}^2 \cdot 9.35 \times 10^{-4} \text{ m}} \cdot \frac{9.8 \text{ m}}{730.6 \text{ m}^2 \cdot \text{s}^2} \\
\frac{1 \text{ kg}}{1000 \text{ g}} \cdot \frac{1 \text{ Pa}}{1 \text{ kg/m}^3} &= 2.68 \text{ kPa}
\end{align*}
\]

Alternate solution:

\[
\begin{align*}
12.7 \text{ cm} \cdot \frac{1 \text{ in}}{0.800} \cdot \frac{1 \text{ ft}}{12 \text{ in}} \cdot \frac{101.3 \text{ kPa}}{2.54 \text{ cm}} & = 1.00
\end{align*}
\]
5.13 Basis: 750 mm Hg

Atmospheric pressure + gage pressure = absolute pressure

\[
\begin{align*}
\text{Absolute pressure} &= \frac{750 \text{ mm Hg} \times 101.3 \text{kPa}}{760 \text{ mm Hg}} = 100 \text{kPa} \\
\text{absolute pressure} &= \frac{440 \text{kPa}}{540 \text{kPa}}
\end{align*}
\]

\[
\begin{align*}
765 \text{ mm Hg} \times 101.3 \text{kPa} &= 102 \text{kPa} \\
540 - 102 &= 438 \text{kPa}
\end{align*}
\]

Alternate Solution: 15 mm Hg \times \frac{101.3 \text{kPa}}{760 \text{ mm Hg}} = 2 \text{kPa so } 440 - 2 = 438 \text{kPa}

5.14

(a) Gage pressure most likely (if assume absolute, then don't add barometric pressure below)

(b) \( p = \rho gh \) or use below

Basis: 2.5 ft of HC (ignore pressure exerted by 4 ft of air)

\[
\begin{align*}
2.5 \text{ ft HC} \times 0.92 \text{ ft H}_2\text{O} &= 14.7 \text{ psia} \\
1 \text{ ft HC} &= 33.91 \text{ ft HC} \\
1.00 \text{ psia} + 20 \text{ psia} + 14.7 \text{ psia (barometer assumed)} &= 35.7 \text{ psia}
\end{align*}
\]
5.15 Basis: 1.3 psia

Pressure reads 27.38 in. Hg

Assume the pressure reading is correct, and the barometer reads 101.8 kPa. Convert all measurements to a common set of units, say psi.

\[
\frac{101.8 \text{ kPa}}{14.696 \text{ psia}} = 6.87 \text{ psi for the barometer}
\]

\[
\frac{27.38 \text{ in. Hg}}{29.92 \text{ in. Hg}} = 0.92 \text{ psi for the reading}
\]

(a) If the tank is at less than atmospheric pressure (i.e., a vacuum), then

14.77-13.45 = 1.32 psi is a legitimate reading. In other words, the reading is 1.3 psi of vacuum but not 1.3 psia (a reading of 14.77-13.45 = 1.3 psia).

(b) If the tank is greater than atmospheric pressure, then

\[14.77 + 13.45 = 28.2 \text{ psis is a legitimate reading.}\]

1.3 psia is not correct but the reading is ok.

5.16 Basis: 26.2 in Hg vacuum

\[
p = \frac{(30.4 - 26.2) \text{ in. Hg}}{29.92 \text{ in. Hg}} = 2.06 \text{ psia}
\]

5.17

\[
p = \frac{(29.31 - 3.53) \text{ in. Hg}}{29.92 \text{ in. Hg}} = 655 \text{ mm Hg}
\]

5.18 Vacuum Basis: 51 psig

(a) Assume the correction to the gauge reading is directly proportional to the gauge reading. The correction is 735/760 times the gauge reading, and 51(735/760) = 49.3 psia

(b) An alternate correction is to assume the needed correction is additive. Then the correction is a fixed (760-735) mm Hg reduction, or 25 mm Hg. The second reading should be 51-251(\frac{14.7}{760}) = 50.5 psig.
5.19

Basis: 31.5 kPa
atmospheric pressure + gauge pressure = absolute pressure
98.2 - 31.5 = 66.7 kPa absolute

5.20
Tell him the tank likely will collapse

\[
\frac{12 \text{ m H}_2\text{O}}{3.2808 \text{ ft}} \cdot \frac{1 \text{ atm}}{1 \text{ m H}_2\text{O}} = 1.16 \text{ atm}
\]

As the tank drains the pressure inside the tank will become much less than the outside pressure of 1 atm; unless air is let in it will collapse. The valve may not let air in.

5.21
The pressure of 50 psig is a gauge pressure.

Basis: 50.0 psig

\[
\frac{50.0 \text{ psig}}{33.91 \text{ ft H}_2\text{O}} = 14.7 \text{ psi} = 115 \text{ ft above atmospheric}
\]

No Insufficient height

Alternate solution can be obtained by applying \( \Delta P = \rho \Delta h g \)

5.22

\[
p_A + \rho_A g h_A + \rho_B g h_B = P_A
\]
\[
p_B + \rho_B g h_B + \rho_B g h_B = P_B
\]

\[
\rho_A \cdot g h_A = -p_A \cdot g h_A - p_B \cdot g h_B = g \Delta h
\]

\[
= \rho_B g \Delta h_B - \rho_A g \Delta h_A = g \Delta h (\rho_B - \rho_A)
\]

\[
= \frac{9.8 \text{ m} \cdot 0.78 \text{ in}}{1 \text{ m} \cdot 13.546 - 0.91 \text{ in}} \cdot \frac{1 \text{ l}}{3.28 \text{ ft} \cdot 113.546 - 0.91 \text{ l}}
\]

\[
\frac{1 \text{ ft} \cdot (100 \text{ cm})^3}{1 \text{ m}^3} \cdot \frac{1 \text{ N}}{1 \text{ kg} \cdot (\text{m/s})^2} = \frac{760 \text{ mm}}{101.3 \times 10}
\]

\[
= 8.4 \text{ mm Hg}
\]

The pressure at A is higher than the pressure at B.

Alternate solution:

\[
\Delta P = \frac{(0.78 \text{ in}) \cdot (13.546 - 0.91)}{13.546} \cdot 760 \text{ mm Hg} = 18.5 \text{ mm Hg}
\]
5.23 Basis: 20 in Hg gauge pressure

\[
\begin{align*}
20 \text{ in. Hg} & \quad 14.7 \text{ psi} = 9.83 \text{ psi} \\
740 \text{ mm Hg} & \quad 14.7 \text{ psi} = 14.3 \text{ psia} \\
14.3 - 9.83 & = 4.47
\end{align*}
\]

5.24 Units for \( g \) and \( \rho \) must be cm & \( \text{cm}^3 \)

\[ p = \rho gh \]

Pressure at M = \( p_M \)
Pressure at 1 = \( p_M + (30)(\rho_{H2O})g \)
Pressure at 2 = \( p_M + (30)(\rho_{H2O})g + h(\rho_{H2O})g \)
Pressure at 3 = Pressure at 4 = \( p_M + (30)(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g \)
Pressure at 5 = \( p_M + (30)(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g \)
Pressure at N = \( p_M + (30)(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g + h(\rho_{H2O})g \)

\[ h(\rho_{H2O})g = p_N \]

\( a \) \quad \[ p_N - p_M = [(30 + h - 6 - h)(\rho_{H2O}) + 6(\rho_{H2O})]g = 10.3 \text{ kPa} \]

or
\[ 24(1) + 6(13.6) = 105.6 \text{ cm H}_2\text{O} \]

\( b \) \quad \[ p_N > p_M \]
5.25

Basis: data given

At 2 and 3 the pressure is the same

\[ p_a + \rho_{lv} g h = p_a + \rho_{al} g \left( \frac{h}{2} \right) \]
\[ p_s = p_a = p_s \] so that
\[ p_a + \rho_{lv} g h = p_s + \rho_{al} g \left( \frac{h}{2} \right) \]

Also \( p_s + \rho_{al} g (60) = p_a \)

Thus: \( p_a + \rho_{lv} g h = p_a - \rho_{al} g (60) + \rho_{al} g (30) + \rho_{al} g \left( \frac{h}{2} \right) \)

Figure 5.25

\[ p_a = p_a + \rho_{lv} g h + \rho_{al} g \left( \frac{h}{2} \right) \]

Basis: Data given in Figure and problem statement

Use \( \Delta p = \rho gh \) twice, once for the CCL4 and oil, and once for the oil and water as systems: \( \rho_{CCL4} = 1.595 g/cm^3 \).

\[ p_a + \rho_{me} g h_{me} + p_{CCL4} g_{CCL4} = p_a + \rho_{al} g (\Delta h_{al}) + p_{CCL4} g_{CCL4} \]
\[ p_o + \rho_{oil} g (\Delta h + 7.5) + p_{H2O} g (22) = p_o + \rho_{oil} g_{H2O} \]

To simplify the two equations, neglect \( \rho_{me} g h_{me} \). Put all of the terms in the units of inches of water. Note \( \rho_1 gh_1 = \rho_2 gh_2 \) for two different fluids exerting the same pressure.

\[ p_a = \frac{6.6 \text{ psia}}{33.91 \text{ ft} \cdot \text{H}_2\text{O}} \cdot \frac{12 \text{ in}}{14.7 \text{ psia}} = 182.7 \text{ in. H}_2\text{O} \]

\[ \rho_{oil} g_{oil} = \frac{7.5 \text{ in. \cdot oil}}{0.7 \text{ g \cdot \ cm}^3} \cdot \frac{0.7 \text{ g \cdot \ H}_2\text{O}}{1.00 \text{ g \cdot \ cm}^3} = 5.3 \text{ in. H}_2\text{O} \]

\[ \rho_{H2O} g_{H2O} \text{ in inches of H}_2\text{O is 22 in. H}_2\text{O} \]

\[ h = 182.7 + 5.3 + 22 = 210 \text{ in. H}_2\text{O} \]
5.27 The pressure measured by the DP cell is \( \Delta p = \rho_{\text{liquid}} \gamma_{\text{liquid}} + \rho_{\text{vapor}} \gamma_{\text{vapor}} \).

The pressure is too high by \( (\rho_{\text{vapor}} \gamma_{\text{vapor}}) \) and \( \Delta p \) is too high by
\[
\left( \frac{\rho_{\text{vapor}} \gamma_{\text{vapor}}}{\rho_{\text{liquid}} \gamma_{\text{liquid}}} \right) + 1
\]

5.28 Surface Area

Top: \( \pi D^2/4 = \pi (8^2) m^2 = 50.3 \ m^2 \)

Walls: \( \pi D h = \pi (8 \text{m})(10 \text{m}) = 251.3 \ m^2 \)

Total area = 301.6 m²

Vented area needed = \( \frac{0.41(\text{kPa})^{0.5} (301.6 \ m^2)}{(7.5 \text{kPa})^{0.5}} \)

= 45.1 m²

Therefore, the area is **not sufficient**.

5.29

\[ p_c = \frac{(420-380) \text{ mm H}_2\text{O}}{13.56 \text{ mm H}_2\text{O}} + (380-180) \text{ mm Hg} \]

\[ = \frac{12.50 \text{ psi}}{14.7 \text{ psi}} = 864 \text{ mm Hg} \]

\[ p_0 = 646 - 3 = 643 \text{ mm Hg} \] \( (8.57 \text{ psi}) \)

5.30

\[ P_A - P_B = (P_{H_2O} - P_{BZ})(36.6) = (0.997 - 0.879)_s \frac{980 \text{ cm}}{100 \text{ cm}} = 0.42 \text{ kPa} \]

5.31 Equate the pressures at the bottom of the two legs of the manometer at the reference plane.

Left hand leg pressure \( P_{CLH} + (2.5 + 1.5)(1590)(9.812) + h_{CLH} \times (13600)(9.812) \text{N/m}^2 \)

Right hand leg pressure \( P_{CLH} + (1.5 + h)(800)(9.812) \text{N/m}^2 \)

\[ P_{CLH} + (2.5 + 1.5)(1590)(9.812) + h (13600)(9.812) = P_{CLH} + (1.5 + h)(800)(9.812) \]

Manometer Reading = 14.6 cm of Hg
5.32 Basis: Data shown in Figure

Assume densities are as shown (ignore temperature effects)

\[ \rho = \rho_a + \rho_a g h_1 + \rho_{H_2O} g h_2 = 15.5 \text{ psia} + \rho_{C_{2}H_4} g h_3 + \rho_{H_2O} g h_4 \]

\[ \uparrow \]

ignore as gas density is small

\[ \rho_a = 15.5 \text{ psia} + \rho_{C_{2}H_4} g h_1 + \rho_{H_2O} (h_4 - h_1) \]

\[ = 15.5 + \frac{(62.4)(0.684)lb}{ft^2} \cdot \frac{g}{ft} \cdot \frac{10.5 \text{ cm}}{2.54 \text{ cm}} \cdot \frac{1 \text{ in}}{1 \text{ ft}} \cdot \frac{1 \text{ ft}}{12 \text{ in}} \]

\[ \times \frac{1 \text{ lb}}{32.2 (lb \cdot s^2)/in} \cdot \frac{1 \text{ ft}}{6.3 \text{ cm}} \]

\[ \times \frac{1 \text{ in}}{2.54 \text{ cm}} \cdot \frac{1 \text{ ft}}{12 \text{ in}} \cdot \frac{1 \text{ lb} \cdot s^2}{32.2 (lb \cdot s^2)/in} \cdot \frac{1 \text{ ft}}{12 \text{ in}} = 15.69 \text{ psia} \]

\[ 15.69 - 14.69 = 1.0 \text{ psig} \]

5.33 Basis: 3.1 cm fluid

\[
\begin{array}{c|c|c|c|c}
3.1 \text{ cm fluid} & (1.30 - 1.00) \text{ cm} & H_2O & 1 \text{ in} & 1 \text{ ft} & 101.3 \text{ kPa} & = 0.091 \text{ kPa} \\
1.00 \text{ cm fluid} & 2.54 \text{ cm} & 12 \text{ in.} & 33.91 \text{ ft} & 1 \text{ in} & 1 \text{ ft} \\
\end{array}
\]

Alternate solution:

\[ p_a + \rho_w g h_1 = p_w + \rho_w g h_2 + \rho_{\text{mol}} g \Delta H \]

\[ p_a - p_w = \rho_w g h_1 + \rho_{\text{mol}} g \Delta H - \rho_w g h_2 - \rho_w g \Delta H = \rho_{\text{mol}} g \Delta H = g \Delta H (\rho_{\text{mol}} - \rho_w) \]

\[ = 1.30 - 1.00 \text{ g} \cdot 980 \text{ cm} \cdot 3.1 \text{ cm fluid} \cdot 1 \text{ kg} \cdot 100 \text{ cm} \cdot 1 \text{ Pa} \cdot (s^2)(m) \]

\[ = 0.091 \text{ kPa} \]
The pressure at BG is

\[ \frac{33.1 \text{ psig}}{720 \text{ mm Hg}} = \frac{14.7 \text{ psia}}{760 \text{ mm Hg}} = 47.0 \text{ psi} \]

\[ \frac{47.0 \text{ psia}}{101.3 \text{ kPa}} = \frac{14.7 \text{ psia}}{324 \text{ kPa}} \]

\[ p_r = 7 \text{ in. oil} + 27 \text{ in. Hg} \]

\[ p_r = 31'' \text{ oil} = p_b \]

\[ p_{can} + 16 \text{ in. oil} = p_u \]

\[ p_{net} = 324 \text{ kPa} - 7 \text{ in. oil} - 27 \text{ in. Hg} + 31 \text{ in. oil} - 16 \text{ in. oil} \]

\[ = 324 \text{ kPa} + 8 \text{ in oil} - 27 \text{ in Hg} \]

Convert in. oil and in. Hg to kPa

\[ p_{can} = 324 + 1.59 - 91 = 235 \text{ kPa} \]
6.1

Basis: 1 minute

<table>
<thead>
<tr>
<th>Accumulation (kg)</th>
<th>In (kg)</th>
<th>Out (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{f_{idd}}$</td>
<td>300 + 100</td>
<td>- 380</td>
</tr>
</tbody>
</table>

$n_{f_{idd}} = 20$ kg

$\frac{20 \text{ kg/60 min}}{\text{min/1 hr}} = 1200$ kg

6.2

Basis: 600 kg solution

<table>
<thead>
<tr>
<th>Accumulation (kg)</th>
<th>In (kg)</th>
<th>Out (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{f_{idd}}$</td>
<td>100 + 500</td>
<td>- 300</td>
</tr>
</tbody>
</table>

$n_{f_{idd}} = 300$ kg if no water evaporates in which case less than 300 kg would remain

6.3

(c) $27.0$ g

6.4

Basis: 1 hr

Overall material balance (kg): $13,500 + 26,300 \neq 39,800$

6.5

Based on the process measurements, there are 5,000 lb/h more flow for the process leaving the heat exchanger than the feed rate to the heat exchanger; therefore, the material balance for the process fluid does not close. The reason for this discrepancy could be faulty flow sensor readings or possibly a leak of the condensate or steam into the process stream.

6.6

Basis: 1 hour

The overall material balance is

<table>
<thead>
<tr>
<th>In (lb)</th>
<th>Out (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>106,000</td>
<td>74,000 + 34,000 = 108,000</td>
</tr>
</tbody>
</table>

The error in the overall material balance is 2000 lb/h or 1.9%; therefore, the overall material balance is within the expected error for industrial flow sensors.

Propylene balance:

| $0.7 \times 106,000 \neq (0.997) (74,000) + (0.1) (34,000)$ |
| $74,200 \neq 73,778 + 3,400 = 77,178$ (3.8% error) |

| $0.4 \times 106,000 \neq (0.003) (74,000) + (0.9) (34,000)$ |
| $31,800 \neq 222 + 30,600 = 30,622$ (3.8% error) |

Note that the relative error for the component balances are twice as large as the relative error for the overall material balance, indicating that there is additional error in the composition measurements used for the component balances.
Solutions Chapter 6

6.7 Basis: Data shown on flowsheet units are MTA

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 x 10^6</td>
<td>404 x 10^3</td>
</tr>
<tr>
<td></td>
<td>228 x 10^3</td>
</tr>
<tr>
<td></td>
<td>152 x 10^3</td>
</tr>
<tr>
<td></td>
<td>101 x 10^3</td>
</tr>
<tr>
<td></td>
<td>67 x 10^3</td>
</tr>
<tr>
<td></td>
<td>36 x 10^3</td>
</tr>
<tr>
<td></td>
<td>100 x 10^3</td>
</tr>
<tr>
<td></td>
<td>1190 x 10^3</td>
</tr>
<tr>
<td></td>
<td>2,278 x 10^3</td>
</tr>
</tbody>
</table>

mass in does not equal to mass out.

Reasons:
1. Some of the material was burned as fuel.
2. Some of the material formed gases that were exhausted to atmosphere (such as H$_2$O, CO$_2$).
3. Errors in measurement.
4. Some process streams are not shown.

6.8 In = 250,000 ton/yr. Out = 244,500 ton/yr.

<table>
<thead>
<tr>
<th>In (ton/yr)</th>
<th>Out (ton/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250,000</td>
<td></td>
</tr>
<tr>
<td>Combustibles</td>
<td>3,800</td>
</tr>
<tr>
<td>Combustibles</td>
<td>39,500</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>30,000</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>5,000</td>
</tr>
<tr>
<td>PVC</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Solutions Chapter 6

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile</td>
<td>20,000</td>
</tr>
<tr>
<td>DB</td>
<td>8,000</td>
</tr>
<tr>
<td>Phenol</td>
<td>10,000</td>
</tr>
<tr>
<td>Acetone</td>
<td>5,750</td>
</tr>
<tr>
<td>Rubber</td>
<td>10,000</td>
</tr>
<tr>
<td>LPG</td>
<td>24,000</td>
</tr>
<tr>
<td>Aromatics</td>
<td>48,000</td>
</tr>
<tr>
<td>Total</td>
<td>244,050</td>
</tr>
</tbody>
</table>

Balance is not exact but very good for an operating plant.

6.9 Basis: 1 week

in (tons) = 920 + 0.6 = 920.6

out (tons) = 3.8 + 620 + 0.01 + 0.01 + 0.08 + 1.1 + 275 + 20 = 920

Yes

6.10 Boundary: Around both pumps and include the soil at the end of the pipes.

It's an open system.

It's at steady-state except at startup (note system boundary limits fluid), or if fluid enters, unsteady state.

6.11 Either open (flow) or closed (batch) is acceptable if explanation is given

1. flow - material comes in and out continuously over a suitably long period of time
2. batch - material is injected into the system, and then in a short period of time, a reaction occurs with the system valves closed.
6.12
a) closed
b) open
c) open
d) closed

6.13
The system is the radiator.

<table>
<thead>
<tr>
<th>Open System</th>
<th>Closed System</th>
<th>Steady-State</th>
<th>Unsteady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>b) X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>c) X (Before filling)</td>
<td>X (After filling)</td>
<td>X (After filling)</td>
<td>X (Before Filling)</td>
</tr>
<tr>
<td>d)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

6.14
(a) open if you have to replace water, and water evaporates; otherwise closed
(b) open

6.15
(c) Unsteady state for any assumptions
   a) assume water (melted ice) leaves the system
   b) assume water stays in system because the ice and water remain on melting

6.16

- Unsteady state open
- Unsteady state open
- Steady state open
6.17 If the overall flows in and out over a time period for several batches are considered, and the local batches ignore, the process can be treated as continuous.

6.18 (a) water and air.
(b) Insulation, air and what is in the atmosphere.
(c) Yes (cold water in, hot water out)
(d) Yes

6.19 If a reaction occurs, some of the entering moles will be used up, and new ones produced that exit but did not enter.

6.20 The density of the crystalline silicon in the cylinder is 2.4 g/cm³.

Basis: 62 kg silicon

The system is the melt, and there is no generation or consumption. Let \( \Delta m \) be the accumulation.

\[
\Delta m = \text{Input} - \text{Output} = 0 - 0.5(62 \text{ kg})
\]

\( \Delta m = -31 \text{ kg} \)

Let \( t \) be the time in minutes to remove one-half of the silicon

\[
\frac{2.4 \text{ g} \times (17.5 \text{ cm})^3 \times 0.3 \text{ cm} \times t \text{ min}}{4 \text{ min}} = \frac{1}{2} \times (62,000 \text{ g})
\]

\( t = 179 \text{ min} \)

6.21 Basis: 100 kg wet sludge

The system is the thickener (an open system). No accumulation, generation, or consumption occur. The total mass balance is

\[
\frac{\text{In}}{100 \text{ kg}} = \frac{\text{Out}}{70 \text{ kg} + \text{kg of water}}
\]

Consequently, the water amounts to 30 kg.

6.22

\begin{array}{ccccccc}
(a) & (b) & (c) & (d) & (e) & (f) & (g) \\
1. & x & x & & & & \\
2. & x & & & & & \\
3. & x & & & & & \\
4. & \text{Depends on the time period considered} & & & & & \\
5. & x & x & x & & & \\
6. & x & x & x & & & \\
7. & x & x & & & & \\
\end{array}

6.23 If the overall flows in and out over a time period for several batches are considered, and the local batches ignore, the process can be treated as continuous.

6.24 It depends on the process of interest – no fixed answer can be given.
7.1

Four balances are possible, 3 component plus 1 total.

\[ 0.10F_1 + 0.50F_2 + 0.20F_3 = 0.35P \]
\[ 0.20F_1 + 0F_2 + 0.30F_3 = 0.10P \]
\[ 0.70F_1 + 0.50F_2 + 0.50F_3 = 0.55P \]

Total balance \( F_1 + F_2 + F_3 = P \)

Only 3 of the equations are independent.

7.2

If you specify \( F, P, W \), you can calculate all of the stream variables.

a) Unknown: three stream values \( F, P, W \) (plus two compositions if you take into account all of the variables).

b) The two known compositions are not given but may be calculated from \( \Sigma x_i = 1 \).

c) Two components exist, hence two independent material balances can be written. The problem cannot be solved unless one stream value is specified.

7.3

(a) No. The equations have no solution — they are parallel lines.

The rank of the coefficient matrix is only 1 because the

\[ \begin{vmatrix} 1 & 2 \\ 1 & 2 \end{vmatrix} = 0 \]

The rank of the augmented matrix is 2.

7.4

The number of independent equations is just 3. The number of unknown quantities is 3, hence a unique solution is possible.
### Solutions Chapter 7

#### 7.5

**a)** Rank of coefficient matrix is 2.

$$\begin{bmatrix} 1 & 1 & 1 \\ 2 & 3 & 5 \\ 4 & 6 & 7 \end{bmatrix}$$

- $r = 2$, $n = 3$
- Multiple solutions exist

**b)** 3rd column is sum of 1st two columns, so rank is 2.

$$\begin{bmatrix} 1 & 0 & 1 \\ 2 & 4 & 6 \end{bmatrix}$$

- $r = 2$, $n = 3$
- Multiple solutions exist

#### 7.6

(a) F; (b) F; (c) F (the maximum can be more than the number of independent equations).

#### 7.7

- $a^1 = 0.10$
- $a^2 = ?$
- $a^3 = 0$ (assumed)
- $P = 16$ kg

Unknowns (4): $a^1, a^2, a^3, a^4$

Equations:

- $F = 10$ kg
- $A = 6$ kg
- $a^1 = 0.30$
- $a^3 = 0.20$

#### 7.8

Examine the row of C$_3$H$_8$. None of the concentrations are greater than the desired 50% so 50% is not achievable by any combination of A, B, or C. Or look at the CH$_4$ row.

#### 7.9

<table>
<thead>
<tr>
<th>Basis: D = 100 lb</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>$x_2$</td>
<td>$x_3$</td>
<td>$x_4$</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

Coefficient matrix is

$$\begin{bmatrix} 5.0 & 0 & 0 & 85.0 \ 0 & 5.0 & 80.0 & 12.6 \
0 & 0 & 12.0 & 14 \end{bmatrix}$$

continued
7.10  You can see by inspection that no combination of tanks 1, 2 and 3 will give a mole fraction of 0.52 for the mixture.

Basis: 2.50 mol of tank 4

Let \( x_i \) be the total moles of tank \( i \)

\[
0.23x_1 + 0.20x_3 + 0.54x_3 = 0.25(2.5) = 0.625
\]

The balances are

\[
0.36x_1 + 0.33x_3 + 0.27x_3 = 0.23(2.5) = 0.575
\]

\[
0.41x_1 + 0.47x_3 + 0.19x_3 = 0.52(2.5) = 1.300
\]

The coefficient matrix has a rank of 3 as does the augmented matrix so the set of equations has a solution. However, the solution is

\[
\begin{align*}
x_1 & = -4.00 \\
x_2 & = 6.36 \\
x_3 & = -0.327
\end{align*}
\]

The values of \( x_1 \) and \( x_3 \) are not physically realizable!
7.13

a. 

b. The remaining gas is 100% minus the N₂, and was put on the figure as R.

c. Basis: 100 mol A

d. Unknowns: A, B, C
Equations: N₂ and R material balances
Basis = A = 100 mol
Note: You could treat the values of R as unknowns in each stream, and then there would be 3 more unknowns and 3 more independent equations (Σx_i = 1 or Σm_i = total mass flow.)

e.&f. N₂: 100(0.90) + B(0.30) = C(0.65)
R: 100(0.10) + B(0.70) = C(0.35)
Total: 100 + B = C

Two of the above equations are independent

g. Solution: B = 71.4 mol C = 171.4 mol

\[
\begin{align*}
\frac{A}{B} &= \frac{100}{71.4} = 1.40
\end{align*}
\]

7.14

a. 

b. The DT is the balance of each stream.

c. Basis: F = 100 kg

d. Unknowns: F, W, P OR F, W, P, DT^f, DT^w, DT^p, H₂O^f, H₂O^w

Equations: 
Basis: F = 100 kg
Material Balances: Water, DT (total); 2 independent
Specifications: 3 for water
Implicit equations: 3 of Σω_i = 1

Degrees of freedom = 0

Evaluating the specifications and basis into the material balances:

Water: (0.201)100 = (1)W + (0.080)P
DT: (0.800)100 = 0 + (0.914)P
Total: 100 = W + P

\[
\begin{align*}
W &\approx 12.5 kg \\
P &\approx 87.5 kg
\end{align*}
\]

\[
\begin{align*}
\frac{W}{F} &= \frac{12.5 kg}{100 kg} = 0.125 kg/kg
\end{align*}
\]
Here are some possibilities. Consult the tables at the end of the Chapter for more suggestions.

1. Rephrase the problem to make sure you understand it?
2. Draw a simple diagram of what was happening?
3. Think about what was going into the tank and what was coming out?
4. Imagine yourself inside the tank, and ask what was going on around you?
5. Ask whether there were any physical laws to consider (such as conservation of matter or energy)?
6. Try to imagine the answer as a number, graph, table, or whatever?
7. Try to identify essential variables?
8. Choose a notation?
9. Look for a ready-made formula for the answer?
10. Look for simplifying assumptions?
11. Try to find an easier version of the problem?
12. Look for bounds (simple models that would definitely underestimate or overestimate the answer)?

More information is needed to solve the problem uniquely.
8.1

<table>
<thead>
<tr>
<th>Cucumber</th>
<th>Initial</th>
<th>Final (P)</th>
<th>Evaporated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 kg</td>
<td>2%</td>
<td>~</td>
</tr>
<tr>
<td>Water</td>
<td>98 kg</td>
<td>98%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>100 kg</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Cucumber balance: 0.02P - 0.01(100) = 0

P = 50 kg, Answer is: Yes

8.2

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>plant</td>
<td>5 ppm</td>
<td>Plant 755 ppm</td>
</tr>
<tr>
<td>soil</td>
<td>6 ppm</td>
<td>Soil 5 ppm</td>
</tr>
</tbody>
</table>

Final - Initial

Arsenic balance: S (5) - S(6) = P(755) - P(5)

750P = S or \( \frac{S}{P} = 750 \)

8.3

Step 5: Basis is 1 ton (2000 lb) sludge

Steps 1, 2, 3, 4:

Sludge

\[ \begin{align*}
0.70 \text{ H}_2\text{O} & \\
0.30 \text{ Solids} & \\
1.00 &
\end{align*} \]

Dried Sludge

\[ \begin{align*}
0.25 \text{ H}_2\text{O} & \\
0.75 \text{ Solids} & \\
1.00 &
\end{align*} \]

Steps 6 and 7:

Basis: 2000 lb F

Balances: H_2O, Solids

Unknowns: P, W

Steps 8 and 9:

Total: 2000 = P + W

Solids: 2000 (0.30) = P (0.75)

P = 800 lb

W = 2000 - 800 = 1200 lb
8.4 Step 5: Basis: 1 min

Steps 2, 3, 4:

- 220 mL B
- Urea 2.30 mg/mL
- H₂O 220 mL
- V 215 mL
- 1.70 mg/mL
- H₂O 215 mL
- P

Steps 6 and 7: Unknowns: m'a₀ and m'w₀ with two equations: urea and H₂O. Degrees of freedom = 0.

Steps 8 and 9:

(a) H₂O balance: 220 mL - 215 mL = 5 mL

Urea balance: \[
\frac{2.30 \text{ mg}}{\text{mL}} \times 220 \text{ mL} - \frac{1.70 \text{ mg}}{\text{mL}} \times 215 \text{ mL} = 141 \text{ mg}
\]

(b) Dialysate: 1500 + 5 = 1505 mL

Urea: 141 mg

Concentration: \[
\frac{141}{1505} = 0.0934 \text{ mg/mL}
\]

---

8.5 Step 5: Basis: 1 day

Steps 2, 3, 4:

- W ton 1.00 H₂O
- F=2 ton
- mass fr
- NaOH: 0.03
- H₂O: 0.27
- 1.00

Steps 6: Unknowns, 2: P, W

Steps 7: Balances 2: NaOH, H₂O, total (2 of the 3)

Steps 8 & 9:

Total: 2 = W + P
NaOH: 2 (.03) = P (.18)

\[
P = \frac{1}{3} \text{ ton} \quad \frac{W = 1}{3} \frac{2/3 \text{ ton}}{666 \text{ lb}} \quad \frac{(3334 \text{ lb})}{1.00} \]

8.6 **Steps 2, 3, 4:**

- 500 lb 10% solution
- 3000 lb 13% polymer

**A**

20% solution

pure solvent

**S**

**Step 5:**
Basis: 3000 lb of final product

**Steps 6 and 7:** Unknowns: A and S; balances: total and polymer

**Steps 8 and 9:**

**Total wt**

\[ A + S + 500 = 3000 \]

\[ A + S = 2500 \]

**Polymer**

\[ 0.2A + 50 = 390 \]

\[ A = 5 (340) = 1700 \]

\[ S = 2500 - 1700 = 800 \]

---

8.7 **Steps 1, 2, 3 and 4:**

- **N** = nitrocellulose
- **S** = solvent

Treat the problem as a steady state flow problem, or as an unsteady state batch system. As a flow system:

\[ M \text{ (lb) N 100%} \]

\[ F \text{ (lb)} \]

\[ N \quad 0.055 \]

\[ S \quad 0.845 \]

\[ 1.000 \]

\[ \text{Plant} \]

\[ P \quad 1000 \text{ lb} \]

\[ \text{Mass fr.} \]

\[ N \quad 0.08 \]

\[ S \quad 0.92 \]

\[ 1.00 \]

**Step 5:**
Basis: 1000 lb P

**Steps 6 and 7:** Two unknowns, F and M. Two balances can be made, N and S.

**Steps 8 and 9:**

Solve to get

\[ N: \quad F(0.055) + M(1.00) = 1000(0.008) \]

\[ F = 973.5 \text{ lb} \]

\[ S: \quad F(9.045) + M(0) = 1000(0.92) \]

\[ M = 26.5 \text{ lb} \]

\[ P = 1000.0 \text{ lb} \]
8.8

Steps 1, 2, 3 and 4:

\[
\begin{align*}
F &= 100 \text{ kg mol/min} \\
\text{Mol fr. CH}_4/\text{He} &= 0.80/0.20 = 4 \text{ kg mol} \\
P/\text{(kg mol)} &= 1.00 \\
\text{Mol fr. CH}_4/\text{He} &= 0.50/0.50 = 1.00 \\
\end{align*}
\]

Step 5: Basis 1 min \(\rightarrow\) 100 kg mol F

Step 4: To get P, calculate first the average mol. wt. of F and P, or transform the mole fractions to mass fractions.

Step 5: Basis: 1.00 mol F

\[
\begin{align*}
\text{Mol} &\quad \text{MW} & \quad \text{kg} \\
\text{CH}_4 &\quad 0.80 &\quad 16.03 &\quad 12.8 \\
\text{He} &\quad 0.20 &\quad 4 &\quad 0.8 \\
1.00 &\quad &\quad 13.6 \\
\end{align*}
\]

Basis: 1.00 mol P

\[
\begin{align*}
\text{Mol} &\quad \text{MW} & \quad \text{kg} \\
\text{CH}_4 &\quad 0.50 &\quad 16.03 &\quad 8.01 \\
\text{He} &\quad 0.50 &\quad 4 &\quad 2.0 \\
1.00 &\quad &\quad 10.01 \\
\end{align*}
\]

100 kg mol F | 13.6 kg F | 0.20 kg F | 1 kg mol P | 1 kg F | 10.01 kg P

(continued)

8.9

\[
P = 27.2 \text{ kg mol}
\]

Steps 6, 7, 8 and 9:

\[
\begin{align*}
100(0.80) &= 27.2(0.50) + n_{\text{CH}} \\
100(0.20) &= 27.2(0.50) + n_{\text{He}} \\
\end{align*}
\]

\[
\begin{array}{c|c|c|c}
\text{Mol} & \text{Mol fr.} \\
\hline
n_{\text{CH}} & 66.4 & 0.912 \\
n_{\text{He}} & 6.4 & 0.088 \\
\hline
n_{\text{tot}} & 72.8 & 1.00 \\
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{Basis: 1000 cm}^3 \text{ F}_1 \\
\hline
\text{Dry cells} &= 1000 \text{ cm}^3 \text{ in fermenter} \quad 60 \text{ cm}^3 \text{ cell} \quad 1.1 \text{ g cell} \quad 25 \text{ g solids} \\
&= 16.5 \text{ g Dry cell} / 1000 \text{ cm}^3 \text{ in fermenter} \\
\end{array}
\]

\[
\begin{array}{c}
\text{Fermenter} \\
\text{40% void} \\
\text{60% cell volume} \\
\hline
\text{Separator} \\
\text{F}_1 \quad \text{discharge} \\
\text{F}_2 \quad \text{wet cell} \\
\text{75% H}_2\text{O} \\
\text{25% dry cell} \\
\hline
\text{W}_1 \\
100\% \text{ H}_2\text{O} \\
\end{array}
\]
8.10
a. Basis: 1 kg mole of mixture

Three components exist: (CH₄)ₓ, (C₂H₆)ₓ, (C₃H₈)ₓ

Let A, B, C respectively represent kg mol of each mixture; these are the unknowns.

Equations:

0.25A + 0.35B + 0.55C = 0.30  (CH₄)ₓ balance
0.35A + 0.20B + 0.40C = 0.30  (C₂H₆)ₓ balance
0.40A + 0.45B + 0.05C = 0.40  (C₃H₈)ₓ balance

There is a unique solution to the set of equations (in kg mol)

The solution is \[ A = 0.600 \quad B = 0.350 \quad C = 0.05 \]

b. It is proposed to prepare the final mixture by blending four different compounds (A, B, C, D); there will still be three equations, but now there will be four unknowns. Since the rank is now less than \( n \), there will be an infinite number of possible blends of the four mixtures. Not required: An optimization of a revenue function subject to the equations is needed.

8.11
a.

\[ \text{CH}_4: 100\% \quad \text{CO}_2: \text{mol} \quad \text{F} = ? \quad \text{P (lb)} = ? \]

\[ \text{MW} = 16 \quad \text{F} = \frac{100 \text{ lb}}{44 \text{ lb mol}} = 2.27 \text{ lb mol} \]

Steps 2, 3, 4:

Steps 5: Basis 1 min

Steps 6: Unknowns: F, P

Steps 7: Balances: CH₄, CO₂

Steps 8 and 9: Balances in moles

\[
\begin{align*}
\text{CH}_4: & \quad F (1.00) + A(0) = P (0.9796) \\
\text{CO}_2: & \quad F (0) + 2.27 = P (0.0204) \quad P = 111.41 \text{ lb mol} \\
F & = \frac{111.27 \text{ lb mol \ CO}_2}{1 \text{ lb mol} \ P} = 111.27 \text{ lb mol \ CH}_4 \\
16 \text{ lb \ CH}_4 & = \frac{1746 \text{ lb/min}}{1 \text{ lb mol \ CH}_4} 
\end{align*}
\]

b. Redo the problem with a new composition for F:

\[
\begin{align*}
\text{CH}_4 & : 0.99 \\
\text{CO}_2 & : 0.01 \\
1.00 & 
\end{align*}
\]

(continued)
8.12 Steps 1, 2, 3, and 4:

- \( \text{NH}_3 \): 72.3 kg/min for 12 min
- \( F(\text{kg}) \) → Pipeline → \( P(\text{kg}) \) → \( \text{NH}_3 \) gas

**Mass fr.**
- \( \text{NH}_3 \) gas: 0.99618
- \( \text{NH}_3 \): 0.00382
- \( P \): 1.00

**Step 5:** Basis: 1 min

**Steps 6 and 7:** Two unknowns, \( F \) and \( P \). Two balances can be made, \( \text{NH}_3 \) and gas. You can use the total balance as a substitute.

**Steps 8 and 9:**

- Total: \( F + 72.3 = P \)
- \( \text{NH}_3 \): \( F(0) + 72.3 = P(0.00382) \)

\[ P = 18,900 \, \text{kg/min} \]

**Step 10:** Check using the gas balance

---

8.13

**Steps 1, 2, 3, and 4:**

- 10 lb/hr
- \( \text{Br} \)
- \( \text{H}_2\text{O} \)

**Step 5:** Basis: 1 hr

**Step 6:** Unknowns: \( F, P \)

**Step 7:** Balances: \( \text{H}_2\text{O}, \text{Br} \)

**Steps 8 and 9:**

- Total: \( F + 10 = P \)
- \( \text{Br} \) (0) + 10 = \( P(0.00012) \); \( P = 8.33 \times 10^4 \) lb/hr
- \( \text{H}_2\text{O} \) (1.00) + 0 = \( P(1.000012) \)

\[ P = 8.33 \times 10^4 - 10 = 8.33 \times 10^4 \text{ lb/hr} \]
8.14 Step 5: Basis: 1 year

Steps 2, 3, 4:

\[
F = 7 \text{ lb}
\]

\[
P = 15 \times 10^6 \text{ lb}
\]

\[
\begin{array}{c|c}
\text{mass fr.} & \text{mass fr.} \\
\hline
\text{PET} & 0.98 \\
PVC & 0.02 \\
\end{array}
\]

\[
\begin{array}{c|c}
\text{PET} & 0.99999 \\
PVC & 0.00001 \\
\end{array}
\]

(10 ppm)

Steps 6 and 7:

Two unknowns: \( F, W \)

Two balances: PET, PVC

Steps 8 and 9:

PET balance:

\[
F \times 0.98 = P \times 0.99999 \implies 15 \times 10^6
\]

PVC balance:

\[
F \times 0.02 = W \times 1.00 + P \times 0.00001
\]

Total balance could be used in lieu of one of the above

\[
F = 15 \times 10^6 + W
\]

From PET:

\[
F = 15.3 \times 10^6 \text{ lb}
\]

\[
W = (15.3 \times 10^6) \times 0.02 - 15 \times 10^6 (10^{-5}) = 0.31 \times 10^6 \text{ lb}
\]

8.15 Basis: 300 g initial solution

\[
\text{MW Na}_2\text{SO}_4 \cdot 10H_2O = 322.2
\]

(a) \[
\begin{array}{c|c|c|c|c|c|c|c}
\text{In} & \text{g} & \text{MW} & \text{g mol} & \text{Out} & \text{g} & \text{g mol} \\
\hline
\text{Na}_2\text{SO}_4 & 100 & 142.05 & 0.704 & \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} & 100 & 0.310 \\
\text{H}_2\text{O} & 200 & 18.016 & 11.10 \\
\end{array}
\]

Material balances in g mol (in = out):

\[
\begin{align*}
\text{g mol} &: \quad 50 \\
\text{Na}_2\text{SO}_4 &: 0.704 = 0.310 + n_{\text{Na}_2\text{SO}_4} \\
n_{\text{Na}_2\text{SO}_4} &= 0.394 & 55.97 \\
\text{H}_2\text{O} &: 11.10 = 0.310 (10) + n_{\text{H}_2\text{O}} \\
n_{\text{H}_2\text{O}} &= 8.0 & 144.1 \\
\text{Total} &= 8.394 & 200.07 & 100 \\
\end{align*}
\]

Mother liquor: \( \text{Na}_2\text{SO}_4 \) is 28% and \( \text{H}_2\text{O} \) is 72%

(b) \[
\frac{100 \text{ g crystals}}{100 \text{ g solution}} = 33.3 \text{ g crystals/100 g initial soln.}
\]

8. Solutions Chapter 8
8.16 Assume steady state flow problem (alternate is unsteady state batch problem).

**Steps 1-4:**

\[
\begin{align*}
\text{200 g H}_2\text{O} & \quad 1.00 \\
100 \text{ g Na}_2\text{B}_4\text{O}_7 & \quad 1.00
\end{align*}
\]

\[
\begin{align*}
\text{No mix.} & \quad \text{No accum.} \\
F (\text{g}) & \quad \text{Final solution}
\end{align*}
\]

\[
\begin{align*}
\text{mol fr.} & \quad \text{Na}_2\text{B}_4\text{O}_7 \quad 0.124 \\
\text{mol fr.} & \quad \text{H}_2\text{O} \quad 0.876 \\
\text{mol fr.} & \quad 1.00
\end{align*}
\]

**Calculate composition of F:** Basis: 100 mol Na_2B_4O_7, 10 H_2O

<table>
<thead>
<tr>
<th>mol</th>
<th>MW</th>
<th>g</th>
<th>mol fr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na_2B_4O_7</td>
<td>1</td>
<td>201.27</td>
<td>201.27</td>
</tr>
<tr>
<td>H_2O</td>
<td>10</td>
<td>18</td>
<td>180.0</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
381.27 & \quad 1.00
\end{align*}
\]

**Step 5:** Basis: 200 g H_2O + 100 g Na_2B_4O_7

**Step 6:** Unknowns: F, B

**Step 7:** balances: Na_2B_4O_7, H_2O

**Step 8:**

\[
\begin{align*}
\text{Na}_2\text{B}_4\text{O}_7: & \quad 100 = P(0.528) + F(0.124) \\
\text{H}_2\text{O}: & \quad 200 = P(0.472) + F(0.876)
\end{align*}
\]

\[
\begin{align*}
\text{2 indept.} \\
\text{Total:} & \quad 100 + 200 = P + F
\end{align*}
\]

**Step 9:** Use H_2O and Total to get P = 155.5 g and F = 144.5 g

\[
\frac{155.5}{300} = \frac{51.8 \text{ g Na}_2\text{B}_4\text{O}_7}{100 \text{ g H}_2\text{O}}
\]

---

8.17 Assume the process is a steady state one without reactions.

**Steps 1, 2, 3, 4:**

\[
\begin{align*}
\text{FeCl}_3 \cdot \text{H}_2\text{O} & \quad 1000 \text{ kg} \\
\text{FeCl}_3 \cdot 2.5 \text{ H}_2\text{O} & \quad P
\end{align*}
\]

**Step 10:** Check use Na_2B_4O_7

\[
100.0 = 100.0 \quad \text{ok}
\]

Calculate the compositions for just one iron compound. FeCl_3 is the simplest to use.

**For F_1:** Basis: 1 kg mol

<table>
<thead>
<tr>
<th>FeCl_3</th>
<th>162.22</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCl_3 \cdot \text{H}_2\text{O}</td>
<td>270.32</td>
</tr>
<tr>
<td>FeCl_3 \cdot 2.5 \text{ H}_2\text{O}</td>
<td>207.26</td>
</tr>
<tr>
<td>H_2O</td>
<td>18.02</td>
</tr>
</tbody>
</table>

**For F_2:** Basis: 1 kg mol

<table>
<thead>
<tr>
<th>FeCl_3</th>
<th>162.22</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCl_3 \cdot \text{H}_2\text{O}</td>
<td>168.18</td>
</tr>
<tr>
<td>FeCl_3 \cdot 2.5 \text{ H}_2\text{O}</td>
<td>207.26</td>
</tr>
<tr>
<td>H_2O</td>
<td>18.03</td>
</tr>
</tbody>
</table>

For P Basis: 1 kg mol

<table>
<thead>
<tr>
<th>FeCl_3</th>
<th>162.22</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCl_3</td>
<td>162.22</td>
</tr>
<tr>
<td>FeCl_3 \cdot \text{H}_2\text{O}</td>
<td>18.03</td>
</tr>
<tr>
<td>FeCl_3 \cdot 2.5 \text{ H}_2\text{O}</td>
<td>45.08</td>
</tr>
<tr>
<td>H_2O</td>
<td>207.30</td>
</tr>
</tbody>
</table>

(continued)
Solutions Chapter 8

Step 5: Basis: 1000 kg FeCl$_3$.6H$_2$O

Step 6: Unknowns P, F

Step 7, 8, 9: Balances (kg)

\[
\begin{align*}
\text{IN} & \quad \text{OUT} \\
\text{FeCl$_3$:} & \quad \frac{162.22}{270.40} + F_1 \left( \frac{162.22}{180.25} \right) = P \left( \frac{162.22}{207.30} \right) \text{ kg FeCl$_3$} \\
\text{Total:} & \quad 1000 + F_2 = P \\
\text{soln:} & \quad F_2 = 1555.7 \text{ kg} \\
\text{P = 2555.7 kg} \\
\text{Step 10: Check:} & \quad F_2 + F_1 = 1554.5 + 1000 = 2554.5 \text{ ok}
\end{align*}
\]

8.18 Steps 2, 3, 4:

The process can be viewed as an unsteady process without reaction, or as a flow process.

Step 5: Take as a basis 100 g of Ba(NO$_3$)$_2$.

Step 4:

The maximum solubility of Ba(NO$_3$)$_2$ in H$_2$O at 100°C is a saturated solution, 34 g/100 g of H$_2$O. Thus the amount of water required at 100°C is

\[
\frac{100 \text{ g H}_2\text{O}}{34 \text{ g Ba(NO$_3$)$_2$}} = 294.1 \text{ g H}_2\text{O}
\]

If the 100°C solution is cooled to 0°C, the Ba(NO$_3$)$_2$ solution will still be saturated so that the composition of the final solution is

\[
\text{mass fr.} \quad \frac{5}{100 + 5} = 0.0476
\]

(continued)
The composition of the crystals is

\[
\text{Ba(NO}_3\text{)}_2: \quad \frac{100}{100+4} = 0.9615
\]

\[
\text{H}_2\text{O}: \quad \frac{4}{100+4} = 0.0385
\]

The composition of the original solution is

\[
\begin{align*}
\text{Ba(NO}_3\text{)}_2 & : \quad 100\text{g} \quad 0.254 \\
\text{H}_2\text{O} & : \quad 294.1\text{g} \quad 0.746
\end{align*}
\]

Steps 6 and 7:

We have two unknowns, \( F \) and \( C \), and can make two independent mass balances so that the problem has a unique solution.

Steps 8 and 9:

<table>
<thead>
<tr>
<th>Balance</th>
<th>Final solution</th>
<th>Initial solution</th>
<th>Transport through boundary (out)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Ba(NO}_3\text{)}_2 ):</td>
<td>( F(0.0476) )</td>
<td>- 100</td>
<td>(- C(0.9615))</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} ):</td>
<td>( F(0.9524) )</td>
<td>- 294.1</td>
<td>(- C(0.0385))</td>
</tr>
<tr>
<td>Total:</td>
<td>( F )</td>
<td>(- (100 + 294.1))</td>
<td>(- C)</td>
</tr>
</tbody>
</table>

Solve the \( \text{Ba(NO}_3\text{)}_2 \) and total balance to get

\[
F = 305.2 \text{g} \quad C = 88.89 \text{g}
\]

Step 10: Check using the water balance

\[
305.2(0.9524) - 294.1 \neq -88.89(0.0385)
\]

The Ba(NO\(_3\)\(_2\)) that precipitates out on a dry basis is

\[
\frac{88.89 \text{ g C}}{1 \text{ g C}} \cdot \frac{0.9615 \text{ g Ba(NO}_3\text{)}_2}{1 \text{ g C}} = \frac{85.5 \text{ g Ba(NO}_3\text{)}_2}{1 \text{ g C}}
\]

8.19

M.W. \( \text{Na}_2\text{S}_2\text{O}_5 = 142 \)
M.W. \( \text{Na}_2\text{S}_2\text{O}_5 \cdot 5\text{H}_2\text{O} = 232 \)

\[
\begin{align*}
\text{W}_0 & \quad \text{H}_2\text{O} \\
\text{S} & \quad \text{Na}_2\text{S}_2\text{O}_5 \cdot 5\text{H}_2\text{O}
\end{align*}
\]

\[
\begin{align*}
\text{C} & \quad \text{H}_2\text{O} \\
\text{I} & \quad \text{Na}_2\text{S}_2\text{O}_5 \cdot 5\text{H}_2\text{O}
\end{align*}
\]

\[
\begin{align*}
\text{II} & \quad \text{Na}_2\text{S}_2\text{O}_5 \cdot 5\text{H}_2\text{O} \\
\text{D} & \quad \text{H}_2\text{O} \
\end{align*}
\]

Process II Compositions:

a) Stream D

Basis: 1 lb mol \( \text{Na}_2\text{S}_2\text{O}_5 \cdot 5\text{H}_2\text{O} \), impurity free

<table>
<thead>
<tr>
<th>Component</th>
<th>lb mol</th>
<th>wt. fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Na}_2\text{S}_2\text{O}_5 )</td>
<td>1</td>
<td>142</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>5</td>
<td>232</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>344</td>
</tr>
</tbody>
</table>
Solutions Chapter 8

Basis: 100 lb D (Na$_2$S$_2$O$_3$·5H$_2$O = 99.9 lb)

<table>
<thead>
<tr>
<th>Comp.</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$S$_2$O$_3$</td>
<td>99(0.612) = 61.1</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>99(0.388) = 38.8</td>
</tr>
<tr>
<td>impurity</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Stream C

Let y = lb impurity/100 lb free water in saturated solution

Basis: 100 lb dry crystals, impurity free

<table>
<thead>
<tr>
<th>lb from dry</th>
<th>lb from adhering soln</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$S$_2$O$_3$</td>
<td>61.2 (6) (85.7 ) / (240 + y)</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>38.8 (6) (154.3 ) / (240 + y)</td>
</tr>
<tr>
<td>impurity</td>
<td>(6) (y ) / (240 + y)</td>
</tr>
</tbody>
</table>

Totals: 100.0 6 106

Stream S

Basis: 100 lb free water in satd. soln., impurity free

<table>
<thead>
<tr>
<th>Comp.</th>
<th>lb from salt</th>
<th>lb from free water</th>
<th>Total</th>
<th>wt. fr.</th>
<th>wt. fr. total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$S$_2$O$_3$</td>
<td>1.4(61.2) = 85.68</td>
<td>85.7</td>
<td>0.357</td>
<td>85.7 (240 + y)</td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1.4(38.8) = 54.32</td>
<td>100</td>
<td>0.643</td>
<td>154.3 (240 + y)</td>
<td></td>
</tr>
</tbody>
</table>

Total: 140.00 100 240.0 1.000

Solutions Chapter 8

impurity = \( \frac{y}{240 + y} \)

Total

Basis: 100 lb F

(Rather than use the impurity balance, use the total balance instead if you want)

Water in, \( W_i \), comes from balances on Unit I.

Total:

\[ 100 + W_i = S + C \]

Na$_2$S$_2$O$_3$\[ \begin{array}{c} 60 = \left( \frac{85.7}{240 + y} \right) S + \frac{61.2 + 6 \left( \frac{85.7}{240 + y} \right) C}{106} \end{array} \]

Unknowns: \( W_i, S, C, y \)

Total: 4

H$_2$O \[ \begin{array}{c} 39 + W_i = \left( \frac{154.3}{240 + y} \right) S + \frac{38.8 + 6 \left( \frac{154.3}{240 + y} \right) C}{106} \end{array} \]

Unknowns: \( W_i, S, C, y \)

Balances on Unit II needed as well because 4 unknowns exist:

Total: \( C = W_0 + D \)

Na$_2$S$_2$O$_3$\[ \begin{array}{c} 61.2 + 6 \left( \frac{85.7}{240 + y} \right) C \end{array} \]

Unknowns: \( W_0, D \)

Total: 2

H$_2$O \[ \begin{array}{c} 38.8 + 6 \left( \frac{154.3}{240 + y} \right) C \end{array} \]

\[ W_0 + 0.388D \]

6 equations and 6 unknowns

Note that the complex term involving \( y \) can be eliminated to solve for \( D, W_0, W_i \) and \( S \), i.e., in (continued)
Solutions Chapter 8

Effect making total Na₂S₂O₃ and H₂O balances overall the process.

The solution is \( a \) \( W = 23.34 \text{ lb} \) \( b \) 66.5%

8.20

Basis: 100 lb pulp as received

<table>
<thead>
<tr>
<th>Comp</th>
<th>lb = %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>22</td>
</tr>
<tr>
<td>Pulp</td>
<td>78</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Assume air dried pulp means the 12% moisture pulp.

Allowed water = \( \frac{78 \text{ lb pulp}}{88 \text{ lb pulp}} \times \frac{12 \text{ lb H₂O}}{88 \text{ lb pulp}} = 10.65 \text{ lb H₂O} \)

Pulp on contract basis = 78 + 10.65 = 88.65 lb

Basis: 1 ton pulp as received

\[
\text{Cost} = \frac{88.65 \text{ lb 12% pulp received}}{100 \text{ lb shipped}} \times \frac{\$60.00}{1 \text{ ton}} = \$33.19 \text{/ton}
\]

8.21 You pay for soap plus transportation.

Basis: 100 kg soap with 30% water

Convert soap in wet soap to soap in dry soap. Data:

<table>
<thead>
<tr>
<th></th>
<th>(wet soap)</th>
<th>(dry soap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>30 kg</td>
<td>5%</td>
</tr>
<tr>
<td>soap</td>
<td>70 kg</td>
<td>95%</td>
</tr>
<tr>
<td>100 kg</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Soap balance: \( 0.70W = 0.95D \) or \( 0.70(100) = 0.95D \)

\( D = 73.68 \text{ kg of which 70 kg is soap} \)

Cost of W at your site (containing 70 kg soap):

\[ 100 (\$0.30 + \frac{\$6.05}{100}) = \$36.05 \]

Cost of D at your site (containing 70 kg soap):

\[ 73.68 \left( \frac{x \text{ kg}}{50} + \frac{\$6.05}{100} \right) = \$36.05 \]

\[ x = \$ 0.43/ \text{kg} \]

8.22

The problem here is to decide on the balances to make. Not all will be indept balances.

Steps 1, 2, 3, and 4: (continued)
Solutions Chapter 8

F = 100 lb

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
<td>VM</td>
<td>0.166</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.575</td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>0.135</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Mixer

P (lb) 0.10 H (lb) 0.082 VM 0.887 C 0.031 H₂O

<table>
<thead>
<tr>
<th>Mass fr.</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>mₕ₂ₒ</td>
</tr>
<tr>
<td>VM</td>
<td>mᵥₘ</td>
</tr>
<tr>
<td>C</td>
<td>mₙ</td>
</tr>
<tr>
<td>Ash</td>
<td>mₐₘ</td>
</tr>
</tbody>
</table>

P 1.000

Step 5: Basis: F = 100 lb

Step 6: Unknowns: mₕ₂ₒ, mᵥₘ, mₙ, mₐₘ, P, H (6)

Step 7: Balances: H₂O, VM, C, Ash, Σm = P, mₕ₂ₒ/P = 0.10

mₐₘ/P = 0.10. (7), and presumably 6 are independent

Steps 8 and 9:

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O (lb):</td>
<td></td>
</tr>
<tr>
<td>100 (0.124) + H (0.082)</td>
<td>mₕ₂ₒ</td>
</tr>
<tr>
<td>VM (lb):</td>
<td></td>
</tr>
<tr>
<td>100 (0.166) + H (0.082)</td>
<td>mᵥₘ</td>
</tr>
<tr>
<td>C (lb):</td>
<td></td>
</tr>
<tr>
<td>100 (0.575) + H (0.887)</td>
<td>mₙ</td>
</tr>
<tr>
<td>Ash (lb):</td>
<td></td>
</tr>
<tr>
<td>100 (0.135) + H (0)</td>
<td>mₐₘ</td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>100 + H</td>
<td>P</td>
</tr>
</tbody>
</table>

Solution:

mₐₘ = 13.5 lb  mₕ₂ₒ = 13.5 lb

(continued)
8.23 Step 5: Basis: 1 day

Steps 2, 3, and 4:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_3</td>
<td>1.9</td>
<td>3.4</td>
</tr>
<tr>
<td>i-C_4</td>
<td>51.6</td>
<td>95.7</td>
</tr>
<tr>
<td>n-C_4</td>
<td>46.0</td>
<td>0.9</td>
</tr>
<tr>
<td>C_5+</td>
<td>0.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

There are two unknowns, and we have 4 independent equations, but the precision of measurement is not the same in each equation, hence different results are obtained depending on the equations used. Choose the most accurate to use.

8.24 Step 1, 2, 3, and 4:

Assume the other components have the same density as water in all flows.

a. $3.785 \times 10^6 \text{ L/day}$

150 mg/L BOD

5 mg/L BOD A B C BOD = x

Step 5: Basis: 1 day

(continued)
Solutions Chapter 8

Steps 6 and 7:

Unknowns: C, x
Balances: H₂O, BOD

Steps 8 and 9:

Total mass balance \( A + B = C \)

\[
\begin{align*}
1 \text{ day} & \frac{A}{L} \frac{1 \text{ kg}}{1 \text{ day}} + 1 \text{ day} & \frac{B}{L} \frac{1 \text{ kg}}{1 \text{ day}} + 1 \text{ day} & \frac{C}{L} \frac{1 \text{ kg}}{1 \text{ day}} = 1 \text{ day} & \frac{C}{L} \frac{x \text{ kg}}{1 \text{ day}}
\end{align*}
\]

BOD mass balance

\[
\begin{align*}
1 \text{ day} & \frac{A}{L} \frac{5 \times 10^{-3} \text{ g BOD}}{1 \text{ day}} + 1 \text{ day} & \frac{B}{L} \frac{150 \times 10^{-3} \text{ g BOD}}{1 \text{ day}} + 1 \text{ day} & \frac{C}{L} \frac{x \text{ g BOD}}{1 \text{ day}} = 1 \text{ day} & \frac{C}{L} \frac{x \text{ g BOD}}{1 \text{ day}}
\end{align*}
\]

\[
2,592 \times 10^7 \text{ kg} + 3,785 \times 10^6 \text{ kg} = C = 2,9705 \times 10^7 \text{ kg}
\]

\[
5 \times 10^{-3} A + 150 \times 10^{-3} B = xC
\]

\[
x = \frac{5 \times 10^{-3} A + 150 \times 10^{-3} B}{C}
\]

\[
= \frac{5 \times 10^{-3} (2.592 \times 10^7) + 150 \times 10^{-3} (3.785 \times 10^6)}{2.9705 \times 10^7} = 23.475 \times 10^{-3} \text{ g/L}
\]

b.

\[
\text{N BOD} = ? \text{ g/'}
\]

\[
\begin{align*}
& 530 \times 10^6 \text{ g/day} \\
& 3 \times 10^3 \text{ g/L BOD}
\end{align*}
\]

\[
\begin{align*}
& A = 15.8 \times 10^6 \text{ L/day} \\
& C = 5 \times 10^3 \text{ g/L BOD}
\end{align*}
\]

Total mass balance \( A + B = C \)

\[
\begin{align*}
1 \text{ day} & \frac{A}{L} \frac{1 \text{ kg}}{1 \text{ day}} + 1 \text{ day} & \frac{B}{L} \frac{1 \text{ kg}}{1 \text{ day}} + 1 \text{ day} & \frac{C}{L} \frac{1 \text{ kg}}{1 \text{ day}} = 1 \text{ day} & \frac{C}{L} \frac{1 \text{ kg}}{1 \text{ day}}
\end{align*}
\]

\[
530 \times 10^6 \text{ kg} + 15.8 \times 10^6 \text{ kg} = C = 5.458 \times 10^6 \text{ kg}
\]

BOD mass balance

\[
\begin{align*}
1 \text{ day} & \frac{A}{L} \frac{3 \times 10^{-3} \text{ g BOD}}{1 \text{ day}} + 1 \text{ day} & \frac{B}{L} \frac{N \times 10^{-3} \text{ g}}{1 \text{ day}} + 1 \text{ day} & \frac{C}{L} \frac{5 \times 10^{-3} \text{ g}}{1 \text{ day}}
\end{align*}
\]

\[
3 \times 10^{-3} A + N \times 10^{-3} B = 5 \times 10^{-3} C
\]

\[
N = 5 \times 10^{-3} C - 3 \times 10^{-3} A
\]

\[
\frac{1.58 \times 10^9}{\text{ L}} \quad \text{ok}
\]

\[
= \frac{(5 \times 10^{-3})(5.458 \times 10^6) - (3 \times 10^{-3})(5.30 \times 10^6)}{1.58 \times 10^9} \approx 72.1 \times 10^{-3} \text{ g/L}
\]
Solutions Chapter 8

\[
\begin{align*}
\text{mass fr.} & \quad \text{mol fr.} \\
\omega_{\text{NH}_3} & \quad x_{\text{NH}_3} \\
\omega_{\text{N}_2} & \quad 1.00 \\
1000 \text{ kg S} & \quad \omega_s = 1.00 \\
\omega_h & \quad 0.0633 \\
0.9367 & \quad 1.00 \\
\end{align*}
\]

\[
\begin{align*}
\text{Gas} & \quad \text{F(kg)} \\
1000 \text{ kg} & \quad \omega_{\text{NH}_3} = 0.10 \\
\text{B kg liquid} & \quad \omega_{\text{N}_2} = 0.90 \\
\omega_{\text{S}} & \quad 1.00 \\
\end{align*}
\]

**Step 2:** Basis 1.0 hr

**Step 3:** The unknowns are \( A, B, \omega_{\text{NH}_3}, \omega_{\text{N}_2}, \omega_{\text{S}}, \omega_h \), a total of 6.

**Steps 7 and 8:** Three compound balances can be made, \( \text{N}_2, \text{NH}_3, \) and \( \text{S} \). One relation is given:

\[
\omega_{\text{S}} = 2\omega_{\text{NH}_3}
\]

Two summations exist:

\[
\Sigma \omega_i = 1 \quad \text{and} \quad \Sigma \omega_i = 1
\]

**Step 4:** (revisited) Material balance equations in grams

**Total:**

\[
\begin{align*}
F + S &= A + B \\
1000 + 1000 &= A + B
\end{align*}
\]

Solutions Chapter 8

\[
\begin{align*}
\text{NH}_3: & \quad 1000(0.0633) + 0 = A\omega_{\text{NH}_3}^A + B\omega_{\text{NH}_3}^B = 1 \\
\text{N}_2: & \quad 1000(0.9367) + 0 = A\omega_{\text{N}_2}^A + 0 \\
\text{S}: & \quad 0 + 1000 = 0 + B\omega_{\text{S}}^B
\end{align*}
\]

**Constraints**

\[
\begin{align*}
\omega_{\text{NH}_3}^A + \omega_{\text{N}_2}^A &= 1 \\
\omega_{\text{S}}^B + \omega_{\text{N}_2}^B &= 1 \\
\omega_{\text{S}}^B &= 2\omega_{\text{NH}_3}^A
\end{align*}
\]

**Solve in Polymath**

Note: the equations can be converted to linear equations by letting \( m_{\text{NH}_3}^A = \omega_{\text{NH}_3}^A A, m_{\text{N}_2}^A = \omega_{\text{N}_2}^A A, \) etc.

The set can be solved in Polymath or reduced to a quadratic equation in \( m_{\text{NH}_3}^B \) or \( m_{\text{NH}_3}^A \).
Solutions Chapter 8

mole fr | MW | mass (g)
---|---|---
NH₃ | 0.10 | 17.03 | 1.703
N₂ | 0.90 | 28.0 | 25.200

1000 kg F | 1 kg mol F | 37.171 kg mol
26.903 kg F

Steps 7 and 8: (repeated) The balances are

\[
\begin{align*}
\text{NH}_3 \text{ (kg mol):} & \quad 0.10 (37.171) + 0 (1000) \text{ MW}_S = \frac{\omega^B_{\text{NH}_3} (B)}{17.03} + x^A_{\text{NH}_3} (A) \\
\text{N}_2 \text{ (kg mol):} & \quad 0.90 (37.171) + 0 (1000) \text{ MW}_S = 0 (B) + x^A_{\text{N}_2} (A) \\
\text{S} \text{ (kg):} & \quad 0 (1000) + 1000 = \omega^B_S (B) S + 0 (A) \text{ MW}_A \\
\end{align*}
\]

Then \(\alpha^A_{\text{NH}_3} = A = n^A_{\text{NH}_3}\), let \(x^A_{\text{N}_2} = A = n^A_{\text{N}_2}\), and \(\omega^B_{\text{NH}_3} B = m^B_{\text{NH}_3}\), etc. Then \(\alpha^A_{\text{N}_2}, n^A_{\text{N}_2}, m^B_{\text{NH}_3}\).

Step 9: A total balance of 1000 + 1000 in kg, but not if in moles, can be used in lieu of one of the above balances. They give (continued)
The results are:

\[ m_i^0 = 1000 \text{kg} \]
\[ n_i^0 = 0.90(37.171) = 33.45 \text{kg mol} \]
\[ \omega_{\text{H}_{2}\text{O}}^0 = 0.0212 \]
\[ \omega_g^0 = 0.979 \]
\[ A = 978 \text{g} \]
\[ B = 1021.7 \text{g} \]
\[ \omega_{\text{H}_{2}\text{O}}^0 = 0.0425 \]
\[ x_i^0 = 0.0681 \]
\[ x_i^0 = 0.958 \]
\[ x_i^0 = 0.932 \]

**8.27**

**Basis: 12 hours**

The process is illustrated in the figure:

\[ \text{MTBE} \rightarrow \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} \rightarrow \text{MTBE} \]

The MTBE entering the pond in 12 hours is

\[ 25 \text{ boats} \times 0.5 \text{ L gasoline} \times 1000 \text{ cm}^3 = 0.72 \text{ g} \]
\[ 1 \text{ boat} \times 1 \text{ L} = 1 \text{ cm}^3 \]
\[ 1 \text{ cm}^3 = 1 \text{ g gasoline} \]
\[ 0.10 \text{ g MTBE} = 900 \text{ g MTBE} \]

The pond holds (ignoring the MTBE in the pond which is negligible)

\[ 3000 \text{ m} \times 1000 \text{ cm}^3 \times 1000 \text{ kg H}_2\text{O} = 9 \times 10^6 \text{ kg H}_2\text{O} \]

The increase in the concentration of MTBE is

\[ \frac{900 \text{ g MTBE}}{9 \times 10^6 \text{ kg H}_2\text{O}} \times 1 \text{ kg} = 1 \times 10^{-6} \text{ g MTBE/g H}_2\text{O} \]
9.1  
\[ \text{BaCl}_2 + \text{Na}_2\text{SO}_4 \rightarrow \text{BaSO}_4 + 2\text{NaCl} \]

Mol. wt.: 208.3 142.05 233.4 58.45

a. Basis: 5.0 g Na\(_2\)SO\(_4\)

Example: 
\[ \frac{5 \text{ g Na}_2\text{SO}_4}{1 \text{ g mol Na}_2\text{SO}_4} \times \frac{1 \text{ g mol BaCl}_2}{208.3 \text{ g BaCl}_2} = \frac{142.05 \text{ g Na}_2\text{SO}_4}{1 \text{ g mol Na}_2\text{SO}_4} \times \frac{1 \text{ g mol BaCl}_2}{58.45 \text{ g NaCl}} = 7.33 \text{ g BaCl}_2 \]

<table>
<thead>
<tr>
<th>Problem</th>
<th>Basis</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>b.</td>
<td>5 g Ba(_2)SO(_4)</td>
<td>4.47 g BaCl(_2)</td>
</tr>
<tr>
<td>c.</td>
<td>5 g NaCl</td>
<td>8.91 g BaCl(_2)</td>
</tr>
<tr>
<td>d.</td>
<td>5 g BaCl(_2)</td>
<td>3.41 g Na(_2)SO(_4)</td>
</tr>
<tr>
<td>e.</td>
<td>5 g Ba(_2)SO(_4)</td>
<td>3.04 g Na(_2)SO(_4)</td>
</tr>
<tr>
<td>f.</td>
<td>5 lb NaCl</td>
<td>6.08 lb Na(_2)SO(_4)</td>
</tr>
<tr>
<td>g.</td>
<td>5 lb BaCl(_2)</td>
<td>5.59 lb Ba(_2)SO(_4)</td>
</tr>
<tr>
<td>h.</td>
<td>5 lb Na(_2)SO(_4)</td>
<td>8.21 lb Ba(_2)SO(_4)</td>
</tr>
<tr>
<td>i.</td>
<td>5 lb NaCl</td>
<td>9.98 lb Ba(_2)SO(_4)</td>
</tr>
</tbody>
</table>

9.2  
\[ \text{AgNO}_3 + \text{NaCl} \rightarrow \text{AgCl} + \text{NaNO}_3 \]

Mol. wt.: 169.89 58.45 143.3 85.01

a. Basis: 5.0 g NaCl

Example: 
\[ \frac{5 \text{ g NaCl}}{1 \text{ g mol NaCl}} \times \frac{1 \text{ g mol AgNO}_3}{169.89 \text{ g AgNO}_3} = \frac{58.45 \text{ g NaCl}}{1 \text{ g mol NaCl}} \times \frac{1 \text{ g mol AgNO}_3}{1 \text{ g mol AgNO}_3} = 14.53 \text{ g AgNO}_3 \]

9.3  
Basis: 1 ton dolomite

\[ \text{CaCO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 + \text{H}_2\text{O} + \text{CO}_2 \]

Assume complete reactions

\[ \text{MgCO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{MgSO}_4 + \text{H}_2\text{O} + \text{CO}_2 \]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>%</th>
<th>lb</th>
<th>mol. wt.</th>
<th>lb mol that react</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO(_3)</td>
<td>68</td>
<td>1360</td>
<td>100.0</td>
<td>13.60</td>
</tr>
<tr>
<td>MgCO(_3)</td>
<td>30</td>
<td>600</td>
<td>84.3</td>
<td>7.13</td>
</tr>
<tr>
<td>Si(_2)O(_5)</td>
<td>2</td>
<td>40</td>
<td>60.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>2000</td>
<td></td>
<td>20.73</td>
</tr>
</tbody>
</table>

a. \[ \text{20.73 lb mol react} \div \text{1 mol CO}_2 \text{ produced} = 1 \text{ lb CO}_2 \]

b. \[ \text{20.73 lb mol react} \div \text{1 mol H}_2\text{SO}_4 \text{ reqd} = 98 \text{ lb H}_2\text{SO}_4 \]

\[ \text{100 lb acid} \div \text{98 lb H}_2\text{SO}_4 = 2160 \text{ lb acid} \]
9.4

a. The balanced equation is:

\[ 3 \text{As}_2\text{S}_3 + 4 \text{H}_2\text{O} + 28 \text{HNO}_3 = 28\text{NO} + 6 \text{H}_3\text{AsO}_4 + 9 \text{H}_2\text{SO}_4 \]

and the reaction is unique within relative proportions.

b. \(2 \text{KClO}_3 + 4 \text{HCl} = 2 \text{KCl} + 2 \text{Cl}_2 + 2 \text{H}_2\text{O}\)

or \(\text{KClO}_3 + 6 \text{HCl} = \text{KCl} + 3 \text{Cl}_2 + 3 \text{H}_2\text{O}\)

or \(3 \text{KClO}_3 + 10 \text{HCl} = 3 \text{KCl} + 2 \text{Cl}_2\text{O}_7 + 4 \text{Cl}_2 + 5 \text{H}_2\text{O}\)

We classify these reactions as non-unique since they are not simply proportional equations, but are linearly independent, and infinitely many equations can be obtained by linear combination.

9.5 Basis: Data given in problem statement

\[
\begin{array}{c|c|c|c}
55.847 \text{g Fe} & 1 \text{g mol Fe} & 1 \text{g mol X}_2\text{O}_3 & 2 \text{g mol X} \\
1 & 55.847 \text{g Fe} & 2 \text{g mol Fe} & 1 \text{g mol X}_2\text{O}_3 \\
55.847 \text{g Fe} & 1 \text{g mol Fe} & 1 \text{g mol X}_2\text{O}_3 & 3 \text{g mol O} & 16 \text{g O} \\
1 & 55.847 \text{g Fe} & 2 \text{g mol Fe} & 1 \text{g mol X}_2\text{O}_3 & 1 \text{g mol O} & 240 \text{g O} \\
50.982 \text{g X}_2\text{O}_3 - 24.0 \text{g O} = 26.982 \text{g X} \\
26.982 \text{g X} = 26.982 \frac{\text{g}}{\text{g mol}} \text{ hence X = Al} \\
\end{array}
\]
Solutions Chapter 9

9.7 Basis: Data given in the problem

Mass of hydrate 10.407 g
Mass of dry sample -9.520 g
Mass of water 0.887 g

\[
\frac{9.520 \text{ g Bal}_2}{1 \text{ g mol Bal}_2} = 0.0243 \text{ g mol Bal}_2
\]

\[
\frac{0.887 \text{ g H}_2\text{O}}{1 \text{ g mol H}_2\text{O}} = 0.0493 \text{ g mol H}_2\text{O}
\]

0.0243 = 0.49, or 2 H₂O for 1 Bal₂. Thus the hydrate is Bal₂·2H₂O.

9.8 Basis: 2 g mol

C: 6 × 12 = 72  H: 8 × 1 = 8  O: 6 × 16 = 96
mol. wt. = 72 + 8 + 96 = 176

\[
\frac{2 \text{ g mol}}{1 \text{ mol}} = \frac{176 \text{ g}}{454 \text{ g}} = 0.775 \text{ lb}
\]

Solutions Chapter 9

9.9 Basis: 2000 tons 93.2% H₂SO₄ (1 day)

a. 2000 tons soln 0.932 ton H₂SO₄ 1 ton mole H₂SO₄ 1 mol S 32 mol S

\[
\begin{align*}
\text{1 ton soln} & = 98 \text{ ton H}_2\text{SO}_4 \\
1 \text{ mol } H_2\text{SO}_4 & = 1 \text{ mol S} \\
1 \text{ mol } H_2\text{SO}_4 & = 32 \text{ mol S} \\
\end{align*}
\]

= 609 ton S

b. 609 ton S 1 ton mol S 1.5 mol O₂ 32 ton O₂

\[
\begin{align*}
32 \text{ ton } O_2 & = 1 \text{ mol } O_2 \\
1 \text{ mol } O_2 & = 32 \text{ ton } O_2 \\
\end{align*}
\]

= 913.5 ton O₂

c. 609 ton S 1 ton mol S 1 mol H₂O 18 ton H₂O

\[
\begin{align*}
32 \text{ ton } H_2O & = 1 \text{ mol } H_2O \\
1 \text{ mol } H_2O & = 32 \text{ ton } H_2O \\
\end{align*}
\]

= 542.6 ton H₂O

9.10 Basis: 1 lb Br₂

\[
2\text{Br}^- + \text{Cl}_2 \rightarrow 2\text{Cl}^- + \text{Br}_2
\]

MW: 70.9  159.8

Br₂ + C₂H₄ → C₂H₄Br₂
MW: 28  187.9

a. \[
\begin{align*}
\frac{0.22 \text{ lb solids}}{2000 \text{ lb seawater}} & = \frac{1 \times 10^6 \text{ lb seawater}}{65 \text{ lb Br}_2} \\
& = 2.08 \text{ lb } 98\% \text{ H}_2\text{SO}_4 \text{ lb Br}_2
\end{align*}
\]

b. \[
\begin{align*}
\frac{1 \text{ lb Br}_2}{159.9 \text{ lb Br}_2} & = \frac{1 \text{ mole Br}_2}{1 \text{ mole } H_2\text{SO}_4} \\
\frac{70.9 \text{ lb } C\text{Cl}_2}{1 \text{ mole } C\text{Cl}_2} & = 0.445 \text{ lb } C\text{Cl}_2
\end{align*}
\]

c. \[
\begin{align*}
\frac{1 \text{ lb Br}_2}{65 \text{ lb Br}_2} & = \frac{1 \times 10^6 \text{ lb seawater}}{15.400 \text{ lb seawater}}
\end{align*}
\]

d. \[
\begin{align*}
\frac{1 \text{ lb Br}_2}{159.9 \text{ lb Br}_2} & = \frac{1 \text{ mole } C\text{H}_2\text{Br}_2}{1 \text{ mole Br}_2} \\
\frac{187.9 \text{ lb } C\text{H}_2\text{Br}_2}{1 \text{ mole } C\text{H}_2\text{Br}_2} & = 1.176 \text{ lb } C\text{H}_2\text{Br}_2
\end{align*}
\]
9.11

<table>
<thead>
<tr>
<th></th>
<th>LHS</th>
<th>RHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>H</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Zn</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>O</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

Yes, the equation is balanced.

b) Basis: 1.5 kg ZnO

\[
\frac{1.5 \text{ kg ZnO}}{1000 \text{ g ZnO}} \times \frac{1 \text{ g mol ZnO}}{1 \text{ g mol DEZ}} = \frac{1500 \text{ g ZnO}}{1000 \text{ g ZnO}} \times \frac{1 \text{ g mol ZnO}}{1 \text{ g mol DEZ}} = 1.5 \text{ g mol DEZ}
\]

\[
\frac{1.0 \text{ kg DEZ}}{1000 \text{ g DEZ}} = 0.001 \text{ kg DEZ}
\]

c) \[
\frac{20 \text{ cm}^3 \text{ H}_2\text{O}}{1 \text{ cm}^3 \text{ H}_2\text{O}} \times \frac{1.0 \text{ g H}_2\text{O}}{1 \text{ g mol H}_2\text{O}} \times \frac{1 \text{ g mol DEZ}}{123.4 \text{ g DEZ}} \times \frac{1 \text{ g cm}^3 \text{ H}_2\text{O}}{1 \text{ cm}^3 \text{ H}_2\text{O}} \times \frac{18.0 \text{ g H}_2\text{O}}{5 \text{ g mol H}_2\text{O}} \times \frac{1 \text{ g mol DEZ}}{1 \text{ g mol DEZ}} = 27.4 \text{ g DEZ}
\]

9.12

\[
\begin{array}{ccc}
\text{FeSO}_4 \cdot 7\text{H}_2\text{O} & \text{MW} & \text{FeSO}_4 \cdot \text{H}_2\text{O} & \text{MW} \\
277.9 & & 169.9 & \\
\text{FeSO}_4 \cdot 4\text{H}_2\text{O} & 223.9 & \text{FeSO}_4 & 151.9
\end{array}
\]

It is best to evaluate the three types of ferrous sulfate in terms of the cost/ton of FeSO₄

Basis: 475 ton material

a. FeSO₄·7H₂O:

\[
\frac{\$83,766.25}{475 \text{ ton FeSO}_4 \cdot 7\text{H}_2\text{O}} = \frac{\$176.35}{\text{ton FeSO}_4 \cdot 7\text{H}_2\text{O}}
\]

\[
\frac{\$176.35}{\text{ton FeSO}_4 \cdot 7\text{H}_2\text{O}} \times \frac{277.9 \text{ ton FeSO}_4 \cdot 7\text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4 \cdot 7\text{H}_2\text{O}} \times \frac{1 \text{ ton mol FeSO}_4 \cdot 7\text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4} = \frac{\$323}{\text{ton FeSO}_4}
\]

151.9 ton FeSO₄ = $323/ton FeSO₄

b. FeSO₄·4H₂O:

\[
\frac{\$323}{151.9 \text{ ton FeSO}_4} \times \frac{1 \text{ ton mol FeSO}_4}{1 \text{ ton mol FeSO}_4 \cdot 4\text{H}_2\text{O}} \times \frac{1 \text{ ton mol FeSO}_4 \cdot 4\text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4} = \frac{\$219}{\text{ton FeSO}_4 \cdot 4\text{H}_2\text{O}}
\]

\[
\frac{\$219}{\text{ton FeSO}_4 \cdot 4\text{H}_2\text{O}} \times \frac{223.9 \text{ ton FeSO}_4 \cdot 4\text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4 \cdot 4\text{H}_2\text{O}} = \frac{\$289}{\text{ton FeSO}_4 \cdot 4\text{H}_2\text{O}}
\]

c. FeSO₄·H₂O:

\[
\frac{\$323}{151.9 \text{ ton FeSO}_4} \times \frac{1 \text{ ton mol FeSO}_4}{1 \text{ ton mol FeSO}_4 \cdot \text{H}_2\text{O}} \times \frac{1 \text{ ton mol FeSO}_4 \cdot \text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4} = \frac{\$289}{\text{ton FeSO}_4 \cdot \text{H}_2\text{O}}
\]
Solutions Chapter 9

9.13 The reaction is \( \text{C}_4\text{H}_10 + 6 \frac{3}{2} \text{O}_2 \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O} \)

Basis: 1 mol \( \text{C}_4\text{H}_10 \)

Minimum \( \text{O}_2 \) (LFL) \( \left( \frac{\text{mol O}_2 \text{ for complete combustion}}{\text{mol C}_4\text{H}_10} \right) \)

\[ \cong (1.9\%) \times (6.5/1) = 12.4\% \]

9.14 Basis: 1 L solution = 1000 g \( \text{H}_2\text{O} \)

\[
\begin{array}{c|c|c|c|c}
50 \text{ g } \text{H}_2\text{S} & 1 \text{ g mol H}_2\text{S} & 1 \text{ g mol HOCI} & 52.45 \text{ g HOCI} & 100 \text{ g HOCI solo} \\
10^8 \text{ g soln} & 34 \text{ g H}_2\text{S} & 1 \text{ g mol HOCI} & 5 \text{ g HOCI} & 1 \text{ L soln}
\end{array}
\]

\[ 1000 \text{ g soln} = 3.08 \text{ g HOCI solution} \]

You can use the density of \( \text{H}_2\text{O} \) for the density of the solution as the \( \text{H}_2\text{S} \) content has negligible effect on the density.

Solutions Chapter 9

9.15 \( \text{Na}_2\text{CO}_3 + \text{Ca(OH)}_2 \rightarrow 2\text{NaOH} + \text{CaCO}_3 \)

Basis: 1 ton of soda ash (\( \text{Na}_2\text{CO}_3 \))

\[
\begin{array}{c|c|c|c|c|c}
1 \text{ ton Na}_2\text{CO}_3 & 1 \text{ ton mol Na}_2\text{CO}_3 & 2 \text{ ton mol NaOH} & 40.0 \text{ ton NaOH} & \text{106 ton Na}_2\text{CO}_3 & 1 \text{ ton mol Na}_2\text{CO}_3 & 1 \text{ ton mol NaOH} \\
0.755 \text{ ton NaOH} & \end{array}
\]

\[ \frac{1 \text{ ton Na}_2\text{CO}_3}{0.755 \text{ NaOH} = \frac{\$130}{\text{1 ton Na}_2\text{CO}_3} \text{ ton Na}_2\text{CO}_3} \]

The above result is for the case of free \( \text{Ca(OH)}_2 \). Otherwise, the value must be reduced to compensate for the cost of the \( \text{Ca(OH)}_2 \) -- which might come from the \( \text{CaCO}_3 \) produced, and possibly be cheaper than \( \text{Ca(OH)}_2 \) purchased directly.
9.16 Basis: 1 kg dichlorobenzene (DCB)

The balanced stoichiometric reaction for dichlorobenzene is shown below:

\[ \text{C}_6\text{H}_4\text{Cl}_2 + 6.5 \text{ O}_2 \rightarrow 6 \text{ CO}_2 + \text{H}_2\text{O} + 2 \text{ HCl} \]

Therefore, for 1 kg of dichlorobenzene, the following moles of HCl are produced:

\[
\begin{array}{c|c|c|c|c|c}
\text{1 kg DCB} & \text{1 kg mol DCB} & \text{2 kg mol HCl} & \text{147 kg DCB} & \text{1 kg mol DCB} \\
\hline
\end{array}
\]

\[ = 0.0136 \text{ kg mol HCl} \]

The balanced stoichiometric reaction for tetrachlorobiphenyl is as shown below:

\[ \text{C}_6\text{H}_4\text{Cl}_4 + 12.5 \text{ O}_2 \rightarrow 12 \text{ CO}_2 + \text{H}_2\text{O} + 4 \text{ HCl} \]

Therefore, for 1 lb of tetrachlorobiphenyl (TCB), the following moles of HCl are produced:

Basis: 1 kg TCB

\[
\begin{array}{c|c|c|c|c|c|c}
\text{1 kg TCB} & \text{1 kg mol TCB} & \text{4 kg mol HCl} & \text{290 kg TCB} & \text{1 kg mol TCB} \\
\hline
\end{array}
\]

\[ = 0.0138 \text{ kg mol HCl} \]

Thus, the amount of acid produced does not change significantly (≈ 1.5%), and neither will the amount of base required for neutralization.

9.17 Basis: 10 lb moles phosgene

For phosgene:

\[ \xi = \frac{n_2 - n_1}{1} = \frac{10 - 0}{1} = 10 \text{ reacting moles} \]

\[ n_{\text{CO}_2} = n_{\text{CO}_2} \cdot \gamma_{\text{CO}_2} = 7 \cdot (-1)(10) = 17 \text{ lb mol} \]

\[ n_{\text{Cl}_2} = n_{\text{Cl}_2} \cdot \gamma_{\text{Cl}_2} = 3 \cdot (-1)(10) = 13 \text{ lb mol} \]

9.18 Basis: 135 mol CH₄

\[ \xi = \frac{0 - 135}{-6} = 22.5 \text{ reacting moles} \]
### 9.19 \[ 2\text{FeS} + 3\text{O}_2 \rightarrow 2\text{FeO} + 2\text{SO}_2 \]

MW 87.85  32  71.85  64

Basis: Use 100 g slag

<table>
<thead>
<tr>
<th>Component</th>
<th>( g = % )</th>
<th>MW</th>
<th>g mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO</td>
<td>80</td>
<td>71.85</td>
<td>1.113</td>
</tr>
<tr>
<td>FeS</td>
<td>100</td>
<td>87.85</td>
<td>0.228</td>
</tr>
</tbody>
</table>

For the FeO:

\[ \xi = \frac{n_1 - n_2}{n_2} = \frac{1.113 - 0}{2} = 0.557 \text{ reacting moles} \]

For the FeS:

\[ \xi = \frac{n_1 - n_2}{n_2} = \frac{0.228 - 0}{2} = 0.557 \]

\( n_{\text{initial FeS}} = 1.341 \text{ g mol} \)

---

### 9.20

Basis: 1080 lb bauxite

\[ \text{Al}_2\text{O}_3 + 3\text{H}_2\text{SO}_4 \rightarrow \text{Al}_2(\text{SO}_4)_3 + 3\text{H}_2\text{O} \]

1080 lb bauxite: 55.4 lb \( \text{Al}_2\text{O}_3 \)

\[ \left( \frac{1 \text{ lb mol \text{Al}_2\text{O}_3}}{101.9 \text{ lb \text{Al}_2\text{O}_3}} \right) = 5.87 \text{ lb mol \text{Al}_2\text{O}_3} \]

\( \xi = \frac{0 - 5.87}{-1} = 5.87 \text{ reacting moles} \)

Basis: 2510 lb \( \text{H}_2\text{SO}_4 \) (77%)

2510 lb \( \text{H}_2\text{SO}_4 \) (77%): 0.77 lb \( \text{H}_2\text{SO}_4 \)

\[ \left( \frac{1 \text{ lb mol \text{H}_2\text{SO}_4}}{98.1 \text{ lb \text{H}_2\text{SO}_4}} \right) = 19.70 \text{ lb mol \text{H}_2\text{SO}_4} \]

\( \xi = \frac{0 - 19.70}{-3} = 6.57 \text{ reacting moles} \)

(a) \( \text{Al}_2\text{O}_3 \) is the limiting reactant and \( \text{H}_2\text{SO}_4 \) is the excess reactant.

(b) \( \% \text{xs} \ \text{H}_2\text{SO}_4: \left( \frac{19.70(1/3) - 5.87}{5.87} \right) = \left( \frac{6.57 - 5.87}{5.87} \right) = (11.9\%) \)

or \( \text{H}_2\text{SO}_4 \) (77%) required: \( \left( \frac{5.87(3\times98.1)}{0.77} \right) = 2244 \text{ lb} \)

\( \% \text{xs} = \frac{2510 - 2244}{2244} = 12\% \)

Basis: 2000 lb \( \text{Al}_2(\text{SO}_4)_3 \)

\[ \left( \frac{1 \text{ lb mol \text{Al}_2(\text{SO}_4)_3}}{342.1 \text{ lb \text{Al}_2(\text{SO}_4)_3}} \right) = 1 \text{ lb mol \text{Al}_2(\text{SO}_4)_3} \]

101.9 lb \( \text{Al}_2\text{O}_3 \)

\( \% \text{bauxite} = 1075 \text{ lb bauxite} \)

1 lb mol \( \text{Al}_2\text{O}_3 \): 0.554 lb \( \text{Al}_2\text{O}_3 \)

1075 lb \( \text{Al}_2\text{O}_3 \): 596.7 lb \( \text{Al}_2\text{O}_3 \)

---
9.21 Basis: 100 kg of fusion mass

\[ \text{BaSO}_4 + 4\text{C} \rightarrow \text{BaS} + 4\text{CO} \]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Wt.%</th>
<th>kg</th>
<th>kg mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaSO4</td>
<td>11.1</td>
<td>233.3</td>
<td>0.0476</td>
</tr>
<tr>
<td>BaS</td>
<td>72.8</td>
<td>169.3</td>
<td>0.430</td>
</tr>
<tr>
<td>C</td>
<td>13.9</td>
<td>12.0</td>
<td>1.16</td>
</tr>
<tr>
<td>Ash</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{BaSO}_4_{\text{equ}} = 0.0476 + 0.430 = 0.4776 \text{ mol} \]

\[ \text{C}_{\text{equ}} = 1.16 + 4(0.430) = 2.88 \text{ mol} \]

Carbon is the limiting reactant.

\[ \% \text{ excess} = \frac{2.88 - 1.91}{1.91} \times 100 = 30.8\% \text{ excess C} \]

\[ \text{Degree of completion} = \frac{0.4776 - 0.0476}{0.4776} = 0.900 \]

You could calculate the extent of reaction from the BaSO₄, and use it to get the original amounts of reactants.

9.22 \[ \text{CO} + \text{Cl}_2 \rightarrow \text{COCl}_2 \]

Basis: 20 kg products

<table>
<thead>
<tr>
<th>Comp.</th>
<th>kg</th>
<th>mol wt.</th>
<th>mol</th>
<th>Cl₂ in</th>
<th>CO in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl₂</td>
<td>3.00</td>
<td>70.91</td>
<td>0.0423</td>
<td>0.0423</td>
<td></td>
</tr>
<tr>
<td>COCl₂</td>
<td>10.00</td>
<td>98.91</td>
<td>0.1011</td>
<td>0.1011</td>
<td>0.1011</td>
</tr>
<tr>
<td>CO</td>
<td>7.00</td>
<td>28.01</td>
<td>0.250</td>
<td></td>
<td>0.250</td>
</tr>
<tr>
<td></td>
<td>20.00</td>
<td></td>
<td>0.393</td>
<td>0.143</td>
<td>0.351</td>
</tr>
</tbody>
</table>

The extent of reaction is

\[ \text{CO: } \frac{0 - 0.351}{-1} = 0.351 \]

\[ \text{Cl}_2: \frac{0 - 0.143}{-1} = 0.143 \text{ (smallest } \xi \text{ )} \]

\[ \text{Cl}_2 \text{ is the limiting reactant; CO is the excess reactant} \]

a. \[ \frac{0.351 - 0.143}{0.143} (100) = 145\% \text{ excess CO} \]

b. \[ \frac{0.1011}{0.143} (100) = 70.7\% \text{ Cl}_2 \text{ converted} \]

c. \[ \frac{0.1011 \text{ kg mol COCl}_2}{(0.143 + 0.351) \text{ kg mol reactants}} = 0.205 \]
Step 4:
The molecular weights needed to solve the problem and the gram moles forming the basis are:

<table>
<thead>
<tr>
<th>Component</th>
<th>kg</th>
<th>Mol. wt.</th>
<th>g mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sb₂S₃</td>
<td>0.600</td>
<td>339.7</td>
<td>1.766</td>
</tr>
<tr>
<td>Fe</td>
<td>0.250</td>
<td>55.85</td>
<td>4.476</td>
</tr>
<tr>
<td>Sb</td>
<td>0.200</td>
<td>121.8</td>
<td>1.642</td>
</tr>
<tr>
<td>FeS</td>
<td>0.872</td>
<td>87.91</td>
<td></td>
</tr>
</tbody>
</table>

The process is illustrated in Fig. P9.19.

![Diagram](image)

Figure P9.19

Step 5: Basis: Data given in problem statement

Steps 6-9:

(a) To find the limiting reactant, we examine the chemical reaction equation. The ratio of Sb₂S₃ to Fe in the equation is 1/3 = 0.33. In the actual reaction the corresponding ratio is 1.766/4.476 = 0.395, hence Sb₂S₃ is the excess reactant and Fe is the limiting reactant. The Sb₂S₃ required to react with the limiting reactant is 4.476/3 = 1.492 g mol.

(b) The percentage of excess reactant is

\[
\text{% excess} = \frac{1.766 - 1.492}{1.492} \times 100 = 18.4\% \text{ excess Sb}_2\text{S}_3
\]

(c) Although Fe is the limiting reactant, not all the limiting reactant reacts. We can compute from the 1.64 g mol of Sb how much Fe actually does react:

\[
\frac{1.64 \text{ g mol Sb}}{2 \text{ g mol Sb}} = 2.46 \text{ g mol Fe}
\]

If by the fractional degree of completion is meant the fraction conversion of Fe to products, then

\[
\text{Fractional degree of completion} = \frac{2.46}{4.48} = 0.55
\]

(d) Let us assume that the percent conversion refers to the Sb₂S₃ since the reference compound is not specified in the question posed.

\[
\frac{1.64 \text{ g mol Sb}}{2 \text{ g mol Sb}} = 0.82 \text{ g mol Sb}_2\text{S}_3
\]

\[
\text{% conversion of Sb}_2\text{S}_3 \text{ to Sb} = \frac{0.82}{1.77} \times 100 = 46.3\%
\]

(e) The yield will be stated as kilograms of Sb formed per kilogram of Sb₂S₃ that was fed to the reaction

\[
\text{Yield} = \frac{0.200 \text{ kg Sb}}{0.600 \text{ kg Sb}_2\text{S}_3} = \frac{0.33 \text{ kg Sb}}{1 \text{ kg Sb}_2\text{S}_3}
\]
9.24 Amount of α-hydrolyzed:
\[
\frac{0.10 \text{ m mol}}{1 \text{ m mol}} = 100 \mu \text{ mol}
\]

Total protein:
\[
\frac{1.00 \text{ mg}}{1 \text{ mL}} = 0.100 \text{ mg}
\]

Specific activity = \[
\frac{100 \mu \text{ mol}}{(5 \text{ min})(0.10 \text{ mg protein})} = 200 \mu \text{ mol/(min)(mg protein)}
\]

9.25

```
\[
\begin{align*}
\text{Basis: 100 kg mol A} \\
100 \text{ kg mol } C_6H_7NO & 86.9 \text{ kg mol } C_6H_7NOCl \quad 0.95 \text{ kg mol } C_6H_7NO & 3 \text{ kg mol } C_6H_7NO_2 \\
100 \text{ kg mol } C_6H_7NO & 1 \text{ kg mol } C_6H_7NOCl \quad 4 \text{ kg mol } C_6H_7NO &
\end{align*}
\]

\[
\to 0.619 \text{ fraction overall conversion}
\]
```
9.27 Reaction on which to base excess is

\[ \text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 2\text{Fe} + 3\text{CO} \]

Basis: 1 ton \( \text{Fe}_2\text{O}_3 \)

a. Theoretical C =

\[
\begin{align*}
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 2000 \text{ lb Fe} \\
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 159.7 \text{ lb Fe}_2\text{O}_3 \\
1 \text{ lb mol Fe}_2\text{O}_3 & \quad 12 \text{ lb C} \\
1 \text{ lb mol Fe}_2\text{O}_3 & \quad 1 \text{ lb mol C}
\end{align*}
\]

\[ = \frac{451 \text{ lb}}{600 - 451} \times 100 = 33\% \text{ excess C} \]

b. \( 1 \text{ ton } \text{Fe}_2\text{O}_3 \)

\[
\begin{align*}
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 1200 \text{ lb Fe} \\
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 159.7 \text{ lb Fe}_2\text{O}_3 \\
12 \text{ lb mol Fe} & \quad 1 \text{ lb mol Fe}_2\text{O}_3 \\
2 \text{ lb mol Fe} & \quad 1 \text{ lb mol Fe}_2\text{O}_3
\end{align*}
\]

\[ = 1720 \text{ lb Fe}_2\text{O}_3 \text{ reacts} \]

\[
\begin{align*}
1720 \text{ lb Fe}_2\text{O}_3 & \quad \times 100 = 86.0\% \text{ Fe}_2\text{O}_3 \\
2000 & \quad \text{ lb}
\end{align*}
\]

c. (i) \( 1 \text{ ton } \text{Fe}_2\text{O}_3 \)

\[
\begin{align*}
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 183 \text{ lb FeO} \\
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 91.85 \text{ lb FeO} \\
1 \text{ lb mol Fe}_2\text{O}_3 & \quad 1 \text{ lb mol CO} \\
28 \text{ lb CO} & \quad 1 \text{ lb mol CO}
\end{align*}
\]

\[ = 35.62 \text{ lb CO} \]

\[
\begin{align*}
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 1200 \text{ lb Fe} \\
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 159.7 \text{ lb Fe}_2\text{O}_3 \\
12 \text{ lb mol Fe} & \quad 1 \text{ lb mol Fe}_2\text{O}_3 \\
2 \text{ lb mol Fe} & \quad 1 \text{ lb mol CO}
\end{align*}
\]

\[ = 902.4 \text{ lb CO} \]

Total (35.62 lb CO + 902.4 lb CO) = 938 lb CO

(ii) \( 1 \text{ ton } \text{Fe}_2\text{O}_3 \)

\[
\begin{align*}
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 1200 \text{ lb Fe} \\
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 159.85 \text{ lb Fe}_2\text{O}_3 \\
12 \text{ lb mol Fe} & \quad 1 \text{ lb mol C} \\
3 \text{ lb mol C} & \quad 1 \text{ lb mol Fe}_2\text{O}_3
\end{align*}
\]

\[ = 387.1 \text{ lb C} \]

\[
\begin{align*}
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 183 \text{ lb FeO} \\
1 \text{ ton } \text{Fe}_2\text{O}_3 & \quad 91.85 \text{ lb FeO} \\
1 \text{ lb mol Fe}_2\text{O}_3 & \quad 1 \text{ lb mol CO} \\
12 \text{ lb C} & \quad 1 \text{ lb mol Fe}_2\text{O}_3
\end{align*}
\]

\[ = 15.3 \text{ lb C} \]

\[ 387.1 + 15.3 = \frac{402.4 \text{ lb C used}}{1 \text{ ton } \text{Fe}_2\text{O}_3} \]
Solutions Chapter 9

9.28

Cl₂ + 2NaOH → NaCl + NaOCl + H₂O

MW: 71.0 40.01 58.5 74.5 18.0

Basis: 1145 lbₚ NaOH + 851 lb Cl₂ (→ 618 lbₚ NaOCl)

a. Determine limiting reactant

Assume all Cl₂ reacts, calculate lb of NaOH required

NaOH required = \frac{2 \text{ lb mol NaOH}}{\text{lb mol Cl₂}} \times \frac{851 \text{ lb Cl₂}}{71 \text{ lb Cl₂}} = 959.11 \text{ lb NaOH}

or use extent of reaction

NaOH: \frac{1145}{40} = 28.63 \text{ lb mol (0-28.63) - 2 = 14.3}

Cl₂: \frac{851}{71.0} = 11.99 \text{ lb mol (0-11.99) - 1 = 12.0 (minimum)}

b. % excess NaOH = \frac{\text{lb mol NaOH in excess}}{\text{lb mol NaOH for rxn}} \times 100

\frac{1145 \text{ lb mol NaOH}}{40.01 \text{ lb mol NaOH}} = \frac{959.11 \times 1}{40.01} \times 100

= 19.4% excess NaOH

b. Degree of completion = \frac{\text{lb mol Cl₂ that reacted}}{\text{lb mol Cl₂ available to react}} = \frac{\frac{851}{71.0}}{0.692}

= 8.30 lb mol Cl₂ reacted

\frac{\xi}{\xi_{max}} = 8.30 = 0.69

(continued)
Solutions Chapter 9

(c) degree of completion = \( \frac{44 - 4.4}{44} = 0.90 \)

(or 9.9 from \( \frac{d}{11.0} \) = 0.90)

(d) extent of reaction \( \xi = \frac{19.8 - 0}{2} = \) reacting moles

9.30 Basis: 30 mol CO, 12 mol CO\(_2\), 35 mol H\(_2\)O feed = 1 hr

\[
\begin{align*}
\text{mol} & \quad \text{CO} & \quad \text{CO} & \quad \text{mol} \\
30 & \quad \text{CO} & \quad \text{CO} & \quad F \\
12 & \quad \text{CO}_2 & \quad \text{H}_2 & \quad P \\
35 & \quad \text{H}_2\text{O} & \quad \text{CO} & \quad \text{mol} \\
& & \quad \text{CO}_2 & \quad \text{H}_2 & \quad \text{H}_2\text{O} \\
& & \quad 18 & \quad 18 & \quad 44 & \quad 2
\end{align*}
\]

MW: 28 18 44 2

(a) \( \text{fed} \) CO \( \frac{30}{35} = 0.86 < \frac{1}{1} \)

H\(_2\)O \( \frac{35}{35} = 1 \)

CO is limiting reactant

(b) H\(_2\)O is the excess reactant

9.31

2C\(_2\)H\(_4\) + O\(_2\) \rightarrow 2C\(_2\)H\(_2\)O

For 100% conversion of C\(_2\)H\(_4\) according to reaction (a):

\[
\frac{2 \text{ mol C}_2\text{H}_4/\text{time}}{2 \text{ mol C}_2\text{H}_4/\text{time}} = 1
\]

For reaction b3:

\[
\frac{1 \text{ mol C}_2\text{H}_4/\text{time}}{1.33 \text{ mol C}_2\text{H}_4/\text{time}} = 0.75
\]
Solutions Chapter 9

9.32

Basis: 100 lb mesitylene (C₆H₁₂)

The reactions are:

$$C₆H₁₂ + H₂ \rightarrow C₆H₁₀ + CH₄$$

$$C₆H₁₀ + H₂ \rightarrow C₇H₈ + CH₄$$

C₆H₁₂  C₆H₁₀  C₇H₈  CH₄

100 lb  106.08  92.06

The initial selectivity is: C₆H₁₀/C₇H₈ = 0.7 and 0.8

The number of moles of C₆H₁₂ in the basis is:

$$\frac{100 \text{ lb C₆H₁₂}}{120.1 \text{ lb C₆H₁₂}} \times 0.833 \text{ lb mol}$$

For the selectivity of 0.7 (the equations are in lb mol):

(1) C₆H₁₀ + (1) C₇H₈ = 0.833

C₆H₁₀ / C₇H₈ = 0.7

with the results:

<table>
<thead>
<tr>
<th>(lb mol)</th>
<th>(in lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆H₁₀</td>
<td>0.490</td>
</tr>
<tr>
<td>C₇H₈</td>
<td>0.343</td>
</tr>
</tbody>
</table>

For the selectivity of 0.8 the results are:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆H₁₀</td>
<td>0.463</td>
</tr>
<tr>
<td>C₇H₈</td>
<td>0.370</td>
</tr>
</tbody>
</table>

The catalyst used in the respective cases is:

Selectivity of 0.7:

1 lb catalyst: 0.490 lb mol C₆H₁₀, 92.06 lb C₆H₁₂

Selectivity of 0.8:

1 lb catalyst: 0.463 lb mol C₆H₁₀, 92.06 lb C₆H₁₂

Solutions Chapter 9

Income change

Increase in C₆H₁₀: $(39.3 - 36.4)\times (0.65) = +1.89$

Decrease in C₇H₈: $(45.1 - 42.6) \times (22) = -0.55$

Expense change (decrease):

Change in catalyst used: $(0.090 - 0.085) \times 25 = +0.13$

Net change: $\$1.47$
10.1

Basis: 1 mol A

\[ A \rightarrow 3B \]

50 percent conversion gives as the product:

<table>
<thead>
<tr>
<th>mol</th>
<th>0.5</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Mole fraction \( A = 0.5/2.0 = 0.25 \)

(b) Extent of reaction \( \xi = \frac{0.5 - 1.0}{-1} = 0.5 \) using A

10.2

Assume a steady state flow process with reaction.

Step 5: Basis: 1 hr (6.22 kg mol = F)

Steps 1, 2, 3 and 4:

\[ H_2(g) + SiHCl_3(g) \rightarrow Si(s) + 3HCl(g) \]

<table>
<thead>
<tr>
<th>F (6.22 kg mol)</th>
<th>HCl</th>
<th>x_{HCl}</th>
<th>n_{HCl}</th>
<th>H_2</th>
<th>x_{H_2}</th>
<th>n_{H_2}</th>
<th>SiHCl_3</th>
<th>x_{SiHCl_3}</th>
<th>n_{SiHCl_3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mol fr: 0.580 H_2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.420 SiHCl_3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mol fr: 1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

MW Si = 28.086

MW Cl = 35.45

MW H = 1.01

\[ n_{H_2}/W = 0.223 \]

Step 6: Unknowns: W, P, 3n_i

Step 7: Balances: element balances are H, Si, Cl, \( \Sigma n_i = W, n_{H_2}/W = 0.223 \)

Or, using the extent of reaction

Step 6: Unknowns = 6:

W, P, \( 3n_i, \xi \)

Step 7: Balances = 6

Species balances: \( H_2, SiHCl_3, HCl, Si \)

\( \Sigma n_i = W \)

\( n_{H_2}/W = 0.223 \)

Steps 8 and 9: Balances are in kg mol.

\[ \begin{align*}
\text{In:} & \quad \frac{\ln}{6.22(0.420)(3)} = \frac{\text{Out}}{n_{HCl} + n_{SiHCl_3}(3)} \\
\text{Si (kg mol):} & \quad 6.22(04.20)(1) = P(1) + n_{SiHCl_3} \\
\text{H (kg mol):} & \quad 6.22[0.580(2) + 0.420(1)] = n_{HCl} + n_{SiHCl_3} + n_{H_2}(2)
\end{align*} \]

Balances using \( \xi \):

\[ \begin{align*}
H_2: & \quad [n_{H_2} - (0.580)(6.22)] = (-1)(\xi) \\
SiHCl_3: & \quad [n_{SiHCl_3} - (0.420)(6.22)] = (-1)(\xi) \\
HCl: & \quad [n_{HCl} - 0] = (+3)(\xi) \\
Si: & \quad [n_{Si} - 0] = (+i)(\xi) \\
\xi & = 1.83 
\end{align*} \]

(continued)
Solution: \( w = 8.05 \quad p = 1.83 \)

\[
\begin{align*}
n_{\text{H}} &= 1.78 \\
n_{\text{SiO}_2} &= 5.49 \\
n_{\text{SiO}_2} &= 0.7824 \\
\frac{1.83 \text{kg mol Si}}{1 \text{ hr}} &\times \frac{1 \text{ hr}}{60 \text{ min}} \\
28.086 \text{ kg Si} &= 17.13 \text{ kg Si} \\
\frac{1.46 \text{ kg Si initial}}{18.59 \text{ kg final Si}} &= 0.079 
\end{align*}
\]

10.3

Step 5: Basis: 100 lb pyrites in

\[2 \text{ FeS}_2 + \frac{3}{2} \text{ O}_2 \rightarrow \text{ Fe}_2\text{O}_3 + 4 \text{ SO}_3\]

Steps 2, 3, and 4:

<table>
<thead>
<tr>
<th>Feed</th>
<th>SO(_3)</th>
<th>(X)</th>
<th>(Y)</th>
<th>(Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(100 \text{ lb pyrite})</td>
<td>(32% \text{ S})</td>
<td>(10 \text{ lb S})</td>
<td>(X)</td>
<td>(Y)</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{Gas} &\quad \text{ mole \%} \\
\text{SO}_2 &\quad 13.4 \\
\text{O}_2 &\quad 2.7 \\
\text{N}_2 &\quad 83.9 \\
\text{Total} &\quad 100.0 \\
\end{align*}
\]

\(\text{Air}\): \(\text{O}_2 = 0.21\), \(\text{N}_2 = 0.79\)

\(\text{Cinder}: \text{Fe}_2\text{O}_3\), inert

Let \(X = \text{mol air in}\), \(Y = \text{mol SO}_3\) out, \(Z = \text{mol flue gas out}\)

Steps 6 and 7:

Using a reduced set of variables:

Unknowns (4): \(X, Y, Z, \text{ cinder}\)

Balances (4): \(O, N, S, \text{ cinder}\)

Steps 8 and 9:

1. \textbf{Sulfur Balance:} \((32 + 10)/32 = Y + 0.134Z\)
2. \textbf{2O Balance:} \(0.21X = 1.5Y + (0.134 + 0.027)Z\)
3. \textbf{2N Balance:} \(0.79X = 0.839Z\)

Solve (1), (2), (3): \(Y = 0.118 \text{ mol}, Z = 8.9 \text{ mol}\)

Step 10:

Check: \(\text{mol S} = 0.118 + 0.134(8.9) = 1.31\)

\% conversion of S to SO\(_3\) = \(\frac{11.8}{1.315} = 8.98\%\)
10.4

Steps 1, 2, 3 and 4:

\[
\begin{array}{c|c|c|c}
\text{Methanol} & \text{F} \quad \text{100\%} & \text{Reacts} & \text{Product} \\
\text{CH}_3\text{OH} & & & \text{H}_2\text{O} 5.9 \\
\text{Air} & A & & \text{O}_2 13.4 \\
\text{mol frac} & \begin{array}{c} \text{O}_2 \quad 0.21 \\ \text{N}_2 \quad 0.79 \end{array} & & \begin{array}{c} \text{CH}_2\text{O} \quad 4.6 \\ \text{HCOOH} \quad 1.2 \end{array} \\
& 1.00 & & 100.0
\end{array}
\]

Step 5: Basis: 100 mol P

Step 6: Unknown F, A

Step 7: Balances N, H, O, C

More balances than unknowns. Are they independent? Consistent?

Steps 8 and 9: Balances in moles

Check by first solving C, N (tie elements)

\[C: \quad F (1) = 4.6 + 12.3 + 1.2 = 18.1 \quad \Rightarrow \quad F = 18.1 \text{ mol}\]

\[2N: \quad A (0.79) = 62.6 \quad \Rightarrow \quad A = 79.24 \text{ mol}\]

10.5

1. Additional information was the molecular weights of the compounds and the chemical reaction equations.

\[
\begin{align*}
\text{MW CaCO}_3 &= 100.0, \quad \text{MW MgCO}_3 = 84.3, \quad \text{MW CO}_2 = 44.0. \\
\end{align*}
\]

2. Assume a batch process

\[
\begin{array}{c|c|c|c|c|c}
\text{Initial} & \text{CaCO}_3 & \text{MgCO}_3 & \text{Final} & \text{CaO} & \text{P} \\
G & & & & & \\
\text{CO}_2 & & & & & \\
\end{array}
\]

3. Basis: 1 g sample

4. \[F = 1.000 \text{ g}; \quad P \text{ is not explicitly given but can be calculated: } P = 0.550 \text{ g}; \quad G \text{ is not explicitly given and can be calculated, } G = 0.450 \text{ g}\]

5. Mass fraction of CaO in P and F, mass fraction MgO in P and F (or mass of each) (continued)
6. Species balances
7. It appears to be a carbon balance
8. 0 degrees of freedom
9. Yes

10.6

Steps 1, 2, 3, and 4: To solve this problem you must recall that CaCO₃ reacts with H₂SO₄ to form CaSO₄ and that CaCO₃ when heated yields CO₂ and CaO whereas when CaSO₄ is heated at the same time it does not decompose. Although the problem seems to be underspecified, when you draw a diagram of the process and place the known data on it, the situation becomes clearer. Assume the process is a steady state open one with reaction. Then the element balances are just \( \text{in} = \text{out} \). If you use the extent of reaction, you make species balances.

Note that we have designated the composition of P and A in terms of the mass of each component, \( m_i \), rather than the mass fraction \( \omega_i \), because this choice makes the element or species balances linear (avoids products such as \( \omega P \)).

The CO₂ liberated from the sludge is equivalent to

\[
\begin{align*}
1 \text{ lb CO}_2 & \quad 1 \text{ lb mol CO}_2 & \quad 1 \text{ lb mol CaCO}_3 & \quad 100.09 \text{ lb CaCO}_3 \\
10 \text{ lb P} & \quad 44 \text{ lb CO}_2 & \quad 1 \text{ lb mol CO}_2 & \quad 1 \text{ lb mol CaCO}_3
\end{align*}
\]

\[
= 0.227 \text{ lb CaCO}_3/\text{lb P}
\]

Step 5: Basis: \( F = 100 \text{ lb} \)

Step 6: The variables whose values are unknown are \( A, m^A_{\text{H}_2\text{SO}_4}, m^A_{\text{H}_2\text{O}}, m^A_{\text{CaCO}_3}, m^P_{\text{CaSO}_4}, m^P_{\text{CaO}} \), \( m^p_{\text{water}}, \) \( P, \) \( W, \) and \( Y, \) a total of 9.

Step 7: The element balances that can be made are \( \text{Ca}, \text{C}, \text{O}, \text{S}, \text{H}, \text{inert} \) (6 total) and we know \( \sum m^A_i = A, \sum m^P_i = P, \) and \( \left( m^P_{\text{CaCO}_3} / P \right) = 0.227 \) for a total of 9. If the equations are independent, we can find a unique solution.

Steps 8 and 9: The equations \( \text{(in = out)} \) are (except for the inert balance which is in lb) in moles

(continued)
Solutions Chapter 10

\[
\begin{align*}
\text{Ca:} & \quad 95 \text{ lb} \text{ CaCO}_3 \quad 1 \text{ lb mol CaCO}_3 \quad 1 \text{ lb mol Ca} \\
& \quad \frac{100.09 \text{ lb CaCO}_3}{1 \text{ lb mol CaCO}_3} \quad \frac{1 \text{ lb mol Ca}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{m^{\text{CaCO}_3}}{1 \text{ lb mol CaCO}_3} \quad \frac{1 \text{ lb mol Ca}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{m^{\text{CaCO}_3}}{1 \text{ lb mol CaCO}_3} \quad \frac{1 \text{ lb mol Ca}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{1 \text{ lb mol Ca}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{1 \text{ lb mol Ca}}{100.09 \text{ lb CaCO}_3} \\
\text{C:} & \quad 0.95 \text{ lb CaCO}_3 \quad 1 \text{ lb mol CaCO}_3 \quad 1 \text{ lb mol C} \\
& \quad \frac{100.09 \text{ lb CaCO}_3}{1 \text{ lb mol CaCO}_3} \quad \frac{1 \text{ lb mol C}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{m^{\text{CaCO}_3}}{1 \text{ lb mol CaCO}_3} \quad \frac{1 \text{ lb mol C}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{m^{\text{CaCO}_3}}{1 \text{ lb mol CaCO}_3} \quad \frac{1 \text{ lb mol C}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{1 \text{ lb mol C}}{100.09 \text{ lb CaCO}_3} \\
\text{S:} & \quad 0.98 \text{ lb H}_2\text{SO}_4 \quad 1 \text{ lb mol H}_2\text{SO}_4 \quad 1 \text{ lb mol S} \\
& \quad 98.08 \text{ lb H}_2\text{SO}_4 \quad 1 \text{ lb mol H}_2\text{SO}_4 \\
& \quad \frac{m^{\text{H}_2\text{SO}_4}}{1 \text{ lb mol H}_2\text{SO}_4} \quad \frac{1 \text{ lb mol S}}{98.08 \text{ lb H}_2\text{SO}_4} \\
& \quad \frac{m^{\text{H}_2\text{SO}_4}}{1 \text{ lb mol H}_2\text{SO}_4} \quad \frac{1 \text{ lb mol S}}{98.08 \text{ lb H}_2\text{SO}_4} \\
& \quad \frac{1 \text{ lb mol S}}{98.08 \text{ lb H}_2\text{SO}_4} \\
\text{H:} & \quad 2 \text{ lb H}_2\text{SO}_4 \quad 1 \text{ lb mol H}_2\text{SO}_4 \quad 1 \text{ lb mol H}_2 \\
& \quad 98.08 \text{ lb H}_2\text{SO}_4 \quad 1 \text{ lb mol H}_2 \\
& \quad \frac{m^{\text{H}_2\text{SO}_4}}{1 \text{ lb mol H}_2\text{SO}_4} \quad \frac{1 \text{ lb mol H}_2}{98.08 \text{ lb H}_2\text{SO}_4} \\
& \quad \frac{m^{\text{H}_2\text{SO}_4}}{1 \text{ lb mol H}_2\text{SO}_4} \quad \frac{1 \text{ lb mol H}_2}{98.08 \text{ lb H}_2\text{SO}_4} \\
& \quad \frac{1 \text{ lb mol H}_2}{98.08 \text{ lb H}_2\text{SO}_4} \\
\text{O:} & \quad 95 \text{ lb mol CaCO}_3 \quad 1 \text{ lb mol CaCO}_3 \quad 3 \text{ lb mol O} \\
& \quad \frac{100.09 \text{ lb CaCO}_3}{1 \text{ lb mol CaCO}_3} \quad \frac{3 \text{ lb mol O}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{m^{\text{CaCO}_3}}{1 \text{ lb mol CaCO}_3} \quad \frac{3 \text{ lb mol O}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{m^{\text{CaCO}_3}}{1 \text{ lb mol CaCO}_3} \quad \frac{3 \text{ lb mol O}}{100.09 \text{ lb CaCO}_3} \\
& \quad \frac{3 \text{ lb mol O}}{100.09 \text{ lb CaCO}_3} \\
\text{Inert:} & \quad 5 \text{ lb inert} = m^{\text{Inert}}/1 \text{ lb inert} \\
\end{align*}
\]

The solution of these equations using a computer code would give all of the values of the unknown quantities. However, a review of the set of equations, after having gone into great detail about each equation, indicates that only 4 of the equations have to be solved to get the desired answer, namely the Ca balance, the S balance, \( \Sigma m^{\text{Inert}} = P \), and the inert balance plus \( m^{\text{CaCO}_3} = 0.227 \).

\[
\begin{align*}
\Sigma m^{\text{Inert}} = P: & \quad m^{\text{CaCO}_3} + m^{\text{CaSO}_4} + 5 = P = m^{\text{CaCO}_3}/0.227 \\
\text{Ca:} & \quad 0.949 = 0.010 m^{\text{CaCO}_3} + 0.00734 m^{\text{CaSO}_4} \\
\text{Inert:} & \quad m^{\text{CaCO}_3} = 28.55 \quad \text{and} \quad 28.55/95 = 50\% \text{unreacted}.
\end{align*}
\]
10.7

Steps 1, 2, 3, and 4:

```
1.81 mol SO_3 | 1 mol S
| 1 mol SO_3  |
9.01 mol CuS that reacts | 1 mol S | 1 mol CuS
```

If you use the extent of reaction, you need to write down the balanced reactions

\[ \text{CuS} + \text{O}_2 \rightarrow \text{CuO} + \text{SO}_3 \]  \hspace{1cm} (1)
\[ \text{SO}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{SO}_3 \]  \hspace{1cm} (2)

Steps 6 and 7:

The unknowns: 4 above plus \( \xi_1 \) and \( \xi_2 \)
Balance: 6 species balances

Steps 8 and 9:

CuO: \[ Y = 0 + (1)(\xi_1) \]
CuS: \[ 0 = n_{\text{Cu}} + (-1)(\xi_1) \]
O_2: \[ P(0.081) = A(0.21) + (-1)(\xi_1) + (-\frac{1}{2})(\xi_2) \]
N_2: \[ P(0.847) = A(0.79) \]
SO_2: \[ P(0.072) = 0 + (1)(\xi_1) + (-1)(\xi_2) \]
SO_3: \[ G = 0 + (1)(\xi_2) \]

\( \xi_1 = 9.01 \)
\( \xi_2 = 1.81 \)
10.8

6HF(g) + SiO₂(s) → H₃SiF₆(g) + 2H₂O(l)

(1)

H₃SiF₆(g) → SiF₄(g) + 2HF(g)

(2)

The net reaction is

4HF + SiO₂ → SiF₄ + 2H₂O

Steps 2, 3, and 4:

The process is an unsteady state, open process

Step 5: Basis: 1 mol F entering

Steps 6 and 7:

Unknowns: 4 n₁, P, ξ, loss SiO₂ from wafer (L)

Balances: HF, N₂, SiF₄, H₂O, SiO₂ (5 species)

Other equations: ∑ nᵢ = P; 10% HF reacts

Steps 8 and 9:

HF: nₑHF = 0.50 + (4)ξ = 0.50(90) = 0.45

ξ = 1.25 × 10⁻² reacting moles

SiF₄: nₑSiF₄ = 0 + (1)(1.25 × 10⁻⁵) = 1.25 × 10⁻⁵ mol

Solutions Chapter 10

H₂O: nₑH₂O = 0 + (2)(1.25 × 10⁻⁵) = 2.50 × 10⁻⁵ mol

N₂: nₑN₂ = 0.50 mol

SiO₂: nₑSiO₂ = nₑSiO₂ = (1)(1) = 1 mol

If you use element balances:

Step 6 and 7:

The unknowns: 4n₁, P, L

The balances: H, F, Si, O, N (presumably 4 are independent)

Other equations: ∑ nᵢ = P; 10% HF reacts

Steps 8 and 9:

H: 0.50(1) = nₑH + 2nₑH₂O

F: 0.50(1) = nₑF + 4nₑSiF₄

Si: (nₑSi + nₑSiO₂) = nₑSiF₄

O: 2(nₑO₂ + nₑSiO₂) = nₑH₂O

N: 2(0.50) = 2nₑN₂

nₑ = 0.90(0.50) = 0.45
10.9

We will view this process as a steady state process in an open system with flow in and out, and a change in the material in the vessel from the initial to the final states. For component i, Equation (10.1) becomes Equation (10.6)

\[ n_i^{\text{out}} = n_i^{\text{in}} + \sum_{j=1}^{n} v_i F_j \]

The bioorganisms do not have to be included in the solution of the problem.

Steps 1, 2, 3, and 4

Figure P10.9 is a sketch of the process.

![Figure P10.9](image)

Step 5 Basis: 3500 kg F

Step 4

Convert the 3500 kg into moles of H₂O and C₆H₁₂O₆

\[ n_{\text{H}_2\text{O}}^{\text{mol}} = \frac{3500(0.88)}{18.02} = 190.4 \]

\[ n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{mol}} = \frac{3500(0.12)}{180.1} = 2.332 \]

Step 6 and 7

The degree of freedom analysis is as follows:

Number of variables: 9

\[ n_{\text{H}_2\text{O}}^{\text{in}}, n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{in}}, n_{\text{H}_2\text{O}}^{\text{out}}, n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{out}}, n_{\text{C}_2\text{H}_4\text{OH}}^{\text{in}}, n_{\text{C}_2\text{H}_5\text{CO}_2\text{H}}^{\text{in}}, n_{\text{CO}_2}^{\text{in}}, \xi_1, \xi_2 \]

Number of equations: 9

Basis: F = 3500 kg of initial solution (equivalent to initial moles of H₂O plus moles of sucrose)

Species material balances: 5

\[ \text{H}_2\text{O}, \text{C}_2\text{H}_5\text{OH}, \text{C}_2\text{H}_5\text{OH}, \text{C}_2\text{H}_5\text{CO}_2\text{H}, \text{CO}_2 \]

Specifications: 4 (3 independent)

\[ n_{\text{H}_2\text{O}}^{\text{in}} = 170.4 \text{ or } n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{in}} = 2.332 \text{ (one is independent, the sum is } F \text{ in mol)} \]

\[ n_{\text{C}_2\text{H}_5\text{OH}}^{\text{in}} = \frac{90}{180.1} = 0.500 \quad n_{\text{CO}_2}^{\text{in}} = \frac{120}{44} = 2.727 \]

The degrees of freedom are zero.

Step 8

The material balance equations, after introducing the known values for the variables are:

\[ \text{H}_2\text{O}: \quad n_{\text{H}_2\text{O}}^{\text{in}} = 170.9 + (0)\xi_1 + (2)\xi_2 \]  

\[ \text{C}_2\text{H}_5\text{OH}: \quad 0.500 = 2.332 + (-1)\xi_1 + (-1)\xi_2 \]  

\[ \text{C}_2\text{H}_5\text{CO}_2\text{H}: \quad n_{\text{C}_2\text{H}_5\text{CO}_2\text{H}}^{\text{in}} + 0 + (0)\xi_1 + (2)\xi_2 \]  

(continued)
### Solutions Chapter 10

\[
\text{CO}_2 \quad 2.727 = 0 + (2)\xi_3 + (0)\xi_1 \quad (e)
\]

If you do not use a computer to solve the equations, the sequence you should use to solve them would be

(e), plus (b), (a), (c), (d)

**Step 9**

The solution of Equations (a) – (e) is

\[
\xi_1 = 1.364 \text{ kg moles reacting} \quad \xi_2 = 0.469 \text{ kg moles reacting}
\]

<table>
<thead>
<tr>
<th>Species</th>
<th>kg moles</th>
<th>MW</th>
<th>kg</th>
<th>mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H\textsubscript{2}O</td>
<td>171.8</td>
<td>18.01</td>
<td>3094.1</td>
<td>89.0</td>
</tr>
<tr>
<td>CH\textsubscript{3}CO\textsubscript{2}H</td>
<td>0.939</td>
<td>72.03</td>
<td>67.5</td>
<td>1.9</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>2.272</td>
<td>44.0</td>
<td>100.0</td>
<td>2.9</td>
</tr>
<tr>
<td>C\textsubscript{2}H\textsubscript{5}O\textsubscript{5}</td>
<td>0.500</td>
<td>180.1</td>
<td>90.1</td>
<td>2.6</td>
</tr>
<tr>
<td>3477.3</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step 10**

The total mass of 3477 kg is close enough to 3500 kg of feed to validate the results of the calculations.

### Solutions Chapter 10

**10.10**

**Steps 1, 2, 3 and 4:**

\[
\begin{align*}
\text{SiH}_4 + \text{O}_2 & \rightarrow \text{SiO}_2 + 2\text{H}_2 \\
4\text{PH}_3 + 5\text{O}_2 & \rightarrow 2\text{P}_2\text{O}_5 + 6\text{H}_2
\end{align*}
\]

\[\begin{array}{c}
100\% \text{ O}_2 \\
A \\
B
\end{array} \quad \begin{array}{c}
100\% \text{ SiH}_4 \\
C
\end{array} \quad \begin{array}{c}
100\% \text{ PH}_3 \\
D
\end{array}
\]

Step 5: Basis: \(1 \text{ g mol PH}_3\)

Step 6: No. Unknowns: \(A, B, D, E, n^n_{\text{SiO}_2}\) \(\text{5}\)

Step 7: Element balances: \(\text{Si, H, P, O}, \omega^n_{\text{SiO}_2}\) \(\text{5}\)

Note: \(n^n_{\text{SiO}_2} + n^n_{\text{SiO}_2} = E\)

Steps 8 and 9:

**P Bal (in grams):**

<table>
<thead>
<tr>
<th>\text{in}</th>
<th>\text{Out}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 g mol PH\textsubscript{3}</td>
<td>2 g mol P, 2 g mol P, 31 g P = 31 g P</td>
</tr>
<tr>
<td>4 g mol PH\textsubscript{3}</td>
<td>1 g mol P, P \text{O}_3</td>
</tr>
<tr>
<td>1 g mol PH\textsubscript{3}</td>
<td>2 g mol P, 5 g mol O, 16 g O = 40 g O</td>
</tr>
<tr>
<td>4 g mol PH\textsubscript{3}</td>
<td>1 g mol P \text{O}_3</td>
</tr>
</tbody>
</table>

Total: \(71 \text{ g P}_2\text{O}_5\)

(continued)
or since all the P is in stream E: \[
\frac{1 \text{ g mol PH}_3}{4 \text{ g mol PH}_4} \times \frac{2 \text{ g mol P}_2\text{O}_5}{1 \text{ g mol P}_2\text{O}_3} = 71 \text{ g P}_2\text{O}_5
\]

Si Bal:
\[
\begin{array}{ccc|c}
\text{in} & \text{Out} & \text{Eq} \\
\text{Bg mol SiH}_4 & \text{lg mol SiO}_2 & \text{lg mol Si} & 28.1 \text{g Si} \\
\text{lg mol SiH}_4 & \text{lg mol SiO}_2 & \text{lg mol Si} & 32B \text{ g Si} \\
\end{array}
\]

\[
\begin{align*}
28.1 \text{g Si} & = 28.1B \text{ g Si} \\
32B \text{ g O} & = 32B \text{ g O}
\end{align*}
\]

Total: \[
\frac{71}{71 + 60.1B} = 0.05 \\
3.55 + 3.0058B = 71 \\
B = 23.5 \text{ g mol}
\]

\[
\frac{1 \text{ g mol PH}_3}{1 \text{ g mol SiH}_4} = 34 \text{ g PH}_3
\]

\[
\frac{23.5 \text{ g mol SiO}_2}{1 \text{ g mol SiH}_4} = 7.54 \text{ g SiO}_2
\]

\[
\frac{754}{34} = 22.3 \frac{\text{g SiO}_2}{\text{g PH}_3}
\]

---

10.11

Steps 1, 2, 3 and 4:

\[
\begin{align*}
\text{Cu} & \quad \text{NH}_4\text{OH} \\
A & \quad B \\
C & \quad D \\
E & \quad \text{Cu(NH}_3\text{)}_4\text{Cl} \\
F & \quad \text{H}_2\text{O}
\end{align*}
\]

Step 5: Basis: 1 board

A: \[
\begin{align*}
\text{Cu foil} & = 4 \text{ in} \times 8 \text{ in} \\
& = 32 \text{ in}^2 \\
& = \frac{32 \text{ in}^2}{2.54 \text{ cm}^2} = 12.54 \text{ cm}^2 \\
& = \frac{12.54 \text{ cm}^2}{163.55 \text{ g} \text{cm}^2} = 0.076 \text{ g Cu}
\end{align*}
\]

F: Cu remaining \[
\begin{align*}
1 - 0.075 & = 0.925 \\
& = 2.219 \text{ g mol Cu}
\end{align*}
\]

Steps 6 and 7: Unknowns: B, C, D, E

Balances: Cu, N, Cl, H, O should be enough if one is redundant

Steps 8 and 9: (Balances to be solved.)

Cu Balance:
Solutions Chapter 10

2.219 g mol Cu + \( \frac{B \text{ g mol Cu(NH}_3)_2 \text{Cl}_2}{1 \text{ g mol Cu}} \) + \( \frac{2 \text{ g mol Cl}}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) = 1.664 g mol Cu + \( \frac{D \text{ g mol Cu(NH}_3)_2 \text{Cl}_2}{1 \text{ g mol Cu}} \) + \( \frac{4 \text{ g mol N}}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \)

Cl Balance:

\( \frac{B \text{ g mol Cu(NH}_3)_2 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) - \( \frac{2 \text{ g mol Cl}}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) = \( \frac{D \text{ g mol Cu(NH}_3)_2 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) - \( \frac{4 \text{ g mol N}}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \)

N Balance:

\( \frac{B \text{ g mol Cu(NH}_3)_2 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) - \( \frac{4 \text{ g mol N}}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) = \( \frac{D \text{ g mol Cu(NH}_3)_2 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \) - \( \frac{4 \text{ g mol N}}{1 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2} \)

Solution:

Cu overall: \( A + B = F + D \to A + B = F + (2B) \)

\( 2.219 + B = 0.555 + (2B) \)

\( B = 2.219 - 0.555 = 1.664 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2 \)

Cl: \( D = 2B = 2(1.664) = 3.328 \text{ g mol Cu(NH}_3)_2 \text{Cl}_2 \)

N: \( 4B + C = 4D \)

\( C = 4(3.328 - 1.664) = 6.656 \text{ g mol NH}_4 \text{OH} \)

MW of NH\(_4\)OH

<table>
<thead>
<tr>
<th>N</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_4)</td>
<td>4</td>
</tr>
<tr>
<td>O</td>
<td>16</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
</tr>
</tbody>
</table>

10.12

Basis: 8 tons of contaminated sand containing 30% PCB

If we want the net feed to be 60% combustible, we see that the sand is a tie component:

A sand balance around the feed mixer: 16000(0.7) = F(0.4) so F = 28,000 lb.

A total balance around the feed mixer: F + H = F' \to H = \text{12,000 lb hexane} (continued)
b) \[ \text{C}_2\text{H}_4\text{Cl}_3 + 13.5\text{O}_2 \rightarrow 12\text{CO}_2 + 2\text{HCl} + 3\text{H}_2\text{O} \]
\[ \text{C}_6\text{H}_4 + 9.5\text{O}_2 \rightarrow 6\text{CO}_2 + 7\text{H}_2\text{O} \]

Even with total combustion, we will produce undesirable \text{HCl} which will adversely affect the environment if it is simply vented. Therefore, it would be wise to condense the \text{HCl} and \text{H}_2\text{O} by cooling. Perhaps the acid solution might be sold to help pay for the process.

\[
\begin{align*}
\text{P} & : 16.54\% \text{ CO}_2 \\
& : 12.20\% \text{ O}_2 \\
& : ? \text{ H}_2\text{O} \\
& : ? \text{ HCl} \\
& : ? \text{ N}_2
\end{align*}
\]

By a tie component for CO\textsubscript{2}, we know:
\[
12(21.62) + 139.5 \times 6 = 0.1654 \text{ P hence P} = 6629 \text{ mol}
\]

By an O tie: 0.40(2)A = 0.1654(2)(6629) + 0.1220(2)(6629) = \(x_{\text{H,O}}\) (1) (6629)
\[
x_{\text{H,O}}(6629) = 21.62 \text{ PCB Reacted} \cdot \frac{3\text{H}_2\text{O}}{1 \text{ PCB Reacted}} = 139.6 \text{ C}_6 \text{ Reacted} \cdot \frac{7\text{H}_2\text{O}}{1 \text{ C}_6} = 1042
\]
\[
so \quad x_{\text{H,O}} = 0.1572
\]

From O tie balance: A = 6065.4 mol of 40\% \text{ O}_2 air

Thus: \(N_2\)\text{in} = (N_2)\text{out} = 0.6 \times (6065.4) = 3639.2 mol \text{ N}_2

\[
x_{\text{HCl}} = \frac{3639.2}{6629.0} = 0.549
\]

We can get \text{HCl} by a Cl balance:
\[
\frac{21.6 \text{ PCB Reacted}}{1 \text{ PCB}} = \frac{2 \text{ HCl}}{1 \text{ PCB}} = 43.2 \text{ mol HCl in product}
\]

\[
x_{\text{HCl}} = 0.0065
\]

<table>
<thead>
<tr>
<th>Component</th>
<th>(x_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{CO}_2</td>
<td>0.1654</td>
</tr>
<tr>
<td>\text{O}_2</td>
<td>0.1220</td>
</tr>
<tr>
<td>\text{H}_2\text{O}</td>
<td>0.1572</td>
</tr>
<tr>
<td>\text{HCl}</td>
<td>0.0065</td>
</tr>
<tr>
<td>\text{N}_2</td>
<td>0.5490</td>
</tr>
</tbody>
</table>

We know % excess \text{O}_2 used is: % excess = \(
\frac{100 [\text{O}_2 \text{ fed} - \text{O}_2 \text{ req'd}]}{\text{O}_2 \text{ req'd}}
\)

\[
\text{O}_2 \text{ fed} = 0.4 \text{ (air fed)} = 0.4 \times (6065.4) = 2426.2 \text{ mol O}_2
\]

Also, since we have total combustion,
\[
(\text{O}_2 \text{ req'd}) = (\text{O}_2 \text{ consumed}) = (\text{O}_2 \text{ fed} - \text{O}_2 \text{ out}) = 2426.2 - 0.1220(6629)
\]
\[
= 1617.5 \text{ mol req'd}
\]

Thus: % \text{O}_2 = \(
\frac{2426.2 - 1617.5}{1617.5}
\) = 50\% excess \text{O}_2 used
10.13

Basis: 100 kg mol

One composition is unknown, the flue gas. After selection of a basis, the air flow is
known. Hence, this problem can be solved by direct addition and subtraction

Unknowns: (CO₂, H₂O, N₂, O₂) = 4
Balances: (C, H, O, N) = 4

<table>
<thead>
<tr>
<th>Comp.</th>
<th>% = mol</th>
<th>Reaction</th>
<th>reqd. O₂</th>
<th>CO₂</th>
<th>H₂O</th>
<th>N₂</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>6.4</td>
<td>----------</td>
<td></td>
<td>6.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>0.2</td>
<td>----------</td>
<td>&lt;0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>40.0</td>
<td>CO+1/2 O₂→CO₂</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td>50.8</td>
<td>H₂+1/2 O₂→H₂O</td>
<td>25.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>2.6</td>
<td>----------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XS O₂: (40.0)(45.2) =</td>
<td>18.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total O₂ in</td>
<td>63.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂ in with O₂ (63.28)(79/21) =</td>
<td>238.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td>46.4</td>
<td>50.8</td>
<td>240.65</td>
<td>18.1</td>
</tr>
</tbody>
</table>

10.14

Step 5:

a. O₂ in = 100 kg mol

\[
\frac{100 \text{ kg mol C}}{1 \text{ mol O}_2} \cdot \frac{79 \text{ mol N}_2}{1 \text{ mol C}} = 376 \text{ kg mol N}_2 \text{ in}
\]

Steps 6 and 7:

Unknowns: moles (n) CO₂, O₂, and N₂ in P, and P
Balances: elements C, O, N
Equations: \[\sum n_i^P = P\]
or add \(\xi\) and have C, CO₂, N₂, O₂ species balances

(continued)
Steps 8 and 9:

Element balances

\[
\begin{align*}
\text{in} & \quad \text{out} \\
C: & \quad 100 = n_{\text{CO}} \\
2O: & \quad 100 = n_{\text{CO}_2} + n_{\text{O}_2} \\
2N: & \quad 376 = n_{\text{N}_2} \\
\end{align*}
\]

<table>
<thead>
<tr>
<th>Component in P</th>
<th>kg mol</th>
<th>mol %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(_2)</td>
<td>376</td>
<td>79</td>
</tr>
<tr>
<td>O(_2)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>100</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>476</td>
<td>100</td>
</tr>
</tbody>
</table>

With 50% \(x_s\) air, \(x_s\)O\(_2\), is 50 mol
The total O\(_2\) in is 150 kg mol
The N\(_2\) in is
\[
\frac{150 \times 0.79}{0.21} = 564
\]
The N and C balance are the same but the 2O balance is

\[
\begin{align*}
\text{in} & \quad \text{out} \quad \text{reacts} \\
150 & \quad n_{\text{O}_2} = 100 \\
\end{align*}
\]

<table>
<thead>
<tr>
<th>Component in P</th>
<th>kg mol</th>
<th>mol %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(_2)</td>
<td>564</td>
<td>79</td>
</tr>
<tr>
<td>O(_2)</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>100</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>714</td>
<td>100</td>
</tr>
</tbody>
</table>

e. Same 150 mol O\(_2\) enter and 564 mol N\(_2\) exit but O\(_2\) is different

---

Solutions Chapter 10

<table>
<thead>
<tr>
<th>in</th>
<th>mol CO(_2) used</th>
<th>Used CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen balance: 150</td>
<td>90</td>
<td>5 = 55 kg mol O(_2) lb fg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>kg mol</th>
<th>mol %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>90</td>
<td>12.51</td>
</tr>
<tr>
<td>CO</td>
<td>10</td>
<td>1.39</td>
</tr>
<tr>
<td>O(_2)</td>
<td>55</td>
<td>7.65</td>
</tr>
<tr>
<td>N(_2)</td>
<td>564</td>
<td>78.45</td>
</tr>
<tr>
<td>Total</td>
<td>719</td>
<td>100.00</td>
</tr>
</tbody>
</table>

10.15
Steps 1, 2, 3, and 4:

\[
\begin{align*}
\text{H}_2\text{O} & \quad \text{mass fr.} \\
\text{C} & \quad 0.80 \quad 30 \text{ lb coal} \\
\text{H} & \quad 0.20 \quad \text{mol fr.} \\
\text{O}_2 & \quad 0.21 \quad \Sigma = F \\
\text{N}_2 & \quad 0.79 \quad \text{mol fr.} \\
\end{align*}
\]

Steps 5 and 6: With a basis of 30 lb coal, only \(n_{\text{N}_2}\), \(n_{\text{O}_2}\), \(n_{\text{CO}}\), \(n_{\text{CO}_2}\), \(F\) and \(W\) are unknown. Total 6

(continued)
### Solutions Chapter 10


\[ \frac{n_{\text{coal}}}{n_{\text{O}}} = \frac{3}{2} \quad \text{and} \quad \sum n_i = F \]

Do calculations in moles, but you don't need to make all of the element balances.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>lb</th>
<th>mol wt</th>
<th>lb mol</th>
<th>Rax</th>
<th>read O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>24</td>
<td>12</td>
<td>2</td>
<td>C+O₂→CO₂</td>
<td>2.0</td>
</tr>
<tr>
<td>2H</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>H₂+1/2O₂→H₂O</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
</tbody>
</table>

\[
3.5\text{lb mol O}_2 \times \frac{1.00\text{lb mole air}}{0.21\text{lb mol O}_2} = 16.67\text{lb mole air reqd.}
\]

or \[
\frac{4.35-3.5}{3.5} \times 100 = 24.33\%
\]

#### 10.16

Steps 1, 2, 3 and 4:

1. **Step 5:** Basis: 100 mol P

2. **Step 6:** Unknowns: x, y, A, W, F Total 5 A and P will be mol

3. **Step 7:** Element Balances: C, H, N, O
   
   Equations:
   
   a) If x and y are moles, not mole fractions, add: \( x + y = F \)

   b) If x, y are mole fr., add \( x + y = 1.00 \)

4. **Steps 8 and 9:** Use x and y as mol:
   
   C balance: \( x = 8.7 + 1.0 = 9.7 \)

   2N balance: \( y + 0.79\text{A} = 86.5 \)

   2H balance: \( 2x = W = 2(9.7) = 19.4 \)

   2O balance: \( 0.21\text{A} = (1/2) (W + 8.7) + 1.0 + 3.8 \)

   Use 2O bal: \( A = \frac{9.7 + 8.7 + 0.5 + 3.8}{0.21} = 108 \)

   Use 2N bal: \( y = 1.10 \)

5. **required O₂:** \( \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \) (1)

6. total O₂ in: \( (0.21)(108) = 22.7 \) excess O₂ = 22.7 - 19.4 = 3.3 mol

7. \% xs air = \% xs O₂ = \[ \frac{3.3}{39.4} \times 100 = 8.4\% \]

   \( (a) \)
Alternate solution: Use extent of reaction and species balances.

Another equation needed for CO: \( \text{CH}_4 + 1.5\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2\text{O} \) (2)

Species balances to get \( \xi \) and \( \zeta \):

- \( \text{CH}_4 \): \( O = n^{\text{reacting}}_{\text{CH}} + (-1)\xi + (-1)\zeta \)
- \( \text{CO}_2 \): \( 8.7 = 0 + (1)\xi \) \( \xi = 8.7 \) reacting moles
- \( \text{CO} \): \( 1.0 = 0 + (1)\zeta \) \( \zeta = 1.0 \) reacting moles

Thus \( n^{\text{reacting}}_{\text{CH}} = 8.7 + 1.0 = 9.7 \) mol and other compounds follow.

10.17
Steps 1, 2, 3 and 4:

Step 5: Basis 100 mol P
Step 6: Unknowns: F, A, W (all compositions known)
Solutions Chapter 10

Balances: C, H, O, inert, N₂

Steps 8 and 9:

Balances (in moles):

C:
\[ \frac{F(0.90)}{12} = \frac{P(0.139 + 0.008)}{12} + \frac{R(0.10)}{12} + W(0) \]

H:
\[ \frac{F(0.06)}{1.005} = \frac{P(0) + R(0)}{2} + W(2) \]

2N:
\[ A(0.79) = \frac{P(0.81) + R(0) + W(0)}{2} \]

2O:
\[ A(0.21) = \frac{P(0.139 + \frac{0.008}{2} + 0.043)}{2} + \frac{W}{2} \]

Inert (mass):
F (0.04) = R (0.90)

From 2N:
\[ A = \frac{100(0.81)}{0.79} = 102.53 \text{ kg mol} \]

From 2O:
\[ W = 5.863 \text{ kg mol} \]

From H:
\[ F = 196.98 \text{ kg} \]

From inert, R = 8.7548 kg

H in:
\[ \frac{196.98(0.06)}{2} = 5.94 \]

O₂ in:
\[ \frac{5.94}{2} = 2.96 \]

(continued)

Solutions Chapter 10

C in = \[ \frac{196.98(0.90)}{12} = 14.77 \]

Step 10:

Check via C:
\[ 196.98 (0.90)/12 = 100 (0.147) + (8.7548 (0.10)/12) \]

ok

Required O₂:
\[ 14.7 + (5.863/2) = 17.63 \text{ kg mol} \]

Total O₂ in = 102.53 (0.21) = 21.53

Excess \[ (21.53 - 17.63)/17.63 = 0.221 \text{ or } 22\% \]

Alternate solution using extent of reaction:

\[
\begin{align*}
C + O₂ \rightarrow CO₂ & \quad (1) \\
C + \frac{1}{2}O₂ \rightarrow CO & \quad (2) \\
2H₂ + \frac{1}{2}O₂ \rightarrow H₂O & \quad (3)
\end{align*}
\]

\[ \text{CO}_₂: \quad n^*_{\text{CO}_₂} = 13.9 = n^*_{\text{CO}_₂} = (1) \xi_1 \]

\[ \xi_1 = 13.9 \]

\[ \text{CO:} \quad n^*_{\text{CO}} = 0.8 = n^*_{\text{CO}} = (1) \xi_1 \]

\[ \xi_1 = 0.8 \]

\[ \text{N₂:} \quad n^*_{\text{N₂}} = 81.0 = n^*_{\text{N₂}} \quad A = 102.5 \text{ mol} \]

\[ n^*_{\text{N₂}} = 0.21(102.5) = 21.5 \text{ mol} \]

\[ \text{O₂:} \quad 4.3 = 21.5 + (-1)(\xi_1) + (-\frac{1}{2})(\xi_1) + (-\frac{1}{2})(\xi_1) \quad \xi_1 = 2.90 \]

\[ \text{C:} \quad 0 = n^*_{\text{C}} + (-1)(13.9) + (-1)(0.8) \quad n^*_{\text{C}} = 14.7 \text{ mol} \]

\[ \text{H:} \quad 0 = n^*_{\text{H}} + (-2)(2.90) \quad n^*_{\text{H}} = 5.80 \text{ mol (some round off)} \]
10.19
Basis: 100 mol F

\[ F = 100 \text{ mol}, \quad \text{Moles} = \% \]

\[ \begin{align*}
\text{CH}_4: & \quad 60 \\
\text{C}_2\text{H}_4: & \quad 20 \\
\text{CO:} & \quad 5 \\
\text{O}_2: & \quad 5 \\
\text{N}_2: & \quad 10
\end{align*} \]

\[ \begin{align*}
\text{Moles} & \quad 281.25 & \quad \Sigma = P \\
0.21 \quad \text{O}_2 & \quad 1058 & \quad \Sigma = 1.00
\end{align*} \]

50% vs air: Calculate O₂ and N₂ in with the air in

\[ \begin{align*}
\text{CH}_4 + 2\text{O}_2 & \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \\
\text{C}_2\text{H}_4 + 3\frac{1}{2} \text{O}_2 & \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O} \\
\text{CO} + \frac{1}{2} \text{O}_2 & \rightarrow \text{CO}_2
\end{align*} \]

Less O₂ in gas

\[ \begin{align*}
\text{read O}_2 \text{ (mole)} & \quad 60 \times 2 = 120 \\
\text{20(3.5)} & = 70
\end{align*} \]

\[ \begin{align*}
5.00 & \\
\text{Net required O}_2 & \quad 187.5 \\
\text{xs O}_2 & \quad 187.5 \times .5 = 93.75 \\
\text{Total} & \quad 281.25
\end{align*} \]

\[ \begin{align*}
\text{N}_2 \text{ in with O}_2 & \quad 281.25 \times 0.79 \\
& \quad 0.21 = 1058
\end{align*} \]
### Solutions Chapter 10

**10.20**

<table>
<thead>
<tr>
<th>mole fr</th>
<th>mol fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>0.70</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>0.05</td>
</tr>
<tr>
<td>CO</td>
<td>0.15</td>
</tr>
<tr>
<td>O₂</td>
<td>0.05</td>
</tr>
<tr>
<td>N₂</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Flare Diagram

- **Fuel** (CH₄, C₂H₆, CO, O₂, N₂)
- **Flare Gas** (CO₂, H₂O)
- **Air** (O₂, N₂)

### Mol frs

<table>
<thead>
<tr>
<th></th>
<th>mol frs</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>0.21</td>
</tr>
<tr>
<td>N₂</td>
<td>0.79</td>
</tr>
<tr>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

### Unknowns A, F, P, x₀₂, xₙ₂

Pick F = 100 as basis

**Balances:** C, H, O, N (is one redundant?) plus 0.0773 + 0.1235 + x₀₂ + xₙ₂ = 1

### Balances:

- **C:**
  \[ 100 \times 0.70 + 100 \times 0.05 \times 3 + 100 \times 0.15 = P \times 0.0773 \]
- **N₂:**
  \[ 100 \times 0.05 + 0.79 \times A = P \times xₙ₂ \]
- **H₂:**
  \[ 100 \times 0.70 \times 2 + 100 \times 0.05 \times 4 = P \times 0.1235 \] (redundant with C)
- **O₂:**
  \[ 100 \times 0.15 \times \frac{1}{2} + 100 \times 0.05 + A \times (0.21) = P \left[ (0.0773) + \frac{0.1235}{2} + x₀₂ \right] \]

### Solve C (or H₂) balance for P:

P = 1294

### Solve N₂, O₂ and Σxᵣ = 1

Simultaneously for A, x₀₂, xₙ₂

---

A = 1203 moles  \[ x₀₂ = 0.0648 \] and \[ xₙ₂ = 0.7344 \] (not needed)

**Calculation of the required O₂**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Required O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄ + 2O₂ → CO₂ + 2H₂O</td>
<td>70(2) = 140</td>
</tr>
<tr>
<td>C₂H₆ + 5O₂ → CO₂ + 4H₂O</td>
<td>5(5) = 25</td>
</tr>
<tr>
<td>CO + ( \frac{1}{2} )O₂ → CO₂</td>
<td>15(( \frac{1}{2} )) = 7.5</td>
</tr>
</tbody>
</table>

**O₂ present in F**

\[ \frac{-5.0}{167.5 \text{ reqd}} \]

A(0.21) = 252.54 O₂ in

less 167.5 reqd O₂
85.04 xs O₂

85.04 (100) = 51% of 167.5
10.21

Steps 1, 2, 3, 4:

\[
\begin{array}{c|c|c|c|c}
& \text{mol fr.} & \text{mol fr.} & \text{mo} & \text{calculated} \\
\hline
\text{F} = 100 \text{ (basis)} & & & & \\
\text{mol} & \text{O}_2 \text{ react} & \text{CO}_2 & \text{x} & 0.143 & 31.96 \\
\text{CO} & 13.54 & 6.77 & & & \\
\text{CO}_2 & 15.22 & & & & \\
\text{H}_2 & 15.01 & 7.505 & & & \\
\text{CH}_4 & 2.60 & 6.40 & & & \\
\text{N}_2 & 22.03 & & & & \\
\text{100.00} & 20.675 & & 0.21 & 0.29 & \text{O}_2 \\
\end{array}
\]

Step 5: Basis: 100 mol F

Step 6: Unknowns: P, x, y, z

Step 7: Balances C, H, O, N ok

Steps 8 and 9:

Air in is based on complete combustion

\[
\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2 \text{ and CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}
\]

\[
\begin{align*}
x \cdot \text{O}_2 &= 0.40 (20.675) = 8.27 \\
\text{reqd O}_2 &= 20.675 - 28.945 = 28.945 \\
\text{total O}_2 &= 28.945 \\
\text{N}_2 \text{ in with air} &= 28.945 \left(\frac{79}{21}\right) = 108.89 \text{ mol} \\
\text{Air} &= [137.84 \text{ mol}]
\end{align*}
\]

Balance

\[
2\text{N}_2 \text{ out} = 108.89 + 53.03 = 161.92 \text{ mol}
\]

(continued)
Solutions Chapter 10

2O balance: \( F \left( \frac{1}{2} \right) + (0.21)A = B \left( \frac{1}{2} \right) + W \left( \frac{1}{2} \right) + 3.95 \)

Solution:
- \( B = 44.1 \) mol
- \( F = 46.9 \) mol
- \( W = 40.2 \) mol

\[
\begin{array}{c|c|c|c|c}
44 \text{ mol acet.} & 44 \text{ kg acet.} & 100 \text{ mol } P & 1 \text{ kg mol EtOH} & 46 \text{ kg} \\
100 \text{ mol } P & 1 \text{ kg mol acet.} & 46.9 \text{ mol EtOH} & & 0.892 \text{ kg acetaldehyde}
\end{array}
\]

kg ethanol

Alternate solution: Use extent of reaction and species balances, but it is more complicated.

---

10.23

Steps 2, 3, and 4:

![Diagram](image)

Step 5:
Basis: 100 mols feed; assume complete combustion

Step 4:
Equations:
- \( \text{CS}_2 + 3\text{O}_2 \rightarrow \text{CO}_2 + 2\text{SO}_2 \)

\( \text{O}_2 \) required: \( \frac{40 \text{ mol CS}_2}{1} : \frac{3 \text{ mol } \text{O}_2}{1 \text{ mol CS}_2} = 120.0 \text{ mol } \text{O}_2 \)

---

Solutions Chapter 10

\[ \% \text{ excess} = \frac{\text{O}_2 \text{ excess}}{\text{O}_2 \text{ required}} \times 100 = \% \text{ excess} \]

Steps 6, 7, 8 and 9:

5 unknowns and 5 equations → unique solution

<table>
<thead>
<tr>
<th>Component</th>
<th>Mol in</th>
<th>Mol out</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>40.0</td>
<td>( P \times x_{r_0} )</td>
</tr>
<tr>
<td>2S</td>
<td>( \frac{1}{2}(10.0) + 40.0 )</td>
<td>( \frac{1}{2}(0.02)P )</td>
</tr>
<tr>
<td>2O</td>
<td>( 10.0 + \frac{1}{2}(50.0) + 0.21A )</td>
<td>( (x_{r_O} + 0.02 + x_{r_O})P + \frac{1}{2}W )</td>
</tr>
<tr>
<td>2N</td>
<td>0.79A</td>
<td>( (1-x_{r_N}, -0.02 - x_{r_N})P )</td>
</tr>
<tr>
<td>2H</td>
<td>50.0</td>
<td>W</td>
</tr>
</tbody>
</table>

\( P = \frac{2(45.0)}{.02} = 4500 \)

\( x_{r_O} = 0.0089 \)

\[ \% \text{ Excess} = \frac{0.1829(4500 \text{ mol O}_2)}{120 \text{ mol}} = 68.6\% \]

Alternate solution: Use extent of reaction and species balances.

(continued)
10.24

Steps 2, 3 and 4:

\[ \begin{align*}
F &: \text{Fuel mass fr.} \\
C &: 0.74 \\
H &: 0.14 \\
\text{ash} &: 0.12 \\
\text{air} &: \frac{0.21}{1.00} \\
\text{N}_2 &: 0.79 \\
\text{O}_2 &: 0.100 \\
\text{W} &: \text{Flue gas mass fr.} \\
H_2O &: 1.00 \\
\text{CO}_2 &: \frac{12.4}{1.00} \\
\text{CO} &: \frac{1.2}{1.00} \\
\text{N}_2 &: \frac{5.7}{1.00} \\
\text{P} &: \text{mg} \\
\end{align*} \]

Step 5: Basis: \( P = 100 \text{ mol} \)

Step 6: Unknowns: \( F, A, R, W \), a discrepancy unless one

Step 7: Balances: \( C, H, O, N, \text{ash} \), balance is not independent

Step 8 and 9: all balances in moles

C balance: \( F(0.74) / 12 = 12.4 + 1.2 = 13.6 \)

\( F = \frac{(13.6)(12)}{0.74} = 220.5 \text{ lb} \)

2N balance: \( A(0.79) = 80.7 \quad A = 102.2 \text{ mol} \)

2H balance: \( F(0.14) / 2 = W; \quad W = 15.44 \text{ mol} \)

2O balance: \( A(0.21) = W \frac{(1.00)}{2} + 12.4 + \frac{1.2}{2} + 5.7 \) (continued)

21.46 = 26.42 not equal hence

Some discrepancy exists

A total balance can be used, but must be in mass, and the mass of P calculated.

10.25

Basis: 100 moles exhaust gas

\[
\begin{array}{ccc}
\text{Comp} & \text{exhaust gas mol} & \text{exit gas} \\
\text{CO}_2 & 16.2 & \text{tie element} \\
\text{O}_2 & 4.8 & 83.8 \\
\text{N}_2 & 79.0 & 100.0 \\
\text{Total} & 100.0 & 13.1 \\
& 1.0 & 16.2 \\
\end{array}
\]

\[ 16.2 \text{ mol CO}_2 \quad 100.0 \text{ mol exit gas} \]

100.0 mol exhaust gas

13.1 mol CO\(_2\) = 123.6 mol exit gas

Exhaust gas = 100.0 mol

Air leaked in = 23.6 mol

\[ \frac{23.6}{100.0} = 0.236 \text{ mol air / mol exhaust gas} \]
10.26

Steps 2, 3, and 4:

\[
\begin{align*}
\text{H}_2\text{O} & \quad 100\% \\
\text{Sludge mass} & \quad \text{mol} \\
\text{mass frac} & \quad \text{W}_\text{mol} \\
\text{C} & \quad 0.40 \\
\text{S} & \quad 0.32 \\
\text{H}_2 & \quad 0.04 \\
\text{O}_2 & \quad 0.24 \\
\text{1.00} & \quad \text{mol frac} \\
\text{F} & \quad \text{mass} \\
\text{Fuel oil lb} & \quad \text{100.00} \\
\text{CO} & \quad 2.02 \\
\text{CO}_2 & \quad 10.14 \\
\text{O}_2 & \quad 4.65 \\
\text{N}_2 & \quad 81.67 \\
\text{SO}_2 & \quad 1.52 \\
\end{align*}
\]

Step 5:

Basis: 100 mol P

Steps 6 and 7:

Unknowns: S, W, F (or m_W), A, m_C

Element Balances: S, C, H, O, N

Element Balances (moles):

\[
\begin{align*}
\text{S:} & \quad \frac{0.32 \times \text{S}}{32} = 1.52 & \quad \text{S = 152 lb} \\
2 \text{N:} & \quad \text{A} = 81.67 & \quad \text{A = 103.38 lb mol (2998.01 lb)} \\
\text{C:} & \quad \text{m}_\text{C} = 85.12 \text{ lb} \\
\end{align*}
\]

(continued)

10.27

Basis: 1 min

\[
\begin{align*}
\text{[CaO]}_\text{in} & = \frac{1000 \text{ gal}}{\text{min}} \cdot \frac{1.05 \times 62.4 \text{ lb soln}}{7.48 \text{ gal}} = 0.02 \text{ lb H}_2\text{SO}_4 \cdot \text{mol H}_2\text{SO}_4 \cdot \text{mol CaO} \\
\text{mol CaO} & = 56.1 \text{ lb CaO} \cdot \frac{100.3 \text{ lb CaO}}{\text{mol CaO}} \\
\text{Feed rate of CaO} & = 1.2 \times 120.4 \text{ lb CaO/min} \\
\end{align*}
\]

(continued)
Solutions Chapter 10

\[
\text{CaSO}_4 \text{ production rate} = \frac{100.3 \text{ lb CaO}}{\text{min}} \times \frac{\text{mol CaO}}{36.1 \text{ lb CaO}} \times \frac{\text{mol CaSO}_4}{\text{136.1 lb CaSO}_4} \times \frac{\text{ton}}{\text{2000 lb}}
\]

\[
\times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{d}} \times \frac{365 \text{ d}}{\text{yr}} = 63,947 \text{ ton/yr}
\]

10.28

Basis: 100 mol of product gas

\[\text{NH}_3 + 2\text{O}_2 \rightarrow \text{HNO}_3 + \text{H}_2\text{O}\]

The product gas from such a reactor has the following composition (water free basis):

- 0.8% \(\text{NH}_3\)
- 9.5% \(\text{HNO}_3\)
- 3.8% \(\text{O}_2\)
- 85.9% \(\text{N}_2\)

Determine the percent conversion of \(\text{NH}_3\) and the percent excess air used.

\[n_{\text{NH}_3}^{\text{in}} = n_{\text{NH}_3}^{\text{in}} + \xi \cdot n_{\text{NH}_3}^{\text{in}} \quad (9.5)\]

\[0.8 = n_{\text{NH}_3}^{\text{in}} + (-1)(9.5)\]

\[F = n_{\text{NH}_3}^{\text{in}} = 0.8 + 9.5 = 10.3 \text{ mol}\]

\[\frac{n_{\text{NH}_3}^{\text{in}} - n_{\text{NH}_3}^{\text{out}}}{\xi} = \xi\]

For \(\text{HNO}_3\):

\[\frac{9.5 - 0}{1} = 9.5 = \xi\]

Percent conversion \(f = (100\%) \quad \frac{\xi}{F} = 92.2\% \quad (continued)\]

Solutions Chapter 10

Calculate the entering oxygen using a \(\text{N}_2\) balance:

\[\text{N}_2: \quad 0.79A = 85.9; \text{ therefore, } A = 108.73 \text{ mol}\]

Calculate the theoretical \(\text{O}_2\) needed for the reaction

\[(\text{O}_2)_{\text{theor}} = 2 \times 10.3 = 20.6 \text{ mol}\]

Feed rate of \(\text{O}_2 = 0.21A = 22.83 \text{ mol}\)

% Excess \(\text{O}_2 = \left(\frac{22.83-20.6}{20.6}\right)\times 100 = 10.84\%\)

10.29

Basis: 100 mol of product gas (20.5%, \(\text{C}_3\text{H}_4\O\); 72.7 \(\text{N}_2\); 2.3 \(\text{O}_2\) and 4.5%\(\text{CO}_2\))

\[\text{C}_3\text{H}_4 + \frac{1}{2} \text{O}_2 \rightarrow \text{C}_3\text{H}_6\text{O}\]

\[\text{C}_3\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}\]

Calculate \(\xi_1\) : \[\xi_1 = \frac{n_{\text{NH}_3}^{\text{in}} - n_{\text{NH}_3}^{\text{out}}}{\xi_1} \quad \text{Use } \text{C}_3\text{H}_4\text{O}: \quad \xi_1 = \frac{20.5 - 0}{1} = 20.5\]

Calculate \(\xi_2\) : \[\text{Use } \text{CO}_2: \quad \xi_2 = \frac{4.5 - 0}{2} = 2.25\]

Calculate the entering air using a \(\text{N}_2\) balance:

\[\text{N}_2: \quad 0.79A = 72.7; \text{ therefore, } A = 92.03 \text{ mol}\]

Calculate the moles of \(\text{C}_3\text{H}_4\) entering (F)

\[n_{\text{NH}_3}^{\text{in}} - n_{\text{NH}_3}^{\text{out}} = \xi_1 \cdot n_{\text{NH}_3}^{\text{in}} + \xi_2 \cdot \xi_1 \]

\[0 - F = -\xi_2 - \xi_1 \quad \text{hence } F = 22.75\]

(continued)
O₂ feed rate = 0.21A = 19.33 mol

(O₂)O₂feed = F/2 = 11.375 mol

% Excess O₂ = [(19.33-11.375)/11.375](100) = 70.0%

To get the ethylene feed:

\[
\frac{22.75 \text{ C}_2\text{H}_4}{\text{ yr}} \cdot \frac{100,000 \text{ ton C}_2\text{H}_4\text{O}}{\text{ yr}} = \frac{2000 \text{ lb C}_2\text{H}_4\text{O}}{\text{ mol C}_2\text{H}_4\text{O}} \cdot \frac{44 \text{ lb C}_2\text{H}_4\text{O}}{\text{ mol C}_2\text{H}_4\text{O}}
\]

\[
\times \frac{\text{ yr}}{365 \text{ d}} \cdot \frac{\text{ d}}{24 \text{ h}} = \frac{28 \text{ lb C}_2\text{H}_4}{\text{ mol C}_2\text{H}_4}\]

\[
\frac{\text{ lb C}_2\text{H}_4}{\text{ c}} = \frac{16.123 \text{ lb C}_2\text{H}_4}{\text{ h}}
\]

10.30 Assume ammonia and glucose (MW = 180.1) are fed in stoichiometric proportions.

The reaction equation has to be set up and balanced to use the value given of 60% (mole assumed) conversion of glucose.

\[
a \text{ C}_6\text{H}_12\text{O}_6 + b \text{ NH}_3 \rightarrow c \text{ CH}_4\text{O}_x\text{N}_y + d \text{ C}_2\text{H}_4\text{O} + e \text{ CO}_2 + f \text{ H}_2\text{O}
\]

Pick a basis of 4.6 kg of EtOH (C₂H₄O₂, MW = 46.07)

\[
\frac{4600 \text{ g EtOH}}{46.07 \text{ g EtOH}} = 100 \text{ g mol EtOH produced}
\]

To balance the chemical reaction equation use element balances. Take a basis of \(a = 1\). Assume 60% conversion of the glucose means that 1 mole of glucose produces 0.6 mol of ethanol, not that one mole of glucose produces 3 mol of ethanol.

C: \(6e + c = 2d + e\)

H: \(12 + 3b = 1.8c + 6d + 2f\)

O: \(6 = 0.5c + d + 2e + f\)

N: \(b = 0.2c\)

Specifications 0.60 = d (continued)

Results

\[
a = 1 \text{ (the basis)} \quad d = 0.6
\]

\[
b = 0.8 \quad e = 0.8 \quad c = 4 \quad f = 1.6
\]

\[
167 \text{ g mol C}_2\text{H}_4\text{O}_6 \quad 0.08 \text{ g mol NH}_3 = 133.6 \text{ g mol NH}_3
\]

\[
167 \text{ g mol C}_2\text{H}_4\text{O}_6 \quad 180.1 \text{ g mol C}_2\text{H}_4\text{O}_6 = 30,076 \text{ g} \quad \text{ or} \quad 30.1 \text{ kg C}_2\text{H}_4\text{O}_6
\]

\[
133.6 \text{ g mol NH}_3 \quad 17.03 \text{ g NH}_3 = 2,275 \text{ g} \quad \text{ or} \quad 2.28 \text{ kg NH}_3
\]

10.31

Basis: \(F = 100 \text{ lb given in Example 10.9}\)

This basis gives \(P = 50 \text{ lb moles} \). Note: If the problem calculations were done because of the stated additional reactions, the value of \(P = 50 \text{ for two significant figures would not change. Similarly, the other values of the moles in P would not change. Thus, the SO}_2 + \text{ CO}_2 \text{ is } 0.134 (50) = 7.7 \text{ lb mol. The values of the pertinent components (for NO}_x \text{ use NO}_x) \text{ for this problem are}\)

\[
\begin{array}{cccccc}
\text{Component} & \text{lb mol} & \text{MW} & \text{kg} & \text{ELU/kg} & \text{ELU} \\
\hline
\text{NO}_x & (0.0024) (80.6) & = & 0.193 & 2.2 & 0.22 & 0.93 \\
\text{CO}_2 & (0.0018) (7.7) & = & 0.090 & 28 & 2.52 & 0.27 & 0.68 \\
\text{SO}_2 & (0.014) (7.7) & = & 0.002 & 64 & 0.128 & 0.09 & 0.012 \\
\text{CO}_2 & (0.986) (7.7) & = & 7.59 & 48 & 364 & 0.10 & 36.4 \\
\hline
\text{Total} & & & \text{38.0} & \\
\end{array}
\]

the total lb mol of nitrogen (N) entering is \(2(50) (0.806) + 0.001 = 80.6\)
### 11.1
2 (The two overall balances on A and B sum up to the overall balance on the system)

### 11.2
4 (such as 2 component balances for each unit)

### 11.3
<table>
<thead>
<tr>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit I involves A, B, C</td>
</tr>
<tr>
<td>Unit II involves D, E</td>
</tr>
<tr>
<td>Unit III involves A, B, C, D</td>
</tr>
</tbody>
</table>

Number of independent balances 9

If A and B are always combined in the same ratio, then you have to reduce the independent balances by 1 for Unit I and 1 for Unit III, a total of 2.

### 11.4
Six independent equations if all compositions are known. The sum of the components (in moles) would equal the total flow, hence not all of the equations that could be written would be independent, only 2 per subsystem.

#### Total balances:

**Condenser**

\[ F_2 = F_4 + F_5 \]  
(F3 does not mix, hence cancels out or can be omitted)

### 11.5

#### Unknowns:

- stream flows including F: 6
- Mass fractions (7 plus 3 in F): 10 16

#### Independent material balances:

- Species in 1:3
  - 2:2
  - 3:3

#### Other independent equations:

\[ \sum \omega_i = 1 \text{ in each stream including F} \]  
8 16

### Solutions Chapter 11

\[ F_1 + F_5 + F_9 = F_2 + F_8 \]

**Reboiler**

\[ F_6 = F_9 + F_7 \]  
(F6 does not mix, hence cancels out or can be omitted)

**Component balances:**

In addition, (2) component balances could be written for each component for each subsystem cited above. Multiply \( F_i \) by the composition \( x_{ik} \).
11.6

Basis: \( F = 100 \text{ kg} \)  \( m = \text{mass fraction} \)

\[
\begin{array}{c|c|c|c|c}
\text{mass fr} & \text{A} & \text{B} & \text{C} & \text{1.00} \\
\hline
\text{A} & 0.60 & & & \\
\text{B} & & 0.85 & & \\
\text{C} & 0.20 & & 1.00 & \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\text{\% = kg} & \text{A} & \text{B} & \text{C} & \text{1.00} \\
\hline
\text{A} & 15 & & & \\
\text{B} & & 30 & & \\
\text{C} & & 35 & & \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\text{mass fr} & \text{A} & \text{B} & \text{C} & \text{1.00} \\
\hline
\text{A} & 0.002 & & & \\
\text{B} & m_1^A & & & \\
\text{C} & m_1^C & & 1.00 & \\
\hline
\end{array}
\]

(a) SEPARATE ANALYSIS

Column (1) balances

(1) A: 015(100) = \( W_1 (m_1^A) + P_1 (0.60) \) any 3 are indept. eqns.
(2) B: 0.30(100) = \( W_2 (m_1^B) + P_1 (0.20) \) 4 indept. eqns.
(3) C: 0.55(100) = \( W_2 (m_1^C) + P_1 (0.20) \)
100 = \( W_1 + P_1 \) indept. eqns.
(4) \( m_1^A + m_1^B + m_1^C = 1 \) unknowns:
\( W_1, P_1, m_1^A, m_1^B, m_1^C \)  5 unknowns

5 - 4 = 1 degree of freedom
ANALYSIS OF OVERALL SYSTEM

System overall balances

(1) A: 100 (0.15) = \( P_1 \) (0.60) + \( P_2 \) (0.10) + 20 (0.002)
(2) B: 100 (0.30) = \( P_1 \) (0.20) + \( P_2 \) (0.85) + 20 (m_b)
(3) C: 100 (0.55) = \( P_1 \) (0.20) + \( P_2 \) (0.05) + 20 (m_c)

4 indept. equ. 3

\[ 0.002 + m_b + m_c = 1 \]

Unknowns: \( P_1 \), \( P_2 \), \( m_b \), \( m_c \) 4 unknowns

4 - 4 = 0 degrees of freedom as expected

11.7

The results show that the system of equations is very sensitive to small perturbations in the coefficients (measurements).
11.8

Basis: 1 hr (1000 kg)

a. Overall balances:

Total: \(1000 = W + D\)
Salt: \(1000 (0.0345) = 0 + 0.069D\)

\[W = 500 \text{ kg} \quad D = 500 \text{ kg}\]

b. Salt balance on the freezer:

\(1000 (0.0345) = 0 + 0.048B\)

\[B = 718.75 \text{ kg}\]

Total balance on the freezer:

\(1000 = A + B\)

\[A = 281.25 \text{ kg}\]

Total balance around filter:

\(B = 718.75 = C + D\)

\[C = 218.75 \text{ kg}\]

11.9

Basis: 220g IgG from the reactor

Fraction recovered = \(\frac{140}{220} = 0.64\)

Solutions Chapter II

11.10

Steps: 1, 2, 3, and 4: This is a steady state process with no reaction taking place. All the compositions are known except for stream C. We can pick the overall system first to get D, and then make balances on the first (or second) units to get C and its composition.

Step 5: Basis: \(F = 290 \text{ kg (equivalent to 1 second)}\)

Step 6: Unknowns: A, B, C, D and E and the composition of C

Step 7: Balances: NaCl, HCl, H₂SO₄, H₂O, inert solid

Step 8: For the overall system there are 4 unknowns (C is excluded) and 5 species balances:

Overall balances (kg)

<table>
<thead>
<tr>
<th></th>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>A(0.040)</td>
<td>= 290(0.0138)</td>
</tr>
<tr>
<td>HCl</td>
<td>A(0.050)</td>
<td>= 290(0.0255)+D(0.020)+E(0.015)</td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>A(0.040)</td>
<td>= 290(0.0221)+D(0.020)+E(0.015)</td>
</tr>
<tr>
<td>H₂O</td>
<td>A(0.870)+B(0.910)</td>
<td>= 290(0.9232)+D(0.960)+F(0.970)</td>
</tr>
<tr>
<td>Inerts</td>
<td>B(0.09)</td>
<td>= 290(0.0155)</td>
</tr>
<tr>
<td>Totals</td>
<td>A + B</td>
<td>= D + E + 290</td>
</tr>
</tbody>
</table>

Steps 6 and 7:

Two of the equations are not independent: HCl and H₂SO₄.

HCl: \(D(0.020) + E(0.015) = 7.40 - 5.00 = 2.40\)

H₂SO₄: \(D(0.020) + E(0.015) = 6.41 - 4.00 = 2.41\)

Thus, overall the degrees of freedom are 0.

Steps 8 and 9:

The solution of the equations is (in kg/s) (continued)
Additional Equations: $\omega_x^e = \omega_x^f$ and $\omega_y^e = \omega_y^f$ (the related equations for benzene are redundant). Total equations = 8.

The solution is simplified if two balances are made first (not an essential step): All material balances are in kg.

Solids balance on Unit 2 and also Unit 1:

$2000 \times 0.9 = F_1 \times 0.9 \quad F_1 = 2000$

$2000 \times 0.9 = F_3 \times 0.9 \quad F_3 = 2000$

Total balance on Unit 1 and also Unit 2:

$2000 + S_1 = 2000 + S_2 \quad S_1 = S_2$

$1000 + 2000 = 2000 + S_1 \quad S_1 = 1000$

$S_2 = 1000$

The other balances are:

Unit 2:

Benzene: $1000(1 - \omega_x^e) = 2000(1 - \omega_x^f) + 1000(1 - \omega_x^f)$

Xylene: $2000(0.1) + 1000\omega_x^f = 2000\omega_y^f + 1000\omega_y^f$

$10\omega_y^f = \omega_y^f$

Unit 1:

Benzene: $1.0(1000) + 2000(1 - \omega_x^e) = 2000(1 - \omega_x^f) + 1000(1 - \omega_x^f)$

Xylene: $0 + 2000\omega_x^e = 2000\omega_x^f + 1000(\omega_y^f)$

$10\omega_x^e = \omega_x^f$

Solve the equations to get the compositions of the streams:

(continued)
### Solutions Chapter 11

<table>
<thead>
<tr>
<th>Stream</th>
<th>Component</th>
<th>wt fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(^0)</td>
<td>Bz 1.0</td>
<td>F(^0)</td>
</tr>
<tr>
<td></td>
<td>Xy 0.0</td>
<td></td>
</tr>
<tr>
<td>S(^1)</td>
<td>Bz 0.97</td>
<td>F(^1)</td>
</tr>
<tr>
<td></td>
<td>Xy 0.03</td>
<td></td>
</tr>
<tr>
<td>S(^2)</td>
<td>Bz 0.82</td>
<td>F(^2)</td>
</tr>
<tr>
<td></td>
<td>Xy 0.18</td>
<td></td>
</tr>
</tbody>
</table>

b) Xylene in Feed = \(2000 \times 0.1 = 200\) kg

Xylene in Product = \(1000 \times 0.18 = 180\) kg

\[
\% \text{ Recovery} = \frac{180}{200} \times 100 = 90\%
\]

11.12

Step 5: Basis: \(F = 100\) kg and \(D_3 = 10\) kg

Steps 2, 3, and 4:

### Solutions Chapter 11

![Diagram](image-url)

- \(A = 0.50\)
- \(B = 0.23\)
- \(C = 0.27\)
- \(D_1 = 0.17\)
- \(D_2 = 0.10\)
- \(D_3 = 0\)
- \(m^{\alpha}_A = 10\) kg

Additional information:

- \(P_3 = 3D_3 = 30\) kg
- \(P_2 = D_2\)
- \(m^{\alpha}_A = 4m^{\alpha}_B\)

Begin with overall balances.

Steps 6 and 7:

- Unknowns 4: \(D_1, D_2, m^{\alpha}_A, m^{\alpha}_B\)
- Balances (3): A, B, C (plus total)
- Implicit equation (1): \(m^{\alpha}_A + m^{\alpha}_B = 10\) kg
- Degrees of freedom = 0

Steps 8 and 9:

Overall balances

(continued)
Solutions Chapter 11

Total: \[ 100 = D_1 + D_2 + 10 + 30 \] or \[ 60 = D_1 + D_2 \]

C: \[ 100 (0.30) = 0.27D_1 + 0.73D_2 + 0 \]

Solve these two equations to get \( D_1 = 30 \) and \( D_2 = 30 \)

Get \( m_A^{D_1} \) and \( m_B^{D_1} \) from A balance and \( m_A^{D_2} - m_B^{D_2} = 1 \)

A: \[ 100(0.50) = 30(0.50) + 30(0.17) + 10m_A^{D_1} + 30(0.70) \] so, \( m_A^{D_1} = 0.89 \)

\[ m_A^{D_1} + m_B^{D_1} = 1 \] so \( m_B^{D_1} = 0.11 \)

Step 10: Note - Can check using the B balance (not independent)

Balances on Unit No. 3

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_A^{D_1} )</td>
<td>( m_A^{D_2} )</td>
<td>0</td>
</tr>
<tr>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\[ P_3 = 30 \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_A^{D_2} )</td>
<td>0.70</td>
<td>0</td>
</tr>
<tr>
<td>1.00</td>
<td>0.30</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_A^{D_3} )</td>
<td>0.80</td>
<td>0.20</td>
</tr>
<tr>
<td>1.00</td>
<td>4m_B^{D_2}</td>
<td></td>
</tr>
</tbody>
</table>

\[ 30(0.80) + 10m_A^{D_3} = 29.9 \] so that \( m_A^{D_3} = 0.59 \) or 59%

\[ m_A^{D_3} + m_B^{D_3} = 1 \]

\[ m_B^{D_3} = 0.41 \] or 41%

Steps 6 and 7:

(D2 = 10; P3 = 30)

Solutions Chapter 11

Unknowns (5): \( E, m_A, m_B, m_C, m_D, m_E \)

Balances (2): \( A, B \)

Implicit equations (2): \( m_A + m_B = 30, m_A + m_B = E \)

Other equations: \( m_B = 4m_A \)

Steps 8 and 9:

Total: \( 30 + E = D_3 + P_3 = 10 + 30 = 40 \) so \( E = 10 \) kg

One component balance:

\[ \begin{align*}
& A: \quad 30m_A^{D_1} + 10m_A^{D_2} = 10(0.89) + 30(0.70) = 29.9 \\
& B: \quad 30m_B^{D_1} + 10m_B^{D_2} = 10(0.11) + 30(0.30) = 10.1 \\
& \sum m_i = m_A^{D_1} + m_B^{D_2} = 1 \\
& m_A^{D_1} = m_B^{D_2} = 0.80 \\
& m_A^{D_2} = 4m_B^{D_2} \\
& 30(0.80) + 10m_A^{D_1} = 29.9 \quad \text{so that} \quad m_A^{D_1} = 0.59 \quad \text{or 59%} \\
& m_A^{D_1} + m_B^{D_1} = 1 \\
& m_B^{D_1} = 0.41 \quad \text{or 41%}
\end{align*} \]

11.13

Two subsystems exist, hence 4 component balances can be written. No reaction occurs and the process is assumed to be in the steady state. Steps are omitted here. The balances are

System: Splitter

Total: \( R = E + P \)

Fiber: \( 2.34 = x^B + x^P \) (a)

Water: \( 7452 = 4161 + 3291 \)

System: Stock Chest

Total: \( P + N = L \)

Fiber: \( x^B + x^N = 103.26 \)

Water: \( 3291 + 18 = 3309 \) (continued)
Solutions Chapter 11

Also $N(0.15) = 18$ $N = 120$

$0.85$ (N) $= x^N = 0.85$ (120) (b)

Overall balances

$\text{Total: } R + N = E + L$

$\text{Fiber: } 2.34 + x^N = x^F + 103.26$ (c)

$\text{Water: } 7452 + 18 = 4161 + 3309$

Substitute (b) into (c), solve (c) for $x^F$, and then solve (a) for $x^E$:

$x^F = 102$ $x^F = 1.26$ $x^F = 1.08$ all in kg

11.14

Steps 1, 2, 3 and 4:

\[
\begin{align*}
\text{mol \%} & \\
64.29 & \text{H}_2 \\
14.29 & \text{SiCl}_4 \\
21.42 & \text{H}_2\text{SiCl}_3
\end{align*}
\]

HCl (g)

A

100% Si

100% Si

B

C

D

E

H$_2$SiCl$_3$

H$_2$SiCl$_3$

H$_2$SiCl$_4$

HCl, HSiCl$_3$

H$_2$Cl

Step 5: Basis: 100 kg B

100 kg Si $1$ kg mol Si $= 3560$ kg mol Si

28.09 kg Si

Steps 6 and 7: Unknowns: A, D, E

Balances: H, Cl, Si

Steps 8 and 9: Balances to be solved:

System: overall process

Si overall mole balance

$\text{kg mol Si} = 3.560$

$= D \text{kg mol gas} \left[ \frac{0.1429 \text{ kg mol SiCl}_4}{\text{kg mol gas}} \right] + 1 \text{ kg mol Si} + 0.2142 \text{ kg mol H}_2\text{SiCl}_3 + 1 \text{ kg mol Si}$

$= E \text{ kg mol HSiCl}_3 \left[ \frac{1 \text{ kg mol Si}}{\text{kg mol HSiCl}_3} \right] = 0.3571D + E$

Cl overall mole balance

$\text{A kg mol HCl} \left[ \frac{1 \text{ kg mol Cl}}{\text{kg mol HCl}} \right] = D \text{ kg mol gas} \left[ \frac{0.1429 \text{ kg mol SiCl}_4}{\text{kg mol Cl}} \right] + 4 \text{ kg mol Cl}$

$= 0.2142 \text{ kg mol H}_2\text{SiCl}_3 \left[ \frac{2 \text{ kg mol Cl}}{\text{kg mol H}_2\text{SiCl}_3} \right] + E \text{ kg mol HSiCl}_3 \left[ \frac{3 \text{ kg mol Cl}}{\text{kg mol HSiCl}_3} \right]$

$A = D + 3E$

H overall balance

(continued)
11.15

Step 5: Basis: 100 kg mol = F

Steps 1, 2, 3, 4:

Assume first an air leak occurs and use material balances to calculate the amount. This is a steady state flow process without reaction.

Overall system

Step 6: Unknowns are: A, B, W, P, x_N₂, x_CO₂ (or n_CO₂)

Step 7: Balances are: C, H, O, N, ∑ x_i = 1 (or ∑ n_i = P)

(continued)
Solutions Chapter 11

Step 8:

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (kg mol):</td>
<td></td>
</tr>
<tr>
<td>0.70(100) + 0.10(100)</td>
<td></td>
</tr>
<tr>
<td>n_{CO} = 90 kg mol</td>
<td>n_{CO} = n_{CO}</td>
</tr>
<tr>
<td>H (kg mol):</td>
<td></td>
</tr>
<tr>
<td>0.70(100)(4) + 0.20(100)(2) + 0.10(100)(6) = W(2)</td>
<td>= W(2)</td>
</tr>
<tr>
<td>W = 190 kg mol</td>
<td></td>
</tr>
<tr>
<td>2O (kg mol):</td>
<td></td>
</tr>
<tr>
<td>0.21A + 0.21B</td>
<td>= \frac{190(1.00)}{2} + 90 + 0.06P</td>
</tr>
<tr>
<td>2N (kg mol):</td>
<td></td>
</tr>
<tr>
<td>0.79A + 0.79B</td>
<td>= n_{N}</td>
</tr>
<tr>
<td>90 + 0.06P + n_{N}</td>
<td>= P</td>
</tr>
</tbody>
</table>

A balance about the furnace or about the duct is needed, or those two alone would have been sufficient, omitting the overall balance.

System: Duct

Step 6: Unknowns: A, E, n_{CO}, n_{O}, n_{H}_O

Step 7: Balances: C, H, O, N, \sum n_{x} = E

Steps 8 and 9:

| C (kg mol):  |             |
| 0.70(100) + 0.10(100) (2) | = n_{CO}   |
| n_{CO} = 90 kg mol |             |
| H (kg mol):  |             |
| 0.70(100)(4) + 0.20(100) (2) + 0.10(100) (6) = n_{H}_O | = n_{H}_O |
| n_{H}_O = 190 |             |
| 2O (kg mol): |             |
| 0.21A = n_{O} + 90 + \frac{190}{2} |             |
| 2N (kg mol): |             |
| 0.79A = n_{N} | = n_{N}   |
| 90 + 190 + n_{O} + n_{N} = E | = E       |

0.02 = \frac{n_{O}}{E}

From the overall 2N balance \begin{align*}
0.79(982) + 0.79B &= n_{N}^e \\
0.21(982) + 0.21B &= 185 + 0.06P
\end{align*}

(1) \begin{align*}
22.2 + 0.21B &= 0.06P \\
B &= 207 kg mol
\end{align*}

(3) \begin{align*}
90 + 0.79(982) + 0.79B &= 0.94P \\
P &= 1095 \text{ kg mol} \quad \text{207 kg mol / 100 kg mol F}
\end{align*}

11.16

Assume steady state process

Basis: 100 mol natural gas

(continued)
Solutions Chapter 11

**Comp.** | mol-% atoms C | atoms O | atoms H | Total
-----|---------------|--------|--------|--------
CH₄ | 96 | 96 | -- | 384
C₂H₂ | 2 | 4 | -- | 4
CO₂ | 2 | 2 | 4 | --
Total | 100 | 102 | 4 | 388

Basis: 100 mol oil

**Comp.** | atoms C | atoms H
-----|--------|--------
(CH₃)₈ | 100 | 180

Basis: 100 mol flue gas (dry)

**Comp. mol%** | mol C | mol O | atoms H | mol N₂
-----|-------|-------|--------|-------
CO₂ | 10.0 | 10.00 | 20.00 | --
CO | 0.63 | 0.63 | 0.63 | --
O₂ | 4.55 | -- | 9.10 | --
N₂ | 84.82 | -- | -- | 84.82
Total | 100.00 | 10.63 | 29.73 | --

Note: If have separate air streams, we have 5 unknowns and can't solve.

Basis: 100 mol natural gas (or use 100 mol dry gas product.)

Let F₂ = mol oil
F₁ or P = mol dry flue gas
A = mol air to natural gas fed boiler plus oil fed boiler
W = mol water associated with the dry flue gas

Four balances: In = Out

**C balance**

\[102 + F₂ = 0.1063 \times P \]

**N₂ balance**

\[0.79 \times A = 0.8482 \times P \]

**H balance**

\[388 + 1.80 \times F₂ = 2 \times W \]

**O balance**

\[4 + 0.42 \times A = 0.2973 \times P + W \]

\[P = 1729 \text{ mol dry flue gas} \]

\[W = 268 \text{ mol } H_2O \]

\[F₂ = 82 \text{ mol oil and } 1 \text{ mol C} = 1 \text{ mol oil so} \]

\[C \text{ in oil} = F₂ = 82 \text{ mol} \]

Total C = 102 + 82 = 184 mol

% C burned from oil = \[\frac{0.82 \times (100)}{184} = 44.5\%\]
11.17

Steady-state, reaction take place

\[ \text{Overall balances} \]

Steps 6 and 7:

5 unknowns: A, B, D, E, G
4 balances: Na, Cl, H, O
other equations: \( A/B = 30/70 \)

Steps 8 and 9:

(a) Percent conversion of salt to sodium hydroxide.

Basis: 1 lb product = H

\[ \begin{align*}
1 \text{ lb mol of NaOH:} & = 1.25 \times 10^{-2} \text{ lb mol NaOH} \\
1 \text{ lb mol NaCl:} & = 1.20 \times 10^{-3} \text{ lb mol NaCl}
\end{align*} \]

Conversion = \( \frac{1.25 \times 10^{-2}}{1.25 \times 10^{-2} + 1.20 \times 10^{-2}} \times 100 = 91.2\% \)

(b) How much chlorine gas is produced per lb of product?

\[ \text{lb mol NaOH} / \text{lb mol NaCl} = 70.9 \text{ lb Cl}_2 / 0.44 \text{ lb Cl}_2 / \text{lb product} \]

(c) \[ A = (1.25 \times 10^{-2} \text{ lb mol} + 1.20 \times 10^{-3} \text{ lb mol}) \times \frac{58.45 \text{ lb}}{\text{lb mol}} = 0.80 \text{ lb} \]

Using salt as a tie component:

\[ C = \frac{A}{0.30} = \frac{1}{0.30} \text{ 0.8 lb} = 2.67 \text{ lb} \]

\[ B = C - A = 2.67 - 0.8 = 1.87 \text{ lb} \]

Balance on oxygen:

\[ G = \frac{1.87 \text{ lb}}{18 \text{ lb}} + \frac{0.43 \text{ lb}}{18 \text{ lb}} + \frac{0.50 \text{ lb}}{40 \text{ lb}} = 1.22 \text{ lb} \]

11.18

Step 5: Basis = 100 lb A

Steps 2, 3, and 4:

Fe added: 36(100) = 3600 lb

\[ \begin{align*}
\text{MW TiO}_2 & = 79.9 \text{ lb/lb mol} \\
\text{MW H}_2\text{SO}_4 & = 98.1 \text{ lb/lb mol} \\
\text{MW TiOSO}_4 & = 159.7 \text{ lb/lb mol}
\end{align*} \]

(continued)
For Part (a), the system boundary has been drawn on a light solid line.

Steps 6 and 7:

Unknowns (9): B, C, J, K, H, F, $\xi_1$, $\xi_2$, $m_r$

Species balances (7): TiO$_2$, Fe, H$_2$SO$_4$, H$_2$O, TiOSO$_4$, O$_2$, inert

Other equations (2): Reactions 1 and 2 are complete

Degrees of freedom = 0

Steps 8 and 9

a. lb H$_2$O removed in evaporator (J):

\[
\text{Mol TiO}_2 \text{ in slag: } \quad \text{Mol Fe in Slag:}
\]

\[
\frac{(0.70)(100 \text{ lb})}{79.9 \text{ lb}} = 0.876 \text{ lb mol} \quad \frac{(0.80)(100 \text{ lb})}{58.8 \text{ lb}} = 0.143 \text{ lb mol}
\]

Amount of H$_2$SO$_4$ based on theoretical requirements of Equations (1) and (2)

\[
0.876 + 0.143 = 1.02 \text{ lb mol H}_2\text{SO}_4
\]

\[
\frac{1.02 \text{ lb mol H}_2\text{SO}_4}{98.1 \text{ lb}} = 100 \text{ lb H}_2\text{SO}_4
\]

\[
B = \frac{100 \text{ lb}}{0.67} = 149.2 \text{ lb} \quad \text{Water in stream } B = 49.2 \text{ lb}
\]

\[
\text{O}_3 \text{ in: } \frac{0.143 \text{ lb mol Fe}}{1 \text{ lb mol Fe}} = 0.5 \text{ lb mol O}_3
\]

\[
32 \text{ lb O}_3 = 2.29 \text{ lb O}_3 = \text{C} (0.0715 \text{ lb mol})
\]

Using TiO$_2$: $\xi_1 = \frac{0 - 0.876}{-1} = 0.876$ moles reacting

Using O$_3$: $\xi_2 = \frac{0 - 0.0715}{0.5} = 0.143$ moles reacting

TiOSO$_4$ in stream K

\[
\frac{n_k}{n_{\text{TiO}_2}} = 0 + (1)(0.876) = 0.876 \text{ lb mol TiOSO}_4
\]

\[
K = \frac{0.876 \text{ lb mol}}{1 \text{ lb mol} \times 0.82} = 170.6 \text{ lb}
\]

\[
\text{H}_2\text{O in } K = 170.6 (0.18) = 30.7 \text{ lb}
\]

Water formed in the reactions (use $\xi_1$ and $\xi_2$): (continued)
Solutions Chapter 11

\[ n_{\text{H}_2\text{O}}^{\text{in}} = (1)(0.876) + (1)(0.143) = 1.019 \text{ lb mol (or 8.36 lb H}_2\text{O)} \]

Water exiting from the evaporator J (lb):

\[ 49.2 + 18.36 - 30.7 = 36.9 \text{ lb} \]

b. Exit H\(_2\)O from dryer:

\[ \text{inlet air} = \frac{18 \text{ lb mol}}{29 \text{ lb}} = 0.617 \text{ lb mol} \]

\[ \text{inlet water} = \frac{0.036 \text{ mol H}_2\text{O}}{18 \text{ mol air}} = 0.002 \text{ mol H}_2\text{O} \]

\[ \text{water added to air} = (0.18)(170.9 \text{ lb}) - (0.876 \text{ lb mol}) = 15.0 \text{ lb} \]

Humidity = (15.0 lb H\(_2\)O + 11.7 lb H\(_2\)O)/522 lb air

\[ = 0.051 \text{ lb H}_2\text{O} / \text{lb air} \]

c. The pounds of TiO\(_2\) produced (P):

By reaction (3), 0.876 lb mol of TiOSO\(_4\) goes to TiO\(_2\).

(0.876)(79.9) = 70 lb TiO\(_2\)
### Solutions Chapter 11

**H (kg mol):**

\[
0.70 (100) + 0.20 (100) + 0.10 (100) = W(2)
\]

\[
W = 190 \text{ kg mol}
\]

**2O (kg mol):**

\[
0.21A + 0.21B = \frac{190(100) + 90 + 0.06P}{2}
\]

**2N (kg mol):**

\[
0.79A + 0.79B = \frac{p}{2}
\]

\[
90 + 0.06P + n_{N_2}^E = P
\]

A balance about the furnace or about the duct is needed; or these two alone would have been sufficient, omitting the overall balance.

**System: Furnace (or Duct)**

**Step 6: Unknowns:**

\[A, n_{CO}, n_{O_2}, n_{H_2O}, n_{N_2}\]

**Step 7: Balances:**

\[C, H, O, N_2, \sum n_i = E\]

**Steps 8 and 9:**

\[C (kg mol): 0.70 (100) + 0.10 (100) = 90 kg mol\]

\[H (kg mol): 0.70 (100) + 0.20 (100) + 0.10 (100) = 190\]

\[2O (kg mol): 0.21A = n_{O_2} + 90 + \frac{190}{2}\]

\[2N (kg mol): 0.79A = n_{N_2}\]

\[90 + 190 + n_{O_2} + n_{N_2} = E\]

### Solutions Chapter 11

**Solution:**

\[
\begin{array}{|c|c|c|}
\hline
\text{kg mol in E} & \text{kg mol} \\
\hline
n_{CO}^E & 90 & A & 982 \\
n_{H_2O}^E & 190 & E & 1077 \\
n_{O_2}^E & 21.5 & \\
n_{N_2}^E & 776 & 1077.5 & \\
\hline
\end{array}
\]

From the overall \(N_2\) balance:

\[
0.79 (982) + 0.79B = n_{N_2}^E \quad (1)
\]

O2 balance:

\[
0.21 (982) + 0.21B = 185 + 0.06P \quad (2)
\]

\[
\begin{align*}
(1) & \quad 22.2 + 0.21B = 0.06P \\
B & = 207 \text{ kg mol} \\
(3) & \quad 90 + (0.79)(982) + 0.79B = 0.94P \\
P & = 1095 \text{ kg mol} \\
\end{align*}
\]

It is an air leak.

\[
\frac{207 \text{ kg mol}}{100 \text{ kg mol P}}
\]
### Solutions Chapter 11

#### 11.20

<table>
<thead>
<tr>
<th>Stage</th>
<th>Activity (units)</th>
<th>Protein present (mg)</th>
<th>Specific Activity (units/mg)</th>
<th>Recovery (%)</th>
<th>Purification</th>
</tr>
</thead>
<tbody>
<tr>
<td>After breakage of cell</td>
<td>6,860</td>
<td>76,200</td>
<td>0.09</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>After adsorption/desorption step</td>
<td>6,800</td>
<td>2,200</td>
<td>3.1</td>
<td>99</td>
<td>34</td>
</tr>
<tr>
<td>After second adsorption/desorption step</td>
<td>5,300</td>
<td>267</td>
<td>19.9</td>
<td>78</td>
<td>213</td>
</tr>
</tbody>
</table>
12.1

a. 1; b. 3; c. 0; d. 7

---

Solutions Chapter 12

---

Solutions Chapter 12
12.2

Step 5: Basis: 60 kg W

Pick the overall system

Steps 6 and 7:

Unknowns: F, P
Balances: A, B

Steps 8 and 9:

Total F = 60 + P \rightarrow F = 380 kg
B: 0.80F = 0 + 0.95P \rightarrow P = 320 kg

Pick mixing point as the system

Steps 6 and 7:

Unknowns: G, R
Balances: A, B (or total as alternate)

Steps 8 and 9:

Total: 380 + R = G \rightarrow R = 126.7
B: 0.80(380) + R(0) - 0.60C \rightarrow G = 320

R = \frac{125.7}{380} = 0.33 \text{ kg R/kg F}

12.3

Basis: 100 kg of fresh feed

Overall balance around junction

100 + R = F

KCl balance around mixing point

20 + 0.6R = 0.4F = 0.4(100 + R)
20 + 0.6R = 40 + 0.4R

R = 100 kg \text{ R/100 kg fresh feed}

12.4

Steps 2, 3, and 4:
**Step 5**: Basic: 1 hr \((A = 5000 \text{ lb})

Select whole process as the system.

**Steps 6 and 7:**

Unknowns: \(B, D\)
Balances: Total, \(B_1, B_2, S\) (not all independent)

**Steps 8 and 9:**

Total balance: \(5000 = B + D\)

\(B_1\) balance: \(5000 \times 0.75 = B(1) + D(0.05)\)

\[D = 1316 \text{ lb} \quad B = 3684\]

Apparently the calculated values are not correct. (The value for \(C\) can be obtained from balances on Unit I or II).

**12.5**

Basis: 1 hour

An overall balance shows that \(R_{\text{out}}\) from the adsorber must equal \(R_{\text{in}}\) to the adsorber if a steady state exists. Let \(R_{\text{in}} = R\).

Adsorber balance of \(U\) (units are \(U\)):

\[
\frac{600 \text{ mL} \times 1.37U}{1 \text{ mL}} + \frac{R \text{ mL} \times 5.2U}{1 \text{ mL}} = \frac{600 \text{ mL} \times 0.08U}{1 \text{ mL}} + \frac{R \text{ mL} \times 9.3U}{1 \text{ mL}}
\]

\[600 \times (1.37 - 0.08) = R(19.3 - 5.2)\]

\[R = 55 \text{ mL/hr}\]
Solutions Chapter 12

Fresh air, Basis 100 mol

<table>
<thead>
<tr>
<th>mol</th>
<th>MW</th>
<th>mass (kg)</th>
<th>mass ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>95.68</td>
<td>2861.7</td>
<td>0.992</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.32</td>
<td>23.76</td>
<td>0.0082</td>
</tr>
<tr>
<td></td>
<td>100.00</td>
<td>2885.48</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Exit air, Basis 100 mol

<table>
<thead>
<tr>
<th>mol</th>
<th>MW</th>
<th>mass (kg)</th>
<th>mass ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>0.737</td>
<td>21.37</td>
<td>0.819</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.263</td>
<td>4.73</td>
<td>0.181</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>26.11</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Air entering dryer, basis 100 mol

<table>
<thead>
<tr>
<th>mol</th>
<th>MW</th>
<th>mass (kg)</th>
<th>mass ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>0.934</td>
<td>27.09</td>
<td>0.958</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.066</td>
<td>1.19</td>
<td>0.042</td>
</tr>
<tr>
<td></td>
<td>28.27</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

Overall balances (unknowns D, E, F; balances H₂O, cereal, air)

Total: can be made in mass: 1000 + F = E + D

Cereal (dry): 1000 (0.80) + F (0) = E (0) + D (0.950) \( \Rightarrow \) D = 842 kg

H₂O: 1000 (0.20) + F (0.0082) = E (0.181) + D (0.050)

air: 1000 (0) + F (0.992) = E (0.819) + D (0)

3 are independent eqns. check by 4th eqn.

a. \( D = 842 \) kg

E = 906 kg

Balance on mixing point (to get R)

Total: \( R + F = G \)

air: \( R (0.819) + F (0.992) = G (0.958) \)

H₂O: \( R (0.181) + F (0.0082) = G (0.042) \)

2 equations are independent, check via 3rd equation

b. \( R = 183 \) kg/hr

12.7

Steps 1, 2, 3 and 4:

\[ \begin{align*}
H₂O & \text{ 100%} \\
\text{Evaporator} & \\
\text{Feed} & \text{10,000 kg/hr} \text{ 20\%} \\
\text{Crystallizer} & \\
\text{Recycle 100 \%} \\
\text{KNO}_3 & \text{Solution} \\
\text{Boundary line for overall balance} & \\
\text{Boundary line for balance around crystallizer} \\
\text{mass frac.} & \\
H₂O & 0.50 \\
\text{KNO}_3 & 0.50 \\
& 1.00 \\
\text{Saturated Solution} & \\
\text{0.6 kg KNO}_3 & \text{kg H₂O} \\
\text{mass frac.} & \\
H₂O & 0.625 \\
\text{KNO}_3 & 0.375 \\
& 1.000
\end{align*} \]

Step 5: Basis: 1 hr = 10,000 kg KNO₃ solution

Step 4 cont’d:

Compute the weight fraction composition of R. On the basis of 1 kg of water, the saturated recycle steam contains (1.0 kg of H₂O + 0.6 kg of KNO₃) = 1.6 kg total. The recycle steam composition is

\[ \frac{0.6 \text{ kg KNO}_3}{1 \text{ kg H₂O}} = 0.375 \text{ kg KNO}_3/	ext{kg solution} \]

or 37.5% KNO₃ and 62.5% H₂O (which has been added to the figure). (continued)
Analysis of complete process (6 streams):

Unknowns: \( W, M, C, R, m_{\text{H}_2\text{O}}, m_{\text{KNO}_3} \) = 6

Balances: (2 units + 1 mix point) \times 2 components = 6

Other compositions are (in %)

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>F</th>
<th>W</th>
<th>C</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>50</td>
<td>80</td>
<td>100</td>
<td>4</td>
<td>62.5</td>
</tr>
<tr>
<td>( \text{KNO}_3 )</td>
<td>50</td>
<td>20</td>
<td>0</td>
<td>96</td>
<td>37.5</td>
</tr>
</tbody>
</table>

Start with overall balances as substitute for unit balances

Steps 6 and 7: Unknowns: \( W, C \)

Balances: 2 components

Overall balance to calculate \( C \):

Total: \( 10,000 = W + C \)

\( \text{KNO}_3 \): \( 10,000 \times 0.20 = W \times 0 + C \times 0.96 \)

\[
\frac{10,000 \text{ kg F}}{\text{hr}} \times \frac{0.20 \text{ kg KNO}_3}{\text{kg F}} = \frac{1 \text{ kg crystals}}{\text{kg F}} \times \frac{0.96 \text{ kg KNO}_3}{\text{kg crystals}} = 2083 \text{ kg/hr crystals} = C
\]

\[
W = 10,000 - 2083 = 7917 \text{ kg}
\]

To determine the recycle stream \( R \), we need to make a balance that involves the stream \( R \). Either (a) a balance around the evaporator or (b) a balance around the crystallizer will do. The latter is easier since only three rather than four (unknown) streams are involved.

**Total balances on crystallizer:**

\[ M = C + R \]

\[
M = 2083 + R \tag{12.8} 
\]

**Component (KNO\(_3\)) balance on crystallizer:**

\[
M \omega_m = C \omega_c + R \omega_R 
\]

\[
0.5M = 0.96C + R (0.375) \tag{12.9} 
\]

Solving equations (12.8) and (12.9) we obtain

\[
0.5(2083 + R) = 0.375R + 2000
\]

\[
R = 7670 \text{ kg/hr} 
\]

**Step 5:** Basis: 1000 lb/hr sea water

**Steps 6 and 7:**

Pick the whole process as the system

Unknowns: \( B, D \)

Balances: salt, water

**Steps 8 and 9:**

Overall mass balance: \( B + D = 1000 \) \( \tag{1} \)

Overall salt balance: \( 0.0525B + 5.0 \times 10^{-4} D = 31 \) \( \tag{2} \)

Pick the mixing point as the system

Unknowns: \( R, W \) (continued)
Balances: salt, water
Mass balance around the junction: \( 1000 + R = W \) (3)

where \( R \) = brine recycle, \( W \) = total soln entering the cell

Salt balance around the junction: \( 31 + 0.0525R = 0.04W \) (4)

From (1) & (2): \[ B = 586 \text{ lb/hr} \quad \text{&} \quad D = 414 \text{ lb/hr} \]

From (3) & (4): \( R = 720 \text{ lb/hr} \)

\[ \frac{R}{720 + 586} = 0.551 \]

12.9

Basis: 1 hr = 1 L = F all concentrations are g/L.

Figure P12.9

Pick the overall process as the system.
To solve for R, make balances on the mixing point, the filter, and the splitter. Not all of the balances are independent:

**Total**

<table>
<thead>
<tr>
<th>Mass frac.</th>
<th>Oil + dirt</th>
<th>H2O</th>
<th>90 gal/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.229</td>
<td>0.771</td>
<td>1.000</td>
</tr>
<tr>
<td>D</td>
<td>0.229</td>
<td>0.771</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**Splitter:**

\[
\omega_{\text{sol}}^\varnothing = \frac{21.9 - 20.61}{2.910} = 4.43 \times 10^{-4}
\]

<table>
<thead>
<tr>
<th>Mass frac.</th>
<th>Oil + dirt</th>
<th>H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.229</td>
<td>0.771</td>
</tr>
<tr>
<td>D</td>
<td>0.229</td>
<td>0.771</td>
</tr>
</tbody>
</table>

**Filter:**

\[
G = 2910 + H
\]

\[
\omega^\varnothing_{\text{sol}} G = 2910 \left(4.43 \times 10^{-4}\right) + H(0.229)
\]

**Mixing point:**

\[
3000 + R = G
\]

\[
0.0073(3000) + 0.229R = \omega^\varnothing_{\text{sol}} G
\]

Unknowns: H, R, G, \(\omega^\varnothing_{\text{sol}}

Balances: 6 (4 independent)

**Steps 8 and 9:**

The solution is

\[
R = 57.2 \text{ gal/day} \quad \omega^\varnothing_{\text{sol}} = 0.01145
\]

**Pick the total process as the system**

**Step 5:**

Basis: 1 day (equivalent to D = 90 gal, F = 3000 gal, P = 2910 gal)

**Steps 6 and 7:**

Unknowns: \(\omega_{\text{sol}}^\varnothing, \omega_{\text{H2O}}^\varnothing\)

Balances: oil + dirt, H2O

**Steps 8 and 9:**

Overall oil + dirt balance:

\[
3000(0.0073) = 2910(\omega_{\text{sol}}^\varnothing) + 90(0.229)
\]
12.11

Start with the overall system

\[
\begin{align*}
\text{mol fr.} & \quad \text{mass fr.} \\
\text{H}_2\text{O} & \quad 0.0473 & \quad 0.95 \\
gas & \quad 0.9527 & \quad \text{H}_2\text{O} & \quad 0.05 \\
1.0000 & \quad & \text{Dryer} & \quad \text{Rice Product} \\
\text{S (lb mol)} & \quad P (lb) & \quad W (lb mol) \\
\text{mass fr.} & \quad \text{mol fr.} \\
rice & \quad 0.75 & \quad x_{\text{H}_2\text{O}}^{\text{w}} & \quad 0.0931 \\
\text{H}_2\text{O} & \quad 0.25 & \quad x_{\text{w}}^{\text{w}} & \quad 0.9069 \\
1.00 & \quad & 1.0000
\end{align*}
\]

Steps 1, 2, 3 and 4: In the diagram use mol and mass percent for compositions and mol and mass for flow as specified.

Step 5: Basis \( P = 100 \text{ lb} \)

Step 6: Unknowns: \( F, S, W \)

Step 7: Can make total and 3 component balances: rice, \( \text{H}_2\text{O} \), dry gas (G)

Steps 8 and 9:

\[
\begin{align*}
\text{lb} & \quad \text{Rice:} & \quad F(0.75) = P(0.95) = 100(0.95) \\
\text{lb mol} & \quad \text{Dry gas:} & \quad S(0.9527) = W(0.9069) \\
\text{lb mol H}_2\text{O} & \quad \text{H}_2\text{O:} & \quad S(0.0473) + \frac{F(0.25)}{18.02} = W(0.0931) + P(0.05) \\
& & \quad \text{or G (only 1 independent equation)} \\
& & \quad 0.0473 S + 0.0931 R = F_1(0.052) \\
& & \quad 27.35 + R = F_1
\end{align*}
\]
Solutions Chapter 12

1.385 + 0.0931 R = 0.052 (27.35 + R) = 1.523 + 0.052R

0.041 R = 0.138

[R = 3.37 / mole]

12.12

Fb
Organic Solvent
100%

Aqueous Phase

F_A = 10 L/min
C_0^A = 100 g/L

C_f^D = 0.01 g/L

F_p

F_f = 10 L/min
C_f^A = 0.1 g/L

Fermentation product balance:

\[
100 \frac{g}{L} \times 10 \frac{L}{min} = F^* (0.01) + 10 \frac{L}{min} \times 0.1 \frac{g}{L}
\]

\[
F^* = \frac{1000 - 1}{0.01} = 99,900 \frac{L}{min}
\]

b.

F_A = 10 L/min
C_0^A = 100 g/L

\[ C_f^A = 0.1 C_f^D \]

Fermentation balance:

Assuming \( F_1^* = F_2^* = F_3^* = F^*/3 \)

I:

\[
100 \frac{g}{L} \times 10 \frac{L}{min} = C_f^A \times 10 \frac{L}{min} + \frac{F^*}{3} \times 0.1 C_f^A \]

\[ (1) \]

II:

\[
C_f^A \times 10 \frac{L}{min} = C_f^A \times 10 \frac{L}{min} + \frac{F^*}{3} \times 0.1 C_f^A \]

\[ (2) \]

III:

\[
C_f^A \times 10 \frac{L}{min} = C_f^A \times 10 \frac{L}{min} + \frac{F^*}{3} \times 0.1 C_f^A \]

\[ (3) \]

Solving (1), (2) and (3) Simultaneously

\[ C_f^A = 10.0 \frac{g}{L} \]

\[ C_f^A = 1.0 \frac{g}{L} \]

\[ C_f^A = 0.1 \frac{g}{L} \]

\[ F = 2702 \frac{L}{min} \]

(continued)
Fermentation Product Balance:

I: \[ 100 \frac{g}{min} + 0.1 C_1^A \cdot F^e = 0.1 C_1^A \cdot F^e + C_1^A \cdot 10 \]

II: \[ C_2^A \cdot 10 + 0.1(0.1)F^e = 0.1 C_2^A \cdot F^e + C_2^A \cdot 10 \]

III: \[ C_2^A \cdot 10 + 0 = 0.1(0.1) \cdot F^e + 0.1 (10) \]

Solving (1), (2) and (3) Simultaneously

\[ C_1^A = 10.36 \text{ g/L} \quad C_2^A = 1.06 \text{ g/L} \quad C_2^A = 0.10 \text{ g/L} \]

\[ F = 960 \frac{g}{min} \quad \text{(This one is the least)} \]

---

12.13

Steps 2, 3, and 4: (Non Bz is non-benzene)

Extract benzene plus \[ 0.15 \text{ kg SO}_2 \]

\[ P (kg) \]

\[ B \]

\[ A \]

\[ C \]

\[ D \]

Sulfur dioxide \[ 3000 \text{ kg/hr} \]

Catalytic reformate \[ 1000 \text{ kg/hr} \]

70% Bz 30% non-Bz

Waste \[ 0.25 \text{ kg Bz} \]

Bz, A-Bz, \[ 10 \text{ kg/hr} \]

Step 5: Basis: 1 hr

Process is steady state, no reaction

Steps 2, 3 and 4:

Compositions:

at P: \[ \text{SO}_2 \]

\[ \frac{0.15 \text{ kg SO}_2}{1 + 0.15} = 0.130 \]

at W:

\[ \begin{align*}
    m_\text{Bz}^r & = \frac{m_\text{Bz}^\text{in}}{\Sigma W} \\
    m_\text{non-Bz}^r & = \frac{m_\text{non-Bz}^\text{in}}{\Sigma W}
\end{align*} \]

Bz: \[ 1 - 0.130 = \frac{0.870}{1.00} \]

(continued)
Pick the overall process as the system

**Steps 6 and 7:**

Unknowns: \( P, 3m_{w}^{w} \) (4)

Balances: \( \text{Bz, SO}_2, \text{non Bz} \), \( \frac{m_{w}}{m_{\text{total}}} = 0.25 \) (4)

**Steps 8 and 9:** Balances are in kg

Total \( 3000 + 1000 = P + W \)

Bz: \( 1000 (0.70) = P \left( \frac{1.00}{1.15} \right) + m_{w, \text{Bz}} \)

Non Bz: \( 1000 (0.30) = P (0) + m_{w, \text{non Bz}} \) \( m_{w, \text{non Bz}} = 300 \) kg

SO\(_2\): \( 3000 = P \left( \frac{0.15}{1.15} \right) + m_{w, \text{SO}_2} \) \( m_{w, \text{SO}_2} = 300 (0.25) = 75 \) kg

a. Solution: \( P = 719 \) kg

\( m_{w, \text{SO}_2} = 2906 \) kg

\( W = 3281 \) kg

System: Unit 1

---

---

---

---

---

---

---

---
Steps 6 and 7:

Steps 8 and 9: Balances are in kg

Bz + nonBz: $C' = 749 + G'$

System: mixing point

$D' = 1375$ kg

$G' = 1375 - 1000 = 375$ kg

c. $C' = 749 + 375 = 1124$ kg

12.14

Single pass conversion is: $f_{sp} = \frac{-\Delta H_{\text{reaction}}}{\Delta H_{\text{LR}}}$

a. Single pass conversion based on $H_2$ as the limiting reactant:

$\xi = \frac{1.979 - 3.96}{-2} = 0.99$

$\xi_{\text{max}} = \frac{0 - 3.96}{-2} = 1.98$

SP conversion $= \frac{-(2)(0.99)}{3.96} = 0.60$

Use Eq. (12.1) and Eq. 12.2 with $H_2$ the limiting reactant
Solutions Chapter 12

G (mol): \[ n_{CO} = 48 + 4 = 52 \]
H (mol): \[ n_{H_2O} = 48 \] \[ n_{H_2} = 48 \]

\[ \text{total 100} \]

Step 10:
O (mol): \[ n_{H_2O} + n_{CO} = 48(2) + 4 \]

check is ok.

a. Composition of fresh feed 40% H₂O and 52% CO

Alternate solution: Use extent of reaction

Based on \[ CO_2: \xi = \frac{48 - 0}{1} = 48 \]

Then \[ n_{CO} = 4 + \xi = 4 + 48 = 52 \text{ mol} \]
\[ n_{H_2O} = 0 + \xi = 48 \text{ mol} \]

To get the recycle, make a balance about the separator (no reaction occurs)

H₂ balance (mol): \[ L(0.03) = 48 \]
\[ L = 1600 \text{ mol} \]

Total (mol): \[ L = 100 + R \]
\[ R = 1500 \text{ mol} \]

b. \[ \frac{1500 \text{ mol R}}{48 \text{ mol H₂}} = 31.3 \]

12.16

Steps 2, 3, and 4:

MW Ca (Ac)₂ = 158.1

MW HAc = 60

\[ 100 \text{ kg Ca(Ac)}_2 \]
| 1 kg mol Ca(Ac)₂ = 0.633 kg mol Ca(Ac)₂ |
| 158.1 kg Ca(Ac)₂ |

Step 5: Basis: 1000 kg of Ca(Ac)₂ feed

R²

Ca(Ac)₂ + H₂SO₄ → CaSO₄ + 2 HAc

Inspection of the diagram shows that the overall conversion of Ca(Ac)₂ is 100%
(none leaves the process). Thus, \( f_{DA} = 1 \). You are given \( f_{DA} = 0.90 \). Then

\[ \frac{f_{DA}}{1} = \frac{6.33}{6.33 + R} \]
\[ R = 0.703 \text{ kg mol} \]
or \[ 111 \text{ kg} \]

b. The single pass conversion for Ca(AC)₂ is 0.90.

\[ 0.90 = \frac{n_{Ca(Ac)}}{n_L} = \frac{-(-1)^{\xi}}{6.33} \]
\[ \xi = 5.697 \]

Overall HAc balance:

\[ \frac{6.33 \text{ kg mol Ca (Ac)₂}}{1 \text{ kg mol Ca(Ac)₂}} = 12.66 \text{ kg mol HAc or 760kg} \]

12.17

Steps 2, 3, 4:

MW C₂H₂ = 26.02

MW C₂H₄Br₄ = 346

MW Zn = 65.37

(continued)
a. C₂H₂ produced per hour

Step 5: Basis: 1 hr = 1000 kg C₂H₂Br₄ (2.890 kg mol)

Make overall balances:

Get the extent of reaction using C₂H₂Br₄

\[ n_{\text{act}} - n_{\text{in}} = \alpha \xi \]
\[ 0 - 2.890 = (-1)(\xi) \quad \xi = 2.890 \text{ reacting moles} \]

C₂H₂ balance: \( n_{\text{in}} = 0 + (1)(2.890) = 2.890 \text{ kg mol} \]
\( 2.890 (26.02) = 75.2 \text{ kg} \)

ZnBr₂ balance: \( n_{\text{in}} = 0 + 2(2.890) = 5.78 \text{ kg mol} \)

Alternate solution

\[
\begin{array}{c|c|c|c}
100 \text{ kg} & 1 \text{ kg mol} & 1 \text{ kg mol} & 26 \text{ kg} \\
C₂H₂Br₄ & C₂H₂Br₄ & C₂H₂ & = 75.2 \\
1 & 346 & 1 & 1 \text{ kg mol} & 1 \text{ kg mol} & C₂H₂ \\
\end{array}
\]

b. Recycle

Make balance on the mixing point. First, get the feed of C₂H₂Br₄ to the reactor

\[ \frac{0.80}{\alpha} = \frac{-\xi}{\alpha} = \frac{-1(2.896)}{\alpha} \quad n_{\text{in}}^\text{mol} = 3.61 \text{ kg mol} \]

C₂H₂Br₄ balance: 2.890 + R = 3.61 \quad R = 0.72 \text{ kg mol} \]
\( 0.72 (346) = 249 \text{ kg} \)

Alternate solution (in kg). Balance over separator.

\[
(1000 \text{ kg} + R) (0.20) = R \\
R = 250 \text{ kg} 
\]

c. Feed rate required for 20% excess Zn in reactor:

\[
\begin{array}{c|c|c|c|c}
1000 \text{ kg} & 1 \text{ kg mol} & 1 \text{ kg mol} & 2 \text{ kg mol} & 65.37 \text{ kg} & 1.2 \text{ kg} \\
C₂H₂Br₄ & C₂H₂Br₄ & Zn & Zn & \text{ in feed} & = 454 \text{ kg} \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
1 & 546 \text{ kg} & C₂H₂Br₄ & 1 \text{ mol} \text{ C₂H₂Br₄} & 1 \text{ kg mol} \text{ Zn} & \text{ required} \\
\end{array}
\]

d. Mole ratio of ZnBr₂ to C₂H₂ in final products:

\[
\frac{5.78}{2.89} = 2.1 \text{ (as per reaction)}
\]

12.18

\[
\begin{array}{c}
F \quad \text{NaCl} \quad \text{Refiner} \quad \text{Separator} \\
\text{CO}_2 \quad \text{CaCO}_3 \quad \text{CaO} \quad \text{100%} \\
\text{Na}_2 \text{CO}_3 \quad \text{100%} \\
\end{array}
\]

Step 5: Basis: 100 kg F₁ = 1 hr

Overall balance

Step 6 and 7:

Unknowns: F₂, P₁, P₂

Element balances: Ca, Na, Cl, CO₂ (enough, not all independent)

CO₂ balance:

\[
900 \text{ kg CaCO}_3 \quad 1 \text{ kg mol CaCO}_3 \quad 1 \text{ kg mol CO}_2 = 9.00 \text{ kg mol CO}_2 \\
100 \text{ kg CaCO}_3 \quad 1 \text{ kg mol CaCO}_3 
\]

(continued)
Solutions Chapter 12

100 kg Na₂CO₃, 1 kg mol Na₂CO₃, 1 kg mol CO₂ = 0.94 kg mol CO₂
94 kg CO₂

106 kg Na₂CO₃, 1 kg mol Na₂CO₃

a. 9.44 kg mol CO₂, 1 kg mol Na₂CO₃, 106 kg Na₂CO₃, 1 kg mol Na₂CO₃ = 1054 kg Na₂CO₃

Species balance about the reactor plus the separator on CaCO₃:

\[
\frac{9.44 \text{ kg mol CO}_2}{1 \text{ kg mol Na}_2\text{CO}_3} \times \frac{106 \text{ kg Na}_2\text{CO}_3}{1 \text{ kg mol Na}_2\text{CO}_3} = 1054 \text{ kg Na}_2\text{CO}_3
\]

Alternate solution:

Use the extent of reaction to get the same results.

12.19

Steps 1, 2, 3, and 4:

Alternate solution:

Na₂S is the limiting reactant (LR). Mole Na₂S = (0.45)(1000)/78 = 5.77. All of it reacts.

\[
1.00 = \frac{1(-1)\xi}{5.77}, \quad \xi = 5.77
\]

(continued)
Overall fraction conversion of Na₂S is 100%, f_{OA} = 1.
\[
f_{SR} = \frac{5.90}{1.00} = \frac{n_{LR}^{\text{in}}}{n_{LR}^{\text{in}} + n_{LR}^{\text{rec}}} = \frac{5.77}{5.77 + R} 
\]
\[5.19 + 0.9R = 5.77 \quad R = 0.64 \text{ lb mol (or 50 lb)}\]

12.20
A basis of 1 hr requires the listing and solution of many simultaneous equations.

A basis of 100 mol of toluene in G is more convenient

Species balances

<table>
<thead>
<tr>
<th>Species</th>
<th>In</th>
<th>Out</th>
<th>Gen</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) toluene: 100</td>
<td>-Rₐ</td>
<td>+0</td>
<td>-100 (.80 + .08)</td>
<td>= 0</td>
</tr>
<tr>
<td>(2) H₂: 100 (4)</td>
<td>-n_{H₂}^{w}</td>
<td>+0</td>
<td>-100 (4)(.80 + .08 \left(\frac{1}{2}\right))</td>
<td>= 0</td>
</tr>
<tr>
<td>(3) CH₄: 100 (4)</td>
<td>-n_{CH₄}^{w}</td>
<td>+100(4)(.80 + .08)</td>
<td>= 0</td>
<td></td>
</tr>
</tbody>
</table>

Solve above for \( Rₐ = 12 \text{ mol} \)

\[
n_{H₂}^{w} = 64 \text{ mol} \\
n_{CH₄}^{w} = 752 \text{ mol} \]

Total = 816 mol

System: mixer plus makeup point (Species balances but no reaction so In = Out)

<table>
<thead>
<tr>
<th>F</th>
<th>M</th>
<th>S₁</th>
<th>S₂</th>
<th>S₃</th>
<th>S₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Toluene: F (1.0) + 0 + 0 + 12 = 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) H₂: 0 + M(1.0) + Rₐ \left(\frac{64}{816}\right) + 0 = 400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) CH₄: 0 + 0 + Rₐ \left(\frac{752}{816}\right) + 0 = 400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Solve (3) for \( Rₐ = 434 \text{ mol} \)

Solve (1) for \( F = 88 \text{ mol} \), \( M = 366 \)

Change basis to 1 hour (continued)
Solutions Chapter 12

\[
\frac{3450 \text{ lb mol}}{92 \text{ lb}} = 37.5 \text{ lb mol of toluene in } F
\]

\[
\begin{array}{c|c|c|c}
\text{100 lb mol tol in G} & 37.5 \text{ lb mol F} & 12 \text{ lb mol R}_{G} & = 5.11 \text{ lb mol R}_{F} / \text{hr}
\
88 \text{ lb mol F} & 1 \text{ hr} & 100 \text{ lb mol tol in G} & \\
\end{array}
\]

\[
\frac{100}{88} \frac{37.5}{1} \frac{434 \text{ lb mol } R_{G}}{100 \text{ lb mol tol in G}} = 185 \text{ lb mol } R_{G} / \text{hr}
\]

If F = 37.5 lb mol of toluene is selected as the basis, you have to make the same balances as above plus benzene and diphenyl balances on the reactor plus separator because F is a known but G becomes an unknown.

The unknowns would be

\[
G, R_{G}, R_{G}, D, B, M n_{R_{G}}, n_{C_{6}H_{6}}
\]

Alternate solution

Calculate the extent of reaction for each reaction, and use them as shown in the book to get the outputs of the reactor plus separator system instead of using generation and consumption terms.

12.21

### Solutions Chapter 12

**Basis:** 1 hr = 50 kg mol \( F_{5} \)

**Unknowns:**

\[ F_{1}, F_{4}, F_{6}, n_{C_{6}H_{6}}, n_{C_{2}H_{4}}, n_{C_{2}H_{6}}, n_{C_{6}H_{5}}, n_{C_{6}H_{5}} \]

**Balances:**

- **Mixing Point:**
  \( C_{2}H_{6}, C_{2}H_{5} \)
- **Reactor:**
  \( C_{2}H_{4}, C_{2}H_{2}, H_{2} \)
- **Abs./Distill.:**
  \( C_{2}H_{4}, C_{2}H_{2}, H_{2} \)

Use overall balances as substitute for some of the above.

### Overall balances (element balances because of the reaction)

\[
\begin{align*}
\text{C:} & \quad F_{1}(3) = F_{5}(3) \\
\text{H:} & \quad F_{1}(8) = F_{4}(2) + F_{6}(6)
\end{align*}
\]

\[
8(50) = 2F_{4} + 50(6)
\]

**Mixing point balances (no rxn):**

\[
\begin{align*}
\text{C}_{2}\text{H}_{4}&: \quad F_{1}(1.0) + F_{4}(0.8) = n_{C_{2}H_{4}}^{F_{5}} = 50 + 0.8F_{6} \\
\text{C}_{2}\text{H}_{6}&: \quad F_{1}(0.0) + F_{4}(0.2) = n_{C_{2}H_{6}}^{F_{5}} = 0.2F_{6}
\end{align*}
\]

(continued)
Solutions Chapter 12

Reactor plus absorber/distillation balances:

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
<th>Generated</th>
<th>Consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₃H₆</td>
<td>( n_{C₃H₆} )</td>
<td>Fₓ(0.80) + 0</td>
<td>0.4 ( n_{C₃H₆} ) = 0</td>
</tr>
</tbody>
</table>

(50 + 0.8Fₓ) · 0.80 Fₓ - 0.4 (50 + 0.8 Fₓ) = 0

Recycle: \( Fₓ = 93.75 \) kg mol
\( n_{C₃H₆} = 75 + 50 = 125 \) kg mol

C₃H₆: \( n_{C₃H₆} \) - \( Fₓ (0.20) - 50 + 0.4 (50 + 0.8 Fₓ) - 0 = 0 \)
\( n_{C₃H₆} = 18.75 \) kg mol

Note: since \( Fₓ = F₁ + F₆ = 50 + 93.75 = 143.75 \) kg mol (easier calculated this way)
\( n_{C₃H₆} = 0.2; F₆ = 18.75 \) kg mol

\( F₂ = 18.75 + 125 = 143.75 \) kg mol

Omit H₂ balance (Use C₃H₆)

Absorption/distillation tower

C₃H₆: \( n_{C₃H₆} = F₁ = 50 \) kgmol
H₂: \( n_{H₂} = F₄ = 50 \) kgmol

Total: \( F₃ = F₁ + F₄ + F₆ = 50 + 50 + 93.75 = 193.75 \) kg mol
\( n_{C₃H₆} = 193.75 - 100 = 93.75 = F₆ \)

Summary (all kg mol):

\( F₁ = 50 \quad F_x = 50 \)
\( F₂ = 143.75 \quad F_y = 50 \)
\( F₆ = 193.75 \quad F₆ = 93.75 \)

Alternate solution using extent of reaction
\( f_{a,k} = 1 - \frac{-1(1)^x}{50} \quad x = 50 \)

\( f_{b,k} = 0.4 = \frac{50}{n_{C₃H₆} + n_{H₂}} = \frac{n_{C₃H₆}}{n_{C₃H₆}} \quad n_{C₃H₆} = 125 \) kg mol

Also
\( \frac{0.40}{1} = \frac{50}{1.50} \)
\( n_{C₃H₆} = 75 \) kg mol
\( n_{H₂} = \frac{0.20}{0.80} (75) = 18.75 \) kg mol

\( n_{C₃H₆} = 125 + 0.8 F₆ \quad F₆ = 93.75 \)
\( n_{H₂} = n_{C₃H₆} + 0 = 18.75 \)
\( F₁ = 18.75 + 125 = 143.75 \)

Similar calculations to these will yield the same results as in the original solution.

12.22

This is a steady state process with reaction and recycle. Pick the overall process as the system.

Step 5: Basis: 100 kg mol CH₄
Steps 1, 2, 3, and 4: The system is as shown in the diagram with recycle added.

\[
\begin{align*}
&\text{CH}_4 \\
&\text{Air} \\
&\text{O}_2 & 230 \\
&\text{N}_2 & 865.24
\end{align*}
\]

\[
\begin{align*}
&\text{CO}_2 \\
&\text{O}_2 \\
&\text{H}_2\text{O} \\
&\text{NO} \\
&\text{N}_2
\end{align*}
\]

R

100 kg mol

Calculate the moles of each component entering.

\[
\text{C}_n\text{H}_m\text{(g)} + 2\text{O}_2\text{(g)} \rightarrow \text{CO}_x\text{(g)} + n\text{H}_2\text{O(g)}
\]

Calculation of the required \(\text{O}_2\) and accompanying \(\text{N}_2\) in moles

\[
\begin{align*}
\text{req'd O}_2 & \quad 100(2) = 200 \\
\times & \quad 200 (0.15) = 30 \\
\text{Total O}_2 & \quad 230 \\
\text{N}_2 & \quad \left(\frac{230}{0.79} \cdot \frac{1}{0.21}\right) = 865.24
\end{align*}
\]

The exit concentrations (via stoichiometry) are

12.23

This is a steady state problem with reaction and recycle.

Step 5: Basis: 100 mol F

Steps 1, 2, 3 and 4: Make the overall balances first

\[
\text{SO}_2 + \frac{1}{2}\text{O}_2 \leftrightarrow \text{SO}_3
\]

Use stoichiometry

\[
\begin{align*}
\text{SO}_2 \quad &10.0 \\
\text{O}_2 \quad &9.0 \\
\text{N}_2 \quad &81.0
\end{align*}
\]

F (mol) \rightarrow \text{Overall Process} \rightarrow P(\text{mol})

Calculation

\[
\begin{align*}
\text{SO}_2 & \quad \text{mol} \quad 0.95 (10) = 9.50 \\
\text{SO}_2 & \quad \text{mol fr} \quad 0.05 (10) = 0.50 \\
\text{O}_2 & \quad \text{mol} \quad 9.50 \\
\text{O}_2 & \quad \text{mol fr} \quad 0.100 \\
\text{N}_2 & \quad \text{mol} \quad 81.0 \\
\text{N}_2 & \quad \text{mol fr} \quad 0.850
\end{align*}
\]

Step 6: The unknowns are the 4 exit compositions plus the extent of reaction if it is to be used.

Steps 7, 8, and 9: We have 3 element balances plus the fraction conversion of the \text{SO}_2 to \text{SO}_3, or 4 species balances (\text{SO}_2, \text{SO}_3, \text{N}_2, \text{O}_2). We can use a mixture of element and species balances.
Element S: 10 = 0.95(10) + 0.05(10) check is ok
Compound N₂: 81.0 = 81.0

Select unit 1 as the system.

<table>
<thead>
<tr>
<th>mol</th>
<th>fract. conv.</th>
<th>calc'd mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>81.0</td>
<td></td>
</tr>
</tbody>
</table>

S : 10
SO₃ : 7.5
SO₂ : 2.5

Element 20: 9.0 + 10.0 = 19 = 1.5(7.5) + 2.5 + n₀₂ = 11.25 + 2.5 + n₀₂
n₀₂ = 5.25

Balance around converter 2 plus separator: Note we need H = P + R, and observe that the composition of H, P and R is the same.

Make a species balance on SO₂

In | Out | Consumption | Generation
---|-----|-------------|-------------
[2.5 + R(0.00525)] | [0.50 + R(0.00525)] | +0 | -(2.5 + R(0.00525))0.65 = 0

[R = 111 kg mol]

12.24 Steady state process with reaction

Step 1, 2, 3, and 4: Get the amount of [reqd., excess] HNO₃ in G.

Step 5: Basis: 1 hr

\[ \frac{1 \times 10^4 \text{ kg Glycerine}}{92.11 \text{ kg Glycerine}} = 10.86 \text{ kg mol Glycerine} \]

Step 4: Glycerine

\[ C_3H_6O_3 + 3\text{HNO}_3 \rightarrow C_6H_8O_7(\text{NO}_3)_3 + 3\text{H}_2\text{O} \]

Required: HNO₃ is 3 (10.86) = 32.58 kg mol (continued)
Excess: \( HNO_3 \) is 32.56 \( (0.20) \) = 6.516

Total: 39.10 kg mol in G

**Steps 6 and 7:** System is overall.

Unknowns: \( F, P, m_{H_2SO_4}, m_{H_2O} \) and \( m_{H_2O} \) \((\Sigma m = W)\)

Equations: C, H, S, O, N

(or you can use stoichiometry and make species balances, or use the extent of reaction)

\[
\begin{align*}
C: & \quad 10.86 = 0.9650P \quad P = 11.25 \text{ kg mol or } 11.25 \times 227.09 = 2556 \text{ kg} \\
\end{align*}
\]

System is the mixing point

Unknowns: \( F, m_{H_2SO_4}, m_{H_2O}, R, G \)

**Balances:** \( H_2SO_4, H_2O, HNO_3 \) and \( m_{H_2O} + m_{H_2SO_4} + 39.10 = G \)

(a) Glycerine Feed \[
= \frac{1000}{92.11} = 10.86 \text{ kg mol}
\]

Nitroglycerine Produced \[
= \frac{1086 \text{ kg mol} \times 227.98 \text{ kg}}{\text{lb mol}} = 2466 \text{ kg}
\]

\[P = 2555 \text{ kg} \]

(b) Mol \( HNO_3 \) req'd \[
= \frac{10.86 \text{ mols Glyc}}{3 \text{ mol } HNO_3} = 3.58 \text{ mol}
\]

Actual \( HNO_3 \) Req'd \[
= 1.200 \times (32.58) = 39.10 \text{ mol}
\]

\( HNO_3 \) in R \[
= 39.10 - 32.58 = 6.52 \text{ mol}
\]

\[
= 6.52 \times (63.01) = 411 \text{ kg}
\]

\( HNO_3 \) is 70.00% R, 0.7000R = 411

\[R = 587 \text{ lb} \]

(c) \( HNO_3 \) in G = 39.10 mol = 2464 kg

\( HNO_3 \) in R = 411 kg

\[F + R = G\]

\( HNO_3 \) Balance: \[F + 411 = 2464 \quad F = 2053 \text{ lb } HNO_3\]

F is 43.00% \( HNO_3 \) so that 0.4300 F = 2053

\[F = 4774 \text{ lb} \]

(d) \( H_2SO_4 \) in F

\[= 0.5000 \times (4774) = 2387 \text{ kg}\]

\[= H_2SO_4 \text{ in W}\]

\( H_2O \) in F

\[= 0.0700 \times (4774) = 334 \text{ kg}\]

\( H_2O \) Generated by reaction

\[= 10.86 \text{ Mole Glyc} \times 3\]

\[= (10.86) \times 3 \times (18.02) = 587 \text{ kg}\]

\( H_2O \) in Stream P

\[= 0.0350 \times (2555) = 89 \text{ kg}\]

\( H_2O \) in W

\[= H_2O \text{ in } F + H_2O \text{ generated} - H_2O \text{ in P} \] (continued)
Solutions Chapter 12

\[ = 334 + 587 - 89 = 832 \text{ kg} \]

**Components**

<table>
<thead>
<tr>
<th></th>
<th>kg</th>
<th>wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2\text{SO}_4 )</td>
<td>2387</td>
<td>74.15</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>832</td>
<td>25.85</td>
</tr>
<tr>
<td>Stream W = 3219 kg/hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{H}_2\text{SO}_4 )</td>
<td>74.15%</td>
<td></td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>25.85%</td>
<td></td>
</tr>
</tbody>
</table>

**Step 10:**

Do numbers check?

\[
\text{Glycerine} + F = P + W \\
1000 + 4774 = 2555 + 3219 \\
5774 = 5774
\]

---

Solutions Chapter 12

12.25

**Step 1, 2, 3 and 4:**

Chemical Reactions

a) \( \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2 \) (main reformer rxn)

b) \( \text{CH}_4 + \text{H}_2 \rightarrow \text{CO} + 3\text{H}_2 \) (reformer side rxn)

c) \( 2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \) (CO converter rxn)

d) \( \text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \) (methanol rxn)

\( \text{CH}_4 \) feed is 1% \( \text{N}_2 \) or 1 kg mol \( \text{N}_2 \)

steam feed is 10% excess based on reaction (a).

99 kg mol \( \text{CH}_4 \) \( \left( \frac{2 \text{ kg mol H}_2\text{O}}{1 \text{ kg mol CH}_4} \right) \times 198 \text{ kg mol steam} \)

1.1 (198) = 217.8 kg mol steam

(continued)
Solutions Chapter 12

Step 5: Basis: 100 kg mol CH₄ in feed

Steps 6 and 7: Unknows:

- 6-CO₂ makeup
- 10-reactor product
- 3-reformer product
- 7-3:1 H₂/CO₂
- 11-Methanol solution
- 4-O₂ feed, stoichiometric
- 8-recycle, H₂/CO₂=3
- 12-condenser tops
- 5-CO conv. products
- 9-reactor feed, H₂/CO₂=3
- 13-purge, 5% N₂

Balances:

- Reformer balance
- Condenser balance
- CO conv. balance
- Purge/recycle balance
- CO₂ makeup balance
- Feed/recycle balance
- Methanol reactor balance

Steps 8 and 9: Solve balances serially.

Reformer balance gives stream 3

\[
\frac{99 \text{ kg mol CH}_4}{\text{conv}} \times \frac{0.9 \text{ conv by(a)}}{1 \text{ conv}} \times \frac{1 \text{ kg mol CO}}{1 \text{ kg mol CH}_4} = 89.1 \text{ kg mol CO}
\]

CO = 99(0.1) = 9.9 kg mol CO

H₂O reacted = \( \frac{2 \text{ kg mol } H₂O}{1 \text{ kg mol CO}} \times \frac{89.1 \text{ kg mol CO₂}}{1 \text{ kg mol CO}} = 188.1 \text{ kg mol H₂O} \)

H₂O remaining = 217.8 - 188.1 = 29.7 kg mol H₂O

H₂ = 4(89.1) + 3(9.9) = 386.1 kg mol H₂

N₂ = 1 kg mol

CO conv. balance gives streams 4 & 5:

Stream 4:

\[
O₂ = \frac{9.9 \text{ kg mol CO}}{(1/2) \text{ kg mol O₂}} \times \frac{1 \text{ kg mol CO}}{1 \text{ kg mol CO}} = 4.95 \text{ kg mol O₂}
\]

Stream 5:

\[
CO₂ = 89.1 + 9.9 = 99 \text{ kg mol CO₂}
\]

H₂O = 29.7 kg mol H₂O

H₂ = 386.1 kg mol H₂

N₂ = 1 kg mol N₂

CO₂ makeup gives streams 6 and 7:

stream 7 is 3:1 H₂/CO₂

CO₂ = 386.1/3 = 128.7 kg mol CO₂ needed

Stream 6:

\[
CO₂ = 128.7 - 99 = \frac{29.7 \text{ kg mol CO₂}}{b.}
\]

purge/recycle gives stream 13:

(continued)
N$_2$ is inert species:

\[
\text{stream 13} = \frac{1.0 \text{ kg mol N}_2}{0.05 \text{ kg mol N}_2 / \text{ kg mol stream 13}} = 20 \text{ kg mol in stream 13}
\]

Stream 13:
\[
\text{H}_2/\text{CO}_2 = 3
\]
Let \( x = \text{ mol frac. of CO}_2 \) in stream 13

\[1 = 0.05 + 3x + x\]
\[4x = 0.95, \quad x = 0.2375\]

\[\text{N}_2 = 1 \text{ kg mol N}_2\]

\[\text{H}_2 = 20(3)(0.2375) = 1.425 \text{ kg mol H}_2\]

\[\text{CO}_2 = 20(0.2375) = 4.75 \text{ kg mol CO}_2\]

**Special balance gives stream 11:**

\[
\begin{array}{c}
\text{128.7 CO}_2 \\
29.7 \text{ H}_2 \text{O} \\
386.1 \text{ H}_2 \\
1.0 \text{ N}_2
\end{array}
\]

1 rxn occurs

\[
\text{CO}_2 \text{ reacted} = 128.7 - 4.75 = 123.95 \text{ kg mol CO}_2 \text{ reacted}
\]

\[
\text{H}_2 \text{ reacted} = 386.1 - 14.25 = 371.85 \text{ kg mol H}_2 \text{ reacted}
\]

\[
\text{CH}_3\text{OH produced} = 123.95 \text{ kg mol CH}_3\text{OH}
\]

\[
\text{H}_2\text{O produced} = 123.95 \text{ kg mol H}_2\text{O}
\]

**Stream 11:**

\[
\text{H}_2\text{O} = 29.7 + 123.95 = 153.65 \text{ kg mol H}_2\text{O}
\]

\[
\text{CH}_3\text{OH} = 123.95 \text{ kg mol CH}_3\text{OH}
\]

mass stream 11 = 153.65 (18) + 123.95 (32) = 6732.1 kg
d.

wt. % CH$_3$OH = $\frac{123.95 (32)}{6732.1}$ = 58.9%

**Methanol reactor balance for 55% conversion**

From special balance, each pass uses 123.95 kg mol CO$_2$
123.95 = 0.55 (CO$_2$)$_{in}$ so (CO$_2$)$_{in}$ = 225.36 kg mol CO$_2$
Stream 8 = stream 9 - stream 7
Stream 8: CO$_2$ = 225.36 - 128.7 = 95.66

\[\text{So recycle \over purge} = \frac{95.66}{4.75} = 20.35\]
c.

12.26
By inspection you can see that the flow of C$_2$H and H$_2$ in the separator is going the wrong way, hence any calculations make no sense.

12.27
No purge stream exists out of the separator so that CO will build up.

12.28
a. No, they all contain AN and/or NH$_3$.

(continued)
b. The bottom stream from the distillation column and the wastewater stream from the condenser are candidates. The bottoms stream from the distillation column contains no NH₃ and has the highest mass fraction of AN of any waste stream so that the entire stream could be fed to the scrubber.

c. The change in the scrubber feed will not affect any of the stream flows or compositions upstream of the scrubber that are connected to the scrubber, namely those associated with the reactor and the subsequent condenser, nor any downstream flows not connected to the scrubber. A sequential set of material balances can be used to get the flows and concentrations in the rest of the process.

Basis: 1 second

(1) The water flow rates will not change except for the stream going to treatment, which will be \((10.1 - 0.7) = 9.4\) kg/s.

(2) The AN clues in the streams can be determined from the following balances.

Let \(x\) be the kg of AN entering or leaving a particular unit.

**Scrubber balance**

\[ x_{\text{scrubber}}^{\text{n}} + 4.6 = x_{\text{decanter}}^{\text{n}} \]

**Decanter balance**

\[ x_{\text{decanter}}^{\text{n}} = x_{\text{distill}}^{\text{n}} + 5.5(0.073) \]

**Distillation column plus two condenser plus stream jet plus product stream balance**

\[ x_{\text{distill}}^{\text{n}} + 0 = x_{\text{jet}}^{\text{out}} + x_{\text{product}}^{\text{out}} + x_{\text{scrubber}}^{\text{n}} \]

**Distribution of AN entering the distillation column**

\[
\begin{align*}
x_{\text{jet}}^{\text{out}} &= 0.2 \\
x_{\text{product}}^{\text{out}} &= 3.9 \\
x_{\text{scrub}}^{\text{in}} &= 0.1 \\
x_{\text{distill}}^{\text{n}} &= 4.2 \\
x_{\text{jet}}^{\text{in}} &= 4.2 \\
x_{\text{distill}}^{\text{in}} &= 4.2
\end{align*}
\]

Solutions Chapter 12

One of these relations is redundant with the distillation column balance.

The solution of these equations is in kg (note the changes are quite small, hence the number of significant figures is exaggerated):

\[
\begin{align*}
x_{\text{distill}}^{\text{in}} &= 4.302 \\
x_{\text{scrub}}^{\text{in}} &= 0.102 \\
x_{\text{jet}}^{\text{in}} &= x_{\text{jet}}^{\text{out}} = 0.205 \\
x_{\text{product}}^{\text{out}} &= 3.995
\end{align*}
\]

Because the changes are so small, the NH₃ concentration changes are negligible.
13.1

\[ n = \frac{pV}{RT} = \frac{15.5 \text{ mm Hg}}{760 \text{ mm Hg}} \times \frac{14.7 \text{ psia}}{(10.73 \text{ psia ft})} = \frac{100 \text{ ft}^3}{(200)(1.3) \text{ R}} = 0.00524 \text{ mol} \]

\[ \text{lb H}_2\text{O} = (0.00524)(18) = 0.0944 \text{ lb H}_2\text{O} \]

13.2

Basis: 1 L gas at 780 mm Hg and T

\[ 1 \text{ L} = \frac{780 \text{ mm Hg}}{760 \text{ mm Hg}} = 1.026 \text{ L} \]

13.3

\( pV_n = (pV)_2 \)

\[ 1 \times 1 = p \times 1.2 \]

\[ p = \frac{1}{1.2} = 0.83 \text{ atm} \]

13.4

Specific volume:

\[ \dot{V} = \frac{(\dot{R}XT)}{p} = \frac{(1545.3)(28.97)}{(14.7)(144)} = 13.56 \text{ ft}^3/\text{lb}_n \]

Molar specific volume:

\[ \dot{V}_m = \frac{(\dot{R}X)}{p} = \frac{(1545.3)(78 + 460)}{(14.7)(144)} = 392.8 \text{ ft}^3/\text{lb mol} \]

Note that

\[ \dot{V} = \frac{\dot{V}_m}{MW} = \frac{392.8}{28.97} = 13.56 \text{ ft}^3/\text{lb}_n \]

13.5

\[ V = ? \]

90°F

4 in. H\text{2}\text{O} gauge

\[ 70\text{°F}, 215 \text{ psia} \]

\[ 460 + 70 = 530^\circ\text{R} \]

\[ 460 + 90 = 550^\circ\text{R} \]

Atmospheric pressure = 29.92 in. Hg = std atm = 14.7 psia

Initial pressure = 200 psig + 14.7 psia = 29.92 in. Hg

Final pressure = 29.92 in. Hg + 4 in. H\text{2}\text{O} = 33.91 ft H\text{2}\text{O}

(continued)
Solutions Chapter 13

\[ \frac{29.92 + 0.29}{0.29} = 30.21 \text{ in. Hg} \]

Basis: 1 ft\(^3\) of oxygen at 70°F and 200 psig

final volume = \[ \frac{1.00 \text{ ft}^3}{\frac{550°F}{530°F}} \times \frac{437 \text{ in. Hg}}{30.21 \text{ in. Hg}} \]

= 15.0 ft\(^3\) at 90°F and 4 in. H2O gauge

Formally, the same calculation can be made using

\[ V_2 = V_1 \left( \frac{P_1}{P_2} \right) \left( \frac{T_2}{T_1} \right) \]

since \( n_1 = n_2 \)

13.6

10 lb CO\(_2\)
known vol.
at S.C.

20 ft\(^3\)
10 lb CO\(_2\)
30°C

Solution

We can write (the subscript 1 stands for standard conditions, 2 for the conditions in the tank)

\[ P_2 = P_1 \left( \frac{V_1}{V_2} \right) \left( \frac{T_2}{T_1} \right) \]


Solutions Chapter 13

\[ \frac{14.7 \text{ psia}}{10 \text{ lb CO}_2} = \frac{44 \text{ lb CO}_2}{1 \text{ lb mol CO}_2} = \frac{359 \text{ ft}^3}{1 \text{ lb mol}} = \frac{303K}{273K} \]

\[ \frac{\nu_1}{\nu_2} = \frac{15.0}{10} \]

Hence the gauge on the tank will read (assuming that it reads gauge pressure and that the barometer reads 14.7 psia) \( 66.6 - 14.7 = 51.9 \text{ psig} \)

13.7

Assume \( p_{\text{H}_2\text{O}} = 62.4 \text{ lb/ft}^3 \), \( p_{\text{bar}} = 14.696 \text{ psia} \)

\[ P = \frac{500 \text{ ft H}_2\text{O}}{33.91 \text{ ft H}_2\text{O}} \times 14.696 \text{ psia} + 14.696 \text{ psia} = 231.387 \text{ psia} \]

\[ \nu = \frac{359 \text{ ft}^3}{\text{lb mol}} \times \frac{14.696 \text{ psia}}{231.387 \text{ lb mol}} = 22.4 \text{ ft}^3/\text{lb mol} \]

13.8

\[ pV = nRT \]

\[ T = \frac{pV}{nR} \]

\[ T = \frac{121 \text{ kPa}}{0.0011 \text{ kg mol}^{-1}} \times \frac{25 \text{ L}}{1000 \text{ L}} = 8.314 \text{ (kPa)(m)} \]

\[ = 330.8 \to 331 \text{K} \]
13.9
You must first convert the temperatures and pressures into absolute units:

\[ 460 + 70 = 530^\circ R \]
\[ 460 + 75 = 535^\circ R \]

atmospheric pressure = 29.99 in. Hg = 14.73 psia

final pressure = 29.99 in. Hg + \( \frac{4 \text{ in. H}_2\text{O}}{12 \text{ in. H}_2\text{O}} \times 29.92 \text{ in. Hg} \)

\[ = 33.91 \text{ in. H}_2\text{O} \]

\[ = 29.99 + 0.29 = 30.28 \text{ in. Hg absolute} \]

The simplest way to proceed, now that the data are in good order, is to apply the ideal gas law. Take as a basis, 16.01 ft\(^3\) (do not forget to include the volume of the O\(_2\) tank in your system) of O\(_2\) at 75\(^\circ\)F and 30.28 in. Hg. Determine the initial pressure in the O\(_2\) tank alone.

\[ P_1 = P_{\text{atm}} \left( \frac{V_1}{V_2} \right) \left( \frac{T_1}{T_2} \right) \]

\[ P_1 = 30.28 \text{ in. Hg} \left( \frac{16.01 \text{ ft}^3}{1 \text{ ft}^3} \right) \left( \frac{530^\circ R}{535^\circ R} \right) = 480 \text{ in. Hg absolute} \]

In gauge pressure,

\[ P_1 = (480 - 29.99) \text{ in. Hg} \]
\[ = 14.696 \text{ psia} = 221 \text{ psig} \]

13.10
Basis: Data in the diagram

State 1 is before corks; state 2 is after equilibrium is reached after filling. Assume \( P_A = P_{Z1} = 29.92 \text{ in. Hg abs.} \)

\[ P_{Z2} = P_A + \rho_{H_2O}h = 29.92 + h \]

where \( P_{Z2} \) is in inches Hg.

Use the ideal gas law:

\[ P_{Z2} V_{Z2} = P_{Z1} V_{Z1} \]

\[ 29.92 \times 8/6 = 39.89 \text{ in. Hg} \]

\[ 39.89 = 29.92 + h \quad \text{or} \quad h = 9.97 \text{ in. Hg} \]

\[ 9.97 + 14 = 24 \text{ in. Hg} \]

13.11
Basis: fixed amount of air in manometer

\[ A = \text{area of manometer} \]
\[ h = \text{height of air, mm} \]
\[ L = \text{length of manometer, mm} \]

\[ p_1 = 755 \quad p_2 = 740 \quad p_3 = 760 \]

\[ V_{\text{air}} = (b)(A) \]

\[ \frac{p_1}{p_2} = \frac{V_2}{V_1} = \frac{h_2}{h_1} \]

\[ p_1 = 755 - 748 = 7 \text{ mm Hg} \]

\[ L = 748 + h_1 \]

(1)

\[ p_2 = 740 - 736 = 4 \text{ mm Hg} \]

\[ L = 736 + h_2 \]

(2)

\[ 7A_{h1} = 4A_{h2} \]

(continued)
Solutions Chapter 13

\[ p_3 = 760 - (L - h_3) \quad \frac{12 + h_1}{h_2} = \frac{1}{h_2} \quad (3) \quad \frac{h_2}{h_1} = \frac{7}{4} \quad (4) \]

Solving (3) and (4): \( h_1 = 16 \text{ mm} \quad L = 764 \text{ mm} \)

\[ 7(A)(h_1) = (760 - (L - h_3))(A)(h_3) \quad (5) \]

Substituting values of \( h_1, L \) in (5), one obtains:

\[ h_3 = 18 \text{ mm} \]

The height of barometer = \( L - h_3 = 751 \text{ mm Hg} \)

13.12

Basis: 5 L at 1 atm and \( T \)

Assume \( T \) is constant throughout the dive.

At the end of the dive the pressure is \( p = \rho gh \), or easier let \( x = \text{depth in m} \).

\[ \frac{x \text{ m}}{10.34} + 1 = \rho \text{ atm} \]

The pressure for 1 L is obtained from \( p_1V_1 = p_2V_2 \)

\[ p_1 = p_1 \left( \frac{V_1}{V_1} \right) = 1 \text{ atm} \left( \frac{5 \text{ L}}{1 \text{ L}} \right) = 5 \text{ atm} \]

\[ \frac{x}{10.34} = 4 \quad \text{hence} \ x = 41.4 \text{ m} \]

13.13

Basis: air at 30 psi and 75°F in volume of tire

<table>
<thead>
<tr>
<th></th>
<th>Initial State</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>( p_1 = 44.7 \text{ psia} )</td>
<td>( p_2 = ? )</td>
</tr>
<tr>
<td>(2)</td>
<td>( T_1 = 535^\circ \text{R} )</td>
<td>( T_2 = 600^\circ \text{R} )</td>
</tr>
<tr>
<td></td>
<td>( V_1 = ? )</td>
<td>( V_2 = ? )</td>
</tr>
<tr>
<td></td>
<td>( N_1 = ? )</td>
<td>( n_2 = ? )</td>
</tr>
</tbody>
</table>

\[ \frac{p_1V_1}{p_2V_2} = \frac{\frac{N_1}{n_1}R}{\frac{T_1}{T_2}} \]

Assume volume is the same

The number of moles are the same

\[ p_2 = \frac{p_1 \left( \frac{T_1}{T_2} \right)}{\frac{V_1}{V_2}} = \frac{44.7 \left( \frac{600}{535} \right)}{500} = 50.2 \text{ psia} \]

\[ 50.2 - 14.7 = 35.5 \text{ psia} \quad \text{just over the limit} \]

13.14

Basis: 1 hr

a) \( Q = v \cdot A \)

\[ Q = \frac{11.3 \text{ ft} \cdot 3600 \text{ s} \cdot (18.0 \text{ in})^2 \cdot 1 \text{ ft}^2}{1 \text{ hr}} \cdot \frac{\pi}{(12 \text{ in})^2} \cdot \frac{2.875 \times 10^{-6} \text{ ft}^3}{\text{hr}} = 2.875 \times 10^{-4} \text{ ft}^3 \text{ hr}^{-1} \]

b) \( m = \rho v s \)

(continued)
13.15 Basis: Flue gas at 1800°F, constant pressure, and given volume

1. Calculate the inlet cross-sectional area A:
   \[ A_i = \pi \left( \frac{D_i}{2} \right)^2 = \pi \left( \frac{11.3}{2} \right)^2 = 12.57 \text{ ft}^2 \]

2. Calculate the inlet volumetric flow rate Q:
   \[ Q = (\text{velocity}) \times \text{(cross-sectional area)} = 25 \times 12.57 = 314.16 \text{ ft}^3/\text{s} \]

3. Calculate the outlet volumetric flow rate using the ideal gas law:
   \[ Q_o = Q_i \left( \frac{T_o}{T_i} \right) = 314.16 \times \frac{460 + 550}{460 + 1800} = 140.40 \text{ ft}^3/\text{s} \]

4. Calculate the outlet cross-sectional area:
   \[ A_o = \frac{Q_o}{v} = \frac{140.40}{20} = 7.02 \text{ ft}^2 \]

5. Calculate the outlet duct diameter:
   \[ (D_o)^2 = 4(A_o)\pi = 4(7.02)\pi \]
   \[ D_o = \sqrt{4(7.02)\pi} = 2.59 \text{ ft} \]

13.16 Basis: 10 kg FeS (MW = 87.9)

\[ \text{FeS} + 2\text{HCl} \rightarrow \text{H}_2\text{S} + \text{FeCl}_3 \]

10 kg FeS \( \frac{1 \text{ mol FeS}}{87.9 \text{ kg FeS}} = 0.114 \text{ kg mol FeS} \)

Assume pressure most likely is gage. Absolute pressure = 15.71 + 76.0 = 91.71 cm Hg = 122.2 kPa

\[ V = \frac{nRT}{p} = \frac{0.114 \text{ kg mol FeS} \times 8.314(\text{kJ/mol})(\text{m}^3)}{122.2 \text{ kPa}} \]

\[ = 0.0235 \text{ m}^3 @ 30^\circ \text{C and 15.71 cm Hg gauge} \]

13.17 Apply pV = nRT twice or use it once with R

Basis: 1 pound mole fg \( \frac{V}{n} = \frac{(0.7302)(560)}{1.54} \)

(1) 100°F (560°F) and 1.54 atm

(2) 32°F (492°F) and 1 atm (SC)

\[ \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \text{ so } V_2 = V_1 \left( \frac{T_1}{T_2} \right) \left( \frac{P_2}{P_1} \right) \]

\[ = 359 \text{ ft}^3 \times \frac{560}{1 \text{ atm}} \times \frac{1 \text{ lb mol}}{492 \text{ °F}} = \frac{265 \text{ ft}^3}{1 \text{ lb mol}} \]
13.18

Basis: 1 hr = 500 lb waste (W)

Get µg/ft^3 at SC 1 µg/mL = 0.001 g/L; ignore HC in totaling W

\[
\frac{500 \text{ lb W}}{1 \text{ lb}} \cdot \frac{454 \text{ g HC}}{1 \text{ g W}} \cdot \frac{0.01 \text{ g HC}}{427,000 \text{ ft}^3/\text{SC}} = 5.32 \times 10^3 \text{ g HC/ft}^3/\text{SC}
\]

The minimum volume of flue gas is

a. \[
\frac{1 \text{ ft}^3/\text{SC}}{5.32 \times 10^3 \text{ g HC/ft}^3} \cdot \frac{1 \text{ g}}{10 \text{ µg}} \cdot \frac{25 \text{ mL}}{10^6 \text{ µg}} = 0.047 \text{ ft}^3/\text{SC}
\]

b. \[
\frac{0.047 \text{ ft}^3/\text{SC}}{427,000 \text{ ft}^3/\text{SC}} \cdot \frac{1 \text{ hr}}{1 \text{ g W}} = 0.1 \times 10^{-2} \text{ hr}
\]

13.19

Basis: 1 min = 10 g VC

\[\text{air} \xrightarrow{P} \text{air} \quad T = 25^\circ \text{C} \quad p = 101.3 \text{ kPa} \quad \text{p} = 101.3 \text{ kPa} \]

Apply \( pV = nRT \) to get the volume of VC at SC and then use the mole fraction information to get the volume of air (the addition of VC to air has negligible effect on the volume)

MW VC = 78

\[
V_{\text{VC}} = \frac{n_{\text{VC}}RT}{p} = \frac{0.0101 \text{ kg VC}}{78 \text{ kg VC}} \cdot \frac{8.314 \text{ (kPa m}^3/\text{mol})}{1 \text{ kg mol VC}} \cdot \frac{298 \text{ K}}{101.3 \text{ kPa}}
\]

\[= 3.01 \times 10^{-3} \text{ m}^3 \text{ VC at SC}
\]

Volume fraction is the same as mole fraction here.

\[3.01 \times 10^{-3} \text{ m}^3 \text{ VC at SC} \cdot \frac{10^6 \text{ m}^3 \text{ air}}{1 \text{ m}^3 \text{ VC}} = 3.01 \times 10^{-3} \text{ m}^3/\text{min} \text{ an absurd number!}
\]

\[= (0.06 \times 10^6) \text{ ft}^3/\text{min}
\]

If a hood is used:

\[
\text{area} = \frac{(30)(25) \text{ in}^2}{144 \text{ in}^2} \cdot \frac{100 \text{ ft}^3}{1 \text{ ft}^3} \cdot \frac{0.3048 \text{ m}^3}{1 \text{ ft}^3} \times \frac{60 \text{ s}}{1 \text{ min}} = 882 \text{ m}^3/\text{min}
\]

a smaller amount of air.

Besides inconvenience, the discharge concentration from the hood vent may be unacceptable.
13.20

Basis: 100 ppm of TCE (MW 131.5) in air

\[ \rho = \frac{p \times \text{MW}}{RT} \]

where \( \text{MW} \) is the average MW. At 100 ppm, \( \text{MW} = (100 \times 10^{-6}) \times (131.5) + (1 - 100 \times 10^{-6}) \times 29) = 29.013 \]

The density is essentially the same as that of air.

13.21

Basis: 1 min

\[ T = \frac{(68 + 460)}{1.8} = 293 \text{K} \]

\( \text{MW} = \text{benzene} = 78.11 \text{ g/mol} \)

\[ \rho_{\text{Bz liq}} = 0.879 \text{ g/cm}^3 \]

\[ pV = nRT \]

\[ R = 0.08206 \text{ (L)(atm)/(g mol)(K)} \]

\[ n = \frac{2.5 \text{ cm}^3 \text{ liq}}{1 \text{ cm}^3} \times \frac{0.879 \text{ g Bz liq}}{78.11 \text{ g Bz}} = 0.28 \text{ g mol/min} \]

\[ V = \frac{0.0281 \text{ g mol}}{0.0206 \text{ (L)(atm)}} \times \frac{293 \text{ K}}{(740 / 760) \text{ atm}} = 0.694 \text{ L/min} \]

To dilute to 1.0 ppm, multiply by \( 10^6 \) or use \( 6.94 \times 10^6 \text{ L/min} \) (695 m³/min or 24.500 ft³/min).

13.22

Basis: 1 m³ gas passing at 10°F and 1 atm. vs 60°F and 1 atm.

\[ (\text{assume } p_1 = p_2), \ T_1 = 520 \text{°R}; \ T_2 = 470 \text{°R} \]

\[ 1 \text{ m}^3 \times \frac{520 \text{°R}}{470 \text{°R}} = 1.106 \text{ m}^3 \]

Since the moles, and mass, are directly proportional to volume at constant pressure, % increase = \( 10.6\% \).

13.23

Basis: \( \text{CO}_2 \) in cylinder

Volume of cylinder

\[ \pi r^2 h = \pi \left( \frac{0.75}{4} \right) (4.33) = 1.91 \text{ ft}^3 \]

Assume 100% \( \text{CO}_2 \) in cylinder at 0°C

\[ 1.91 \text{ ft}^3 \times 14.7 \text{ psia} / 530 \text{°R} = 11.55 \text{ ft}^3 \text{ at 14.7 psia, 70°F} \]

If the machine has a 4 gal capacity

\[ \frac{4 \text{ gal}}{7.48 \text{ gal}} = 0.535 \text{ ft}^3 \text{ at 14.7 psia and 70°F} \]

You have more than enough \( \text{CO}_2 \) to fill the machine, if it operates under atmospheric pressure.
13.24

(a) \(1.987 \text{ cal/(g mol)(K)}\), (b) \(1.987 \text{ Btu/(lb mol)(°R)}\),

(c) \(14.7 \text{ psiia} \left[ \frac{359 \text{ ft}^3}{492^\circ \text{R}} \right] = \left[ \frac{0.73 \text{ (psi) ft}^3}{\text{atm}} \right] \left[ \frac{\text{°R}}{\text{lb mol}} \right] \)

(d) \(\frac{1.013 \times 10^{-5} \text{ N/m}^2}{273 \text{ K}} = \left[ \frac{22.4 \text{ m}^3}{\text{kg mol} \cdot \text{L (N) / (mol)} \cdot 10^5 \text{ g mol} \cdot \text{°R}} \right] = 8.314 \text{ J/(g mol)(K)}\)

(e) \(\frac{1 \text{ atm} \left[ \frac{22.4 \text{ cm}^3}{273 \text{ K}} \right]}{1 \text{ g mol}} = \left[ \frac{82.06 \text{ (cm}^3\text{ atm)} / (\text{K} \cdot \text{g mol})}{\text{atm}} \right] \)

(f) \(\frac{1 \text{ atm} \left[ \frac{359 \text{ ft}^3}{492^\circ \text{R}} \right]}{1 \text{ lb mol}} = \left[ \frac{0.7302 \text{ (ft}^3\text{ atm)(lb mol)} / (\text{°R})}{\text{atm}} \right] \)

13.25

Basis: 1 ft\(^3\) O\(_2\) at 100°F, 740 mm Hg

\[ n = \frac{(740)(14.7)(1)}{(760)(10.73)(560^\circ \text{R})} = 0.00238 \text{ lb mol} \]

Density at 100°F, 740 mm Hg

\[ \rho = \frac{(0.00238)(32)}{1} = 0.0761 \text{ lb/ft}^3 \]

\[ (1.22 \text{ g/liter}) \]

13.26

Basis: 1 kg mol gas at 200 kPa and 40°C

(a) \[ R = 8.311 \text{ (kPa)(m}^3\text{) / (K)(kg mol)} \]

\[ T = 40 + 273 = 313 \text{ K} \]

\[ \frac{\text{MW} = 44 \text{ kg/kg mol}}{\rho = 200 \text{ kPa}} \]

Density \(= \rho \cdot (\text{MW}) / RT\)

\[ = \frac{200 \text{ kPa} \cdot 44 \text{ kg}}{313 \text{ K} \cdot 1 \text{ kg mol}} = \frac{3.38 \text{ kg/m}^3}{8.311 \text{ (kg mol)(K)}} \]

(b) Specific gravity here is assumed to be density of propane at SC/density of air at SC.

\[ \text{Sp. gr.} = \frac{\frac{\text{PC}_{3}H_{8}}{\text{RT}_{C_{3}H_{8}}} \left[ \frac{\text{MW}_{C_{3}H_{8}}}{\text{RT}_{air}} \right]}{\text{MW}_{air}} = \frac{44}{29} = 1.52 \]

13.27

Basis: 1 lb mol gas at 760 mm Hg and 60°F

\[ \text{Sp. gr.} = \frac{\frac{\text{PC}_{3}H_{8}}{\text{RT}_{C_{3}H_{8}}} \left[ \frac{\text{MW}_{C_{3}H_{8}}}{\text{RT}_{air}} \right]}{\text{MW}_{air}} = \frac{800(44)}{560} = \frac{520}{760} = 1.483 \]
13.28
Basis: 1 m$^3$ H$_2$ at 5°C and 110 kPa

a. $\frac{1 \text{ m}^3}{273} \frac{273}{101.3 \text{ kPa}} \frac{1 \text{ kg mol}}{22.4 \text{ m}^3} \frac{2 \text{ kg}}{1 \text{ kg mol}} = 0.0952 \text{ kg/m}^3$

b. $\frac{2 \text{ kg H}_2}{1 \text{ kg mol H}_2} \frac{11 \text{ kg mol air}}{29 \text{ kg air}} = 0.069 = \text{ specific gravity}$

13.29

Basis: 100 kg mol gas.

<table>
<thead>
<tr>
<th>Mol</th>
<th>MW</th>
<th>kg</th>
<th>wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>87</td>
<td>16</td>
<td>1392</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>12</td>
<td>30</td>
<td>360</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>1</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>1796</td>
<td>100.0</td>
</tr>
</tbody>
</table>

b) composition in vol. percent = mol percent

CH$_4$ 87%
C$_2$H$_6$ 12%
C$_3$H$_8$ 1%

c) MW of gas = $\frac{1796 \text{ kg}}{100 \text{ kg mol}} = 17.96 \text{ kg/mol}$

R = 8.314 (kPa)(m$^3$)/(kg mol)(K) $\quad T = 9°C = 282.15 K$

Solutions Chapter 13

no. of moles of gas = $\frac{80 \text{ kg}}{17.96 \text{ kg/mol}} = 4.45 \text{ kg mol}$

$V = \frac{nRT}{p} = \frac{4.45 \text{ kg mol}}{8.314 \text{(kPa)(m$^3$)}} \frac{282.15 \text{ K}}{600 \text{ kPa}} = 17.4 \text{ m}^3$

d) density = $\frac{17.96 \text{ kg}}{1 \text{ kg mol}} \frac{1 \text{ kg mol}}{22.415 \text{ m}^3 \text{ at SC}} = 0.801 \text{ kg/m}^3$

e) Specific gravity = $\frac{\text{density of gas at 9°C and 600kPa}}{\text{density of SC}}$

$\frac{600}{17.96} \frac{1}{8.314} = 282$

$\frac{101.3}{29} \frac{8.314}{273} = 3.55 \frac{\text{kg/m}^3 \text{gas at 9°C, 600 kPa}}{\text{kg/m}^3 \text{ gas at SC}}$
### Solutions Chapter 13

#### 13.30

Basis: 100 mol mixture

<table>
<thead>
<tr>
<th>Comp</th>
<th>Mol</th>
<th>Mol Wt.</th>
<th>lb</th>
<th>Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>99</td>
<td>29</td>
<td>2870</td>
<td>94.72</td>
</tr>
<tr>
<td>Br2</td>
<td>1</td>
<td>159.8</td>
<td>160</td>
<td>5.28</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>3030</td>
<td>100.00</td>
</tr>
</tbody>
</table>

b. \[ \text{Avg. Mol. Wt.} = \frac{3030}{100} = 30.3 \text{ lb mol} \]

c. \[ \text{sp.gr at SC} = \frac{30.3}{29} = 1.045 \]

d. \[ \text{sp.gr} = \frac{30.3}{159.8} = 0.1895 \]

c. \[ \frac{(30.3)(492)}{(359)} = \frac{(14.7)(29)}{(30)} = 7.54 \]

#### 13.31

Basis: 2 m³ at 200 kPa and 25°C

\[ p_{CO_2} = 200(0.8) = 160 \text{ kPa} \]

#### 13.32

Basis: Gas at 30 psig and 20°C

Assume the barometric pressure = 14.7 psia

\[ 14.7 + 30.0 = 44.7 \text{ psia} \]

\[ p_{N_2} = (44.7)(0.01) = 0.447 \text{ psia @ 20°C} \]

#### 13.33

Basis: 1 liter final volume

Assumptions:

1. Temperature is constant
2. Ideal gas law applies

\[ p_f = p_{N_2} + p_{H_2} = (760 + 760) = 1520 \text{ mm Hg} \]
13.34

Basis: 1 lb mol of gas mixture

At 20°C

$P_{CO} = P_T y_{CO} = 0.20(740) = 148 \text{ mm Hg}$

$P_{O_2} = P_T y_{O_2} = 0.60(740) = 444 \text{ mm Hg}$

$P_{N_2} = P_T y_{N_2} = 0.20(740) = 148 \text{ mm Hg}$

At 40°C the pressure is

$740 \text{ mm Hg} \times \frac{313 \text{ K}}{293 \text{ K}} = 790.5 \text{ mm Hg}$

$(P_T y_{CO})_{40°C} = (0.20)(790.5) = 158.1 \text{ mm Hg}$

$(P_T y_{O_2})_{40°C} = (0.60)(790.5) = 474.3 \text{ mm Hg}$

$(P_T y_{N_2})_{40°C} = (0.20)(790.5) = 158.1 \text{ mm Hg}$

13.35

Steps 1, 2, 3:

\[ \begin{array}{c}
\text{(F)} \\
\text{CH}_4 \\
\text{C} \quad 100 \\
\text{H} \quad 400 \\
\text{Air} \quad A \\
\text{O}_2 \quad 0.21 \\
\text{N}_2 \quad 0.79 \\
\text{CH}_4 + 3/2 \text{O}_2 \rightarrow \text{CO} + 2 \text{H}_2\text{O} \quad 1258 \\
\text{CO}_2 \quad 30 \\
\text{O}_2 \quad 55 \\
\text{H}_2\text{O} \quad 903 \\
\end{array} \]

Step 4: Unknowns: P and all the compositions of P (5 unknowns)

Step 5: Balances: C, H, O, N + fact that 30% of C → CO

Step 6: Basis: 100 mol F

Steps 7, 8:

C balance: 100 mol in CO = 30 mol

$CO_2 = 70 \text{ mol} \quad \text{out}$

100 mol

2N balance: Req'd O2: 200 mol

$\text{XS O}_2: 0.20(200) = 40$

Total O2 in 240 mol

(continued)
total \( N_2 \) in = \( \frac{240 \text{ O}_2}{0.21 \text{ O}_2} \times 0.79 \text{ N}_2 = 903 \text{ mol} = n_{\text{out}} \)

2H balance: \( \text{mol } H_2O \text{ out} = \text{mol } H_2 \text{ in} = \frac{400}{2} = 200 \text{ mol} \)

2O balance: \( O_2 \text{ in} = O_2 \text{ in } \text{CO, CO}_2, H_2O = O_2 \text{ out} \)

\[
240 - \left( \frac{30}{2} + 70 + \frac{200}{2} \right) = 55 \text{ mol}
\]

Alternate: \( XS \text{ O}_2 + O_2 \text{ not used for } \text{CO} = 40 + \frac{30}{2} = 55 \text{ mol} \)

\[
P_{\text{CO}} = P_{\text{f}Y_{\text{CO}}}
\]

\[
= (740) \frac{30}{1258} = 17.7 \text{ mm Hg}
\]

13.36

a. F  
b. F  
c. T

Solutions Chapter 13

Steps 2, 3, 4:

Step 5: Basis: Gas listed in the figure

Steps 6 and 7:

Unknowns \( p \text{ (final)}, V \text{ (final)} \); Equations: ideal gas laws

\[
V_{\text{final}} = 1 \text{ m}^3
\]

\[
\alpha_1 + \alpha_2 = \alpha_{\text{final}}
\]

Steps 8 and 9:

\[
\alpha_1 = \frac{p_1 V_1}{R T_1}, \quad \alpha_2 = \frac{p_2 V_2}{R T_1}, \quad \alpha_\text{f} = \frac{p_\text{f} V}{R T_\text{f}}
\]

\[
\frac{(600 \text{ kPa})(0.5 \text{ m}^3)}{293 \text{ K}} + \frac{(150 \text{ kPa})(0.5 \text{ m}^3)}{303 \text{ K}} = \frac{P_{\text{f}} (\text{kPa}) (1.0 \text{ m}^3)}{283 \text{ K}}
\]

\[
P_{\text{from}} = 366 \text{ kPa}
\]
13.38
Steps 2, 3, and 4: \( p_1 = 55 + 14.7 = 69.7 \text{ psia} \)

Step 5: Basis: Gas with given data

Step 6 and 7: Unknowns: \( T_1, T_2, T_r, p_r \) \( (V_r = 400 + 50 = 450 \text{ ft}^2) \)

Equations:
\[
\begin{align*}
    p_1V_1 &= n_1RT_1 \\
    p_2V_2 &= n_2RT_2 \\
    n_1 + n_2 &= n_r \\
    p_rV_r &= n_rRT_r \\
    n_1 &= \frac{p_1V_1}{RT} = \frac{400(69.7)}{RT} \\
    n_2 &= \frac{(50)(14.7)}{RT} \\
    p_rV_r &= \frac{\left(50(14.7) + 400(69.7)\right)RT}{450} = \frac{28635}{450} = 63.8 \text{ psia} = 48.9 \text{ psig} \\
    p_1 &= \frac{50(14.7) + 400(69.7)}{450} = 63.8 \text{ psia} = 48.9 \text{ psig}
\end{align*}
\]

13.39
Steps 2, 3, and 4:

100 psig = 114.7 psia

MW = \frac{28 \text{ lb}}{1 \text{ lb mole}}

60°F = 520°F

Step 5: Basis: 100 ft³ N₂ @ 100 psig and 60°F final moles

Final Moles:
\[
\begin{align*}
    &100 \text{ ft}^3 \left| 114.7 \text{ psia} \right| 492°F \left| 1 \text{ lb mol} \right| \\
    &14.7 \text{ psia} \left| 520°F \right| 359 \text{ ft}^3 = 2.056 \text{ lb mol}
\end{align*}
\]

Initial moles: \( 2.056 + \frac{1}{26} = 2.092 \text{ lb mol} \)

Initial pressure:
\[
\begin{align*}
    p &= \frac{nRT}{V} = \frac{2.092 \text{ lb mol} \cdot (80 + 460) \text{R}}{100 \text{ ft}^3} = \frac{0.7302(\text{ft}^2)(\text{ atm})}{(\text{lb mol})(\text{ R})} \\
    &= 8.24 \text{ atm abs} (121.2 \text{ psia}) \\
    &= (106.5 \text{ psig})
\end{align*}
\]

13.40
Step 5: Basis: 1 min

Steps 2, 3, and 4:

\[
\begin{align*}
    SF_e &= 1.29 \text{ kg mol} \\
    F &= ? \text{ kg mol} \\
    T &= 60°C \\
    P &= ? \text{ kg mol} \\
\end{align*}
\]

(continued)
28.8 m³ at SC : 1 kg mol  = 1.29 kg mol
22.4 m³ at SC

Step 6: Unknowns: P, F
Step 7: Indep. balances: air, SF6
Step 8-9: Balances are in moles

SF6: F(0) + 1.29 = P(4.15×10⁴) hence P = 3.098×10⁴ kg mol

3.098×10⁴ kg mol  = 8.46×10⁴ m³/min
22.4 m³ at SC 60 + 273
1 kg mol 273

Alternate solution:

28.8 m³ at SC 333K 1
273K 4.15×10⁹

13.41

Step 5: Basis: 15 lb CO₂ added = 30 min

Step 2, 3, and 4:

<table>
<thead>
<tr>
<th>P(pF)</th>
<th>P(Fg)</th>
<th>CO₂</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°F</td>
<td>14.79 lb mol</td>
<td>21.9(lb mol)(R)</td>
<td>60 + 460°F</td>
</tr>
</tbody>
</table>

at 60°F and 31.2 in Hg
13.44

The gas in the cell is composed partly of NO and partly of NO₂. We can use the ideal gas law to calculate the total gram moles present in the cell.

\[ R = \frac{101.3 \text{ kPa} \times 22.41 \text{ L}}{273 \text{ K} \times 1 \text{ g mol}^{-1} \times 1 \text{ L}} = \frac{8.316 \times 10^3 \text{(Pa) cm}^3}{\text{(K) g mol}^{-1}} \]

\[ n = \frac{pV}{RT} = \frac{170 \text{ kPa} 	imes 100 \text{ cm}^3}{8.316 \times 10^3 \text{(Pa) cm}^3/(\text{K g mol}^{-1}) \times 303 \text{ K}} = 0.00675 \text{ g mol} \]

If the mixture is composed of NO (MW = 30) and NO₂ (MW = 46), because we know the total mass in the cell we can compute the fraction of, say, NO. Let \( x \) = grams of NO, then (0.291 - \( x \)) = g NO₂. In a table format the calculation is

<table>
<thead>
<tr>
<th>Component</th>
<th>( g )</th>
<th>Mol. Wt.</th>
<th>( g ) mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>( x )</td>
<td>30</td>
<td>( \frac{x}{30} )</td>
</tr>
<tr>
<td>NO₂</td>
<td>0.291 - ( x )</td>
<td>46</td>
<td>( \frac{0.291-x}{46} )</td>
</tr>
<tr>
<td>Total</td>
<td>0.291</td>
<td></td>
<td>0.00675</td>
</tr>
</tbody>
</table>

or

\[ \frac{x}{30} + \frac{0.291-x}{46} = 0.00675 \]

\[ 0.0333x + (0.291 - x)(0.0217) = 0.00675 \]

\[ x = 0.0366 \text{ g} \]

The weight percent NO is

\[ \frac{0.0366}{0.291}(100) = 12.5\% \]

and the mole percent NO is

\[ \frac{0.0366 \text{ g NO}}{0.00675 \text{ g mol total}} \times 1 \text{ g mol NO}^{-1} = 18\% \]

Can you let \( x \) be the mole fraction NO and obtain the same result? (Answer: Yes.)

13.43

Steps 2, 3, and 4:

Steps 6, 7, 8 and 9:

\[ \text{mol of gas out} = \frac{30.000 \text{ ft}^{-3}}{720 \text{ mm Hg}} = 492^\circ \text{ R} = 1 \text{ mole} = 75 \text{ mol} \]

\[ \text{60 mol gas CO}_2 \Leftrightarrow 0.162 \text{ mol CO}_2 \text{ in} \]

\[ 1 \text{ mol gas} \]

\[ \text{75 mol gas CO}_2 \Leftrightarrow 0.131 \text{ mol CO}_2 \text{ out} \]

\[ 1 \text{ mol gas} \]

\[ \text{mol of gas in} = \frac{47.800 \text{ ft}^{-3}}{740 \text{ mm Hg}} = 492^\circ \text{ R} = 1 \text{ mole} = 60 \text{ mol} \]

Thus since there are more moles out than in, one may assume the system does contain a leak. Also, assuming a leak would bring no additional CO₂ into the system, the above CO₂ balance calculations indicate the given analysis is probably correct.
13.44

Basis: 1 mol of NH₃ fed

NH₃ balance:  
\[
(1 + R) \times (0.2) = R \\
0.8 \times R = 0.2
\]

\[
R = 0.25 \left( \frac{\text{mol NH}_3 \text{ recycled}}{\text{mol NH}_3 \text{ fed}} \right)
\]

\[
R = 0.25 \left( \frac{0.25 \text{ mol recycled}}{1 \text{ mol NH}_3 \text{ fed}} \right)
\]

\[
1 \text{ m}^3(100^\circ \text{C}, 150 \text{ kPa}) \text{NH}_3 \text{ fed} \times 0.25 \text{ mol recycled} / (150 + 273) \text{K}
\]

\[
= 0.284 \left( \frac{\text{m}^3 \text{ recycled at } 150^\circ \text{C}, 150 \text{ kPa}}{\text{m}^3 \text{ NH}_3 \text{ fed at } 100^\circ \text{C}, 150 \text{ kPa}} \right)
\]

13.45

Process: Steady state with reaction and recycle

Step 5: Basis: 1 min 260L C₆H₆

13.46

Solutions Chapter 13

Steps 2, 3, and 4:

C₆H₆ + 3 H₂ \rightarrow C₆H₁₂

Convert L \rightarrow mol

\[
\text{feed: } n = \frac{\rho V}{RT} \quad p = 150 \text{ kPa}
\]

\[
n_{\text{H}_2} = 45.96 \text{ g mol} \quad T = 100^\circ \text{C} + 273 = 373K
\]

\[
n_{\text{C}_6\text{H}_6} = 12.58 \text{ g mol} \quad R = 8.314 \left( \frac{(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})} \right)
\]

Steps 6, 7, 8 and 9:

Select the overall system for the first balances.

\[
\text{H}_2: \quad 45.96 \quad n_{\text{H}_2} \quad + \quad 0 \quad - \quad 0.75(45.96) \quad = \quad 0
\]

\[
\text{C}_6\text{H}_6: \quad 12.58 \quad n_{\text{C}_6\text{H}_6} \quad + \quad 0 \quad - \quad 0.75(45.96)\frac{3}{2} \quad = \quad 0
\]

\[
n_{\text{H}_2} = 11.5 \text{ g mol}
\]

\[
n_{\text{C}_6\text{H}_6} = 1.09 \text{ g mol}
\]

\[
n_{\text{C}_6\text{H}_6} = 11.5 \text{ g mol}
\]

b. Volumetric flow rates: T = 200°C = 473K

\[
P = 100 \text{ kPa} = 0.987 \text{ atm}
\]

(continued)
Solutions Chapter 13

\[ V_{\text{n}} = \frac{(n_{\text{w}})(RT)}{p} = 452 \text{ liters/min} \]

\[ V_{\text{cm}} = 42.8 \text{ liters/min} \]

\[ C_4H_8 = 452 \text{ liters/min} \]

c. \text{ H}_2 \text{ balance on Reactor + Separator}

\[ H_2: (45.95 + 0.90R) - (0.90R + 11.5) + 0 - 0.48(45.95 + 0.90R) = 0 \]

Substitute for \( n_{H_2} \) and solve to get \( R = 28.7 \text{ kg mol} \)

Volumetric flow rate (R) = 800 liters/min

13.46 Basis: 1 day = 10^4 kg C_2H_4O

Step 5: Basis

\[ \frac{10,000 \text{ kgf}}{1.00 \text{ kg mol day}} \times \frac{1.00 \text{ kg mol}}{44 \text{ kg}} = 227.3 \text{ kg mol C}_2\text{H}_4\text{O/day} \]

Steps 6, 7, 8 and 9:

Mixing point: \( F_1 + R = F_2 = 1.0 F_1 + R = n_{C_2H_4} \), \( 0.60 F_1 = n_{O_2} \). Unknowns: \( F_1, F_2, R, n_{O_2}, n_{C_2H_4} \).

Reactor plus separator:

### C_2H_4 balance:

\[ \begin{array}{c}
\text{in} & \text{out} & \text{consumed} \\
0.4(F_1) + R & -R & 0.4(F_1) + 0.5R = 0
\end{array} \]

### C_2H_4O balance:

\[ 0 - 227.3 + [F_1(0.4) + R]_0 (0.50) (0.70) = 0 \]

\( F_1 = 811.79 \text{ kg mol/day} \)

\( F_1 + R = F_2 = 1136.49 \)

(a) \[ \frac{1136.5 \text{ kg mol}}{22.40 \text{ m}^3 \text{ at SC day}} \times \frac{1 \text{ kg mol}}{44 \text{ kg}} \times \frac{1 \text{ day}}{24 \text{ hr}} = 1059 \text{ m}^3 \text{ at SC/hr} \]

(b) \[ \frac{811.79(0.40) \text{ kg mol of C}_2\text{H}_4 \text{ in F}_1}{22.40 \text{ m}^3 \text{ at SC} \times 283 \text{ K} \times 101.3 \text{ kPa} = 4.05} \]

Overall balances (kg mol): unknowns \( n_{O_2} \)

\[ \text{Balances} \]

(continued)
\[
\text{C: } 811.79 \times (40) \times (2) = 227.3 \times (2) + n_{\text{CO}_2} \quad n_{\text{CO}_2} = 194.83 \\
\text{H: } 811.79 \times (40) \times (4) = 227.3 \times (4) + n_w \times (2) \times n_w = 194.83 \\
\text{O: } 811.79 \times (60) \times (2) = 227.3 \times (1) + 194.83 \times (2) \\
\quad + 194.83 \times (1) + n_{\text{O}_2} (2) \\
\quad n_{\text{O}_2} = 81.18 \\
\text{G} = 194.83 + 194.83 + 81.18 = 470.84 \\
\]
\[
\text{470.84 kg mol} \times \frac{P}{\text{day}} \times \frac{22.4 \text{ m}^3}{\text{kg mol}} \times \frac{273}{100} = 353 \times 101.3 \text{ m}^3 \text{ at SC} \\
\boxed{\text{(c) } 1.38 \times 10^4 \text{ m}^3 \text{ gases/day at 80°C and 100 kPa}}
\]

**Step 4:**
\[
\text{mol in} \\
pV = nRT \\
n = \frac{pV}{RT} = \frac{689 \text{ kPa} \times 3,000 \text{ m}^3}{8.314 \text{ (kJ mol}^{-1}\text{K}^{-1}) \times 294 \text{ K}} = 845.635 \text{ kg mol/day} \\
y = \frac{p}{Pr} = \frac{586 \text{ kPa}}{689 \text{ kPa}} = 0.8505 \text{ mol C}_4\text{H}_{10} \text{ mol feed} \\
\text{Steps 6-9:} \\
\text{mol C}_4\text{H}_{10} \text{ out} \\
L = \frac{845.635 \text{ kg mol} \times 0.8505 \text{ mol C}_4\text{H}_{10}}{\text{day} \times \text{mol feed}} = \frac{0.8 \text{ mol C}_4\text{H}_{10} \text{ feed}}{575.35 \text{ mol C}_4\text{H}_{10} \text{ day}} \\
\text{overall mol balance (no reaction)} \\
F = L + V \\
V = F - L = 845.635 - 575.35 = 270.26 \text{ kg mol} \\
pV = nRT \\
\frac{V}{P} = \frac{270.26 \text{ kg mol} \times 8.314 \text{ (kJ mol}^{-1}\text{K}^{-1}) \times 311 \text{ K}}{550 \text{ kPa}} = 1,270.57 \text{ m}^3
13.48
Steps 1, 2, 3, 4: Steady state problem with a reaction.

\[ \text{mol fr} \rightarrow 100 \text{kPa} \rightarrow 260^\circ \text{C} \rightarrow \text{mol fr} \]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>( n_{\text{CO}_2} )</td>
</tr>
<tr>
<td>H₂O</td>
<td>( n_{\text{H}_2\text{O}} )</td>
</tr>
<tr>
<td>O₂</td>
<td>( n_{\text{O}_2} )</td>
</tr>
<tr>
<td>N₂</td>
<td>( n_{\text{N}_2} )</td>
</tr>
</tbody>
</table>

\[ \Sigma n_i = P \]

\[ 40\% \text{ xs (mol)} \]

Air

<table>
<thead>
<tr>
<th>mol fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
</tr>
<tr>
<td>N₂</td>
</tr>
<tr>
<td>1.00</td>
</tr>
</tbody>
</table>

Step 5: Basis: 1 kg mol n-butane

Step 6: Unknowns are the moles in P (4) plus P.

Step 7: The element balances are C, H, O, N, and we can use \( \Sigma n_i = P \) so we can get a unique solution. You can use element balances or compound balances. The former is easier.

Step 4: Calculate A given the 40.0% excess air.

\[ \text{C}_4\text{H}_{10} + 6\frac{1}{2} \text{O}_2 \rightarrow 4 \text{CO}_2 + 5 \text{H}_2\text{O} \]

\[ \frac{1.00 \text{ kg mol C}_4\text{H}_{10}}{1 \text{ kg mol C}_4\text{H}_{10}} \times 6.5 \text{ kg mol O}_2 = 6.5 \text{ kg mol O}_2 \]

\[ 6.5(0.40) = 2.60 \text{ kg mol O}_2 \text{ xs} \]

\[ = 9.10 \text{ kg mol O}_2 \text{ total} \]

\[ n_{\text{CO}_2} = 4 \]

\[ n_{\text{H}_2\text{O}} = 5 \]

\[ n_{\text{O}_2} = 2.6 \]

\[ n_{\text{N}_2} = 34.23 \]

\[ P = 4 + 5 + 2.6 + 34.23 = 45.83 \text{ kg mol} \]

\[ V = \frac{nRT}{p} = \frac{45.83 \text{ kg mol} \times 8.314 \text{ (kPa)} \text{ (m}^3\text{) K}^{-1}}{100.0 \text{ kPa} \times \frac{(\text{kg mol})}{(\text{K})}} \]

\[ = 2.03 \times 10^4 \text{ m}^3 \]
Solutions Chapter 13

a. Flue gas analysis

<table>
<thead>
<tr>
<th></th>
<th>kg mol</th>
<th>mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>H₂O</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>O₂</td>
<td>2.6</td>
<td>6</td>
</tr>
<tr>
<td>N₂</td>
<td>34.23</td>
<td>75</td>
</tr>
<tr>
<td>Total</td>
<td>45.83</td>
<td>100</td>
</tr>
</tbody>
</table>

13.49

\[ F_1 \xrightarrow{H_2, 100\%} \text{Reactor} \xrightarrow{1000°C} HCl \xrightarrow{100\%} W \]

\[ F_2 \xrightarrow{HSiCl_3, 100\%} \text{P} \]

Si 100% 644.95 mol

\[ P = (D)(V) = \left[ \frac{\pi}{4} L (D_o^2 - D_i^2) \right] = \frac{2.33 \pi}{4} \left[ 100 \text{ cm}^3 \right] \left[ (10 \text{ cm})^2 - (1 \text{ cm})^2 \right] \frac{\text{g mol}}{28.086 \text{ g}} = 644.95 \text{ g mol Si product} \]

\[ \text{Si balance} \]

\[ \frac{F_2 \text{ g mol HSiCl}_3}{1 \text{ g mol HSiCl}_3} = \frac{1 \text{ g mol Si}}{P \text{ g mol Si}}, \text{ hence } F_2 = P \]

\[ \text{H g mol balance} \]

\[ \frac{F_2 \text{ g mol H}_2}{1 \text{ g mol H}_2} = \frac{F_1 \text{ g mol HSiCl}_3}{1 \text{ g mol HSiCl}_3} = \frac{W \text{ g mol HCl}}{1 \text{ g mol HCl}} \]

Cl mol balance

\[ F_1(0) + \frac{F_2 \text{ g mol HSiCl}_3}{1 \text{ g mol HSiCl}_3} = \frac{3 \text{ g mol Cl}}{1 \text{ g mol HSiCl}_3} = \frac{W \text{ g mol HCl}}{1 \text{ g mol Cl}} \]

Solution:

\[ F_2 = P = 1 \text{ g mol HSiCl}_3 \]

\[ 3F_2 = W = 3 \text{ g mol HCl} \]

\[ 2F_1 + F_2 = W \]

\[ F_1 = \frac{3 \text{ g mol} - 1 \text{ g mol}}{2} = 1 \text{ g mol H}_2 \]

\[ 1 \text{ g mol H}_2 \frac{644.95 \text{ g mol Si}}{644.95 \text{ g mol H}_2} = 644.95 \text{ g mol H}_2 \]

\[ \text{pV = nRT} \]

\[ V = \frac{nRT}{p} \]

\[ = \frac{644.95 \text{ g mol} \cdot 82.06 \left( \text{cm}^3 \text{ atm} \right)/\left( \text{g mol} \left( \text{K} \right) \right) \cdot 1273 \text{ K} \cdot 1 \text{ L}}{(1 \text{ atm} \cdot 1000 \text{ cm}^3)} = 67.373 \text{ L} \]
Solutions Chapter 13

13.50

From incineration at 60°F and 30 in Hg abs, the product H₂O (100%)

\[ W = 1200 \text{ ft}^3 \]

CO₂ 12.2%
CO 0.7%
O₂ 2.4%
CH₄ 2.0%
H₂ 16.0%
N₂ 52.0%

W = 1200 ft³ @ 60°F and 30 in Hg abs.

80.5% CH₄
17.8% C₂H₆
1.7% N₂

Step 1, 2, 3, and 4: Steady state process with reaction.

Step 5: Basis: 1 min.

Step 6, 7, 8, 9:

Element balance: have C, H, O, N, and have 4 unknowns P, Y, F, A.

Basis: 1200 ft³ of W at 60°F and 20 in. Hg

<table>
<thead>
<tr>
<th></th>
<th>Fin</th>
<th>Air</th>
<th>Win</th>
<th>Yout</th>
<th>Pout</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>(0.04 + 0.26 + 0.02) F</td>
<td>+</td>
<td>0</td>
<td>+ (0.805 + 2x0.178) W</td>
<td>-</td>
</tr>
<tr>
<td>N₂</td>
<td>(0.52) F</td>
<td>+</td>
<td>0.79A</td>
<td>+</td>
<td>0.07W</td>
</tr>
<tr>
<td>H₂</td>
<td>(0.04 + 0.16) F</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>(1.61 + 0.534) W</td>
</tr>
<tr>
<td>O</td>
<td>(0.08 + 0.26) F</td>
<td>+</td>
<td>0.42A</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>

Introduce W = 1200 ft³

C: 0.32F + 0 + 1393.2 ft³ - 0 - 0.129P = 0
N₂: 0.52F + 0.79A + 20.4 ft³ - 0 - 0.847P = 0
H₂: 0.20F + 0 + 2572.8 ft³ - Y - 0 = 0
O: 0.34F + 0.42A + 0 - Y - 0.299P = 0

Solutions Chapter 13

Solve: \[ F = 3,975 \text{ ft}^3 \]
\[ A = 19,510 \text{ ft}^3 \]
\[ Y = 3,370 \text{ ft}^3 \]
\[ P = 26,660 \text{ ft}^3 \]

Air in = \[ 19,510 \text{ ft}^3 @ 60°F & 30 \text{ inches Hg} \]
\[ 540°F \\
520°F \\
29.6 \text{ inches Hg} \]
\[ = 20,535 \text{ ft}^3 \]

13.51

Basis: 1 lb mol of 50% H₂ and 50% C₂H₆O

\[ p_1 V_1 = n_1 R T_1 \]
\[ p_2 V_2 = n_2 R T_2 \]
\[ T_1 = T_2 \]

\[ \frac{p_1}{p_2} = \frac{n_1}{n_2} \]
\[ \frac{760 \text{ mm Hg}}{700 \text{ mm Hg}} = \frac{1}{h n_2} \]

hence \[ n_2 = 0.922 \text{ lb mol} \]

Let \[ y = \text{mol of C₂H₆O formed} \]

\[ (0.5 - y) + (0.5 - y) + y = 0.922 \]

from which \[ y = 0.079 \text{ lb mol} \]

C₂H₆O formed

Degree of completion = \[ \frac{0.079}{0.5} \times 100 = [15.8\%] \]

13.52

C₆H₁₂O₆ is glucose and C₃H₆O₃ is glyceroct

The reaction equation is

\[ a \text{CH}_₃\text{O}_₆ \text{N}_₅ + b \text{NH}_₃ + c \text{C}_₃\text{H}_₆\text{O}_₃ \]

(continued)
\[ d \text{ C}_2\text{H}_4\text{O}_2 + c \text{ CO}_2 + f \text{ N}_2 + g \text{ H}_2\text{O} \]

The amount of CO\(_2\) measured (52.4L at 95 kPa and 300 K) is

\[
\frac{52.4 \text{ L CO}_2}{1 \text{ m}^3} \times \frac{1 \text{ m}^3}{1000 \text{ L}} \times \frac{1 \text{ kg mol}(\text{K})}{300 \text{ K} \times 8.314 \text{ (kPa)(m}^3\text{)}} = 2 \times 10^{-7} \text{ kg mol or 2.00 g mol} \]

Use element balances and specifications to get the coefficients in the reaction equation. Let c = 1 (divide both sides by c) be the basis for obtaining the coefficients: then there are 6 unknowns, 4 equations, and two specifications:

\[
\begin{align*}
\text{C:} & \quad a + 6c = 3d + e \\
\text{H:} & \quad 1.8a + 3b + 12 = 8d + 2g \\
\text{O:} & \quad 0.5a + 6 = 3d + 2.00(2) + g \\
\text{N:} & \quad 0.5a + b = 2b \\
\end{align*}
\]

Specifications:

\[
\begin{align*}
\frac{a}{b} = 1 & \quad \text{and} \quad \frac{e}{c} = 2
\end{align*}
\]

The solution of the equations is:

\[
\begin{align*}
a = 7.27, & \quad b = 3.64, & \quad d = 1.09, & \quad f = 3.64, & \quad g = 1.64
\end{align*}
\]

The glycerol produced was \(1.09 \text{ g mol}\), and

The biomass reacted was \(7.27 \text{ g mol}\).
### Solutions Chapter 13

#### Exit gas

<table>
<thead>
<tr>
<th>Component</th>
<th>kg</th>
<th>MW</th>
<th>g mol</th>
<th>m³ at SC on the basis of 10⁶ kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>44,613</td>
<td>43,812</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td>N₂ exiting</td>
<td>369,227</td>
<td>0.722</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O exiting</td>
<td>(2)(44,613)</td>
<td>0.174</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂ exiting</td>
<td>(0.10)(89,226)</td>
<td>0.017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td>(9.6)/46</td>
<td>0.15</td>
<td>2.9 x 10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>NO₂</td>
<td>3040/46</td>
<td>66</td>
<td>1.3 x 10⁻³</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>1344/28</td>
<td>48</td>
<td>9.3 x 10⁻⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>640/28</td>
<td>23</td>
<td>4.5 x 10⁻⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total (about)</td>
<td>511,200</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

On a dry basis:

mol%:

- SO₂: 3.5 x 10⁻⁵
- NO₂: 1.6 x 10⁻⁴, 8.2 x 10⁻⁴, and 7.8 x 10⁻⁴ respectively
- CO: 1.1 x 10⁻⁴ and 5.5 x 10⁻⁵, respectively

#### 13.55

Basis: 10³ L of No. 6 fuel oil

\[
10^3 \text{ L oil} \times 0.86 \text{ g} = 8.6 \times 10^3 \text{ g or } 8.6 \times 10^3 \text{ kg of oil}
\]

To get the moles of pollution components alone in the gas produced, the kg have to be converted using MW (ignore the particulate matter)

---

#### Example of calculating the m³ at SC on the basis of 1 metric ton (10⁶ kg) of No. 6 fuel oil burned:

\[
\text{SO}_2: \frac{0.249 \text{ kg mol}}{8.6 \times 10^3 \text{ kg oil}} \times \frac{22.415 \text{ m}^3 \text{ at SC}}{1 \text{ kg mol}} = 6.5 \text{ m}^3 \text{ at SC}
\]

#### 13.56

Basis: 10³ L of No. 6 fuel oil

\[
10^3 \text{ L oil} \times 0.86 \text{ g} = 8.6 \times 10^3 \text{ g or } 8.6 \times 10^3 \text{ kg of oil}
\]

Calculate the kg mol of each compound in the oil:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Mass fraction</th>
<th>kg</th>
<th>MW</th>
<th>kg mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.8726</td>
<td>759.4</td>
<td>12</td>
<td>62.53</td>
</tr>
<tr>
<td>H</td>
<td>0.1049</td>
<td>90.21</td>
<td>1.008</td>
<td>89.49</td>
</tr>
<tr>
<td>O</td>
<td>0.64 x 10⁻²</td>
<td>5.5</td>
<td>16</td>
<td>0.34</td>
</tr>
<tr>
<td>N</td>
<td>0.28 x 10⁻²</td>
<td>2.4</td>
<td>14</td>
<td>0.17</td>
</tr>
<tr>
<td>S</td>
<td>0.84 x 10⁻²</td>
<td>7.2</td>
<td>32</td>
<td>0.23</td>
</tr>
<tr>
<td>ash</td>
<td>0.04 x 10⁻²</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Calculate the moles of product gas

(continued)
### Solutions Chapter 13

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>kg mol</th>
<th>MW</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂:</td>
<td>C + O₂ → CO₂</td>
<td>62.53</td>
<td>44</td>
<td>2751</td>
</tr>
<tr>
<td>N:</td>
<td>N + O₂ → NO₂</td>
<td>0.17</td>
<td>46</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**S:** The SO₂ and SO₃ are from the EPA data and Problem 13.55

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>kg</th>
<th>kg mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂:</td>
<td></td>
<td>0.58</td>
<td>0.0073</td>
</tr>
<tr>
<td>SO₃</td>
<td></td>
<td>15.96</td>
<td>0.249</td>
</tr>
</tbody>
</table>

If the S + O₂ → SO₂ is used as the product from the S in the oil, the value of 0.23 can be compared with 0.25 (ignoring the SO₃).
14.1

Basis: 7 lb N₂ or 7/28 = 0.25 lb mol N₂

a. \[ p = \frac{nRT}{V} = \frac{0.25 \text{ lb mol} \left[ \frac{(120 + 460)^0R}{0.732 \text{ atm}(\text{ft}^3)} \right]}{0.75 \text{ ft}^3} = 141 \text{ atm} \]

b. \[ T_r = \frac{T}{T_c} = \frac{126.3}{580} = 0.218 \]
\[ p_r = \frac{p}{p_c} = \frac{33.54}{4.3} = 7.79 \]
\[ V_r = \frac{V}{V_c} = \frac{0.75 \text{ ft}^3}{(126.3)(1.8)} = 0.407 \]

From the compressibility charts:
\[ p_c = 4.3 \text{ atm/ft}^3 \]
so that \[ p = p_r p_c = (4.3)(33.54) = 144 \text{ atm} \]

Note: You calculate \( z \) from \( T_r \) and \( V_r \), and then use \[ p = \frac{nRT}{V} \]

14.2

Basis: 2 g mol C₂H₅

\[ p_c = 50.5 \text{ atm} \]
\[ T_c = 283.1 \text{ K} \]
\[ T = 95 + 273.1 = 368.1 \text{ K} \]
\[ V_r = \frac{RT}{p} = \frac{82.06 \text{ cm}^3(\text{atm})(\text{mol})}{(50.5 \text{ atm})(283.1 \text{ K})} = 460 \text{ cm}^3/\text{g mol} \]

14.3

Basis: 3 lb mol of gas at 252°C and 463 psia.

Volume = 50 ft³

\[ R = \frac{(1 \text{ atm})(359 \text{ ft}^3)}{(1 \text{ lb mol})(273 \text{ K})} = 1.315 \left( \frac{\text{atm}(\text{ft}^3)}{(\text{lb mol})(\text{K})} \right) \]

\[ z = \frac{463 \text{ psia}}{14.7 \text{ psia atm}} \left( \frac{50 \text{ ft}^3}{1 \text{ lb mol}} \right) \left( \frac{1 \text{ atm}}{1.315 \left( \frac{\text{atm}(\text{ft}^3)}{(\text{lb mol})(\text{K})} \right)(273 + 252°C)} \right) = 0.76 \]

The Pitzer aspheric factor is not as convenient to use as the compressibility charts.

From compressibility charts (see the CD for better precision)
\[ z = 0.76 \]
\[ T_r = \frac{525}{500} = 1.05 \]
\[ p_r = 0.7 \]

(continued)
Solutions Chapter 14

Thus
\[
\frac{463 \text{ psia}}{p_e} = 0.7
\]
\[p_e = 661 \text{ psia} \times 45.0 \text{ atm}
\]

14.4

Basis: 1 lb n-octane
\[T_e = 1025^\circ R \quad p_e = 24.6 \text{ atm} \quad \text{MW} = 114
\]
\[p_r = \frac{27}{24.6} = 1.10
\]

To get the temperature of the gas
\[
\begin{align*}
1 \text{ lb} & \quad 1 \text{ lb mol} & 359 \text{ ft}^3/\text{SC} & 1 \text{ atm} & T & K & z \\
114 \text{ lb} & & 27 \text{ atm} & 273 \text{ K} & = 0.20 \text{ ft}^3
\end{align*}
\]
\[T_z = 845 \quad zT_e = 845/1025 = 0.825
\]

From the compressibility Chart Fig. 14.4b (expanded in the CD)
read \(T = 1.16\), so that \(T = (1.16)(1025) = 1189^\circ R \) (729°F)

Alternate solution: Calculate \(z = 0.71\) and use \(pV = znRT\).

Solutions Chapter 14

14.5

Basis: 50 lb CO\(_2\) (50/44) = 1.138 lb mol CO\(_2\)
\[V = 5.0 \text{ ft}^3 \quad p = 1600 + 14.7 = 1614.7 \text{ psia}
\]
\[P_e = 1070 \text{ psia} \quad T_e = 547.5^\circ R
\]
\[p_r = \frac{1614.7}{1070} = 1.51 \quad \dot{V} = \frac{5.0}{1.138} = 4.40 \text{ ft}^3/\text{lb mol}
\]
\[V_d = 5.50 \text{ ft}^3/\text{lb mol} \quad \text{so that} \quad V_e = \frac{4.40}{5.50} = 0.800
\]
\[T_f \text{ from Figure 14.4b is (expanded in the CD) is 1.44}
\]
\[T = (1.44)(547.5) = 788^\circ R \quad (328^\circ F)
\]
The Pitzer asentric factor is less convenient to use for this problem.

14.6

Basis: 10 kg CH\(_4\)
\[\text{MW CH}_4 = 16.03 \quad 10 \text{ kg} \quad 1 \text{ kg mol} = 0.624 \text{ kg mol}
\]
\[T_e = 305.4 K \quad \text{and} \quad p_e = 4883 \text{ kPa}
\]
\[V = 0.0250 \text{ m}^3 \quad p = 14,000 \text{ kPa gauge} = 14,015 \text{ kPa absolute}
\]
\[p_r = \frac{14,015}{4883} = 2.87
\]

(continued)
\[ V_v = \frac{RT_v}{P_v} = \frac{(8.314)(305.4)}{4883} = 0.520 \text{ m}^3/\text{kg mol} \]

\[ V_i = 0.0250 \]

\[ V_i = 0.048 \]

\[ V_i = 0.520 \]

From the compressibility chart, \( T_v \approx 1.05 \) hence \( T = (1.05)(305.4) = 321 \text{ K} \)

**14.7**

**Basis:** 1 ft\(^3\) CH\(_4\)

\[ pV = nRT \quad p = 214.7 \text{ psia} \]

\[ R = \frac{10.73(\text{psia})(\text{ft})}{(\text{lb mol})(\text{°R})} \]

\[ T_v = 191.9 \text{ °K} \rightarrow 344 \text{ °R} \]

\[ p_v = 45.79 \text{ atm} \rightarrow 672.9 \text{ psia} \]

\[ T_i = \frac{540}{344} = 1.57 \quad p_i = \frac{214.3}{214.7} = 1.0 \]

\[ z = 0.975 \]

\[ n = \frac{214.3(1)}{10.73(540)(0.975)} = 0.038 \text{ lb mol} \]

\[ \text{weight (mass)} = (0.038)(16.03) = 0.608 \text{ lb} \]

By use of the Pitzer ascentric factor (\( \omega = 0.008 \) for CH\(_4\))

\[ z = z^2 + z^2\omega = 0.976 + 0.024(0.008) = 0.976 \]

**14.8**

**Basis:** 25L of CO\(_2\) at 25°C and 200 kPa

For CO\(_2\):

\[ p_v = 7385 \text{ kPa} \]

\[ T_v = 304.2 \text{ K} \]

\[ p_i = \frac{P}{p_v} = \frac{200 \text{ kPa}}{7385 \text{ kPa}} = 0.0271 \]

\[ T_i = \frac{T}{T_v} = \frac{25 + 273}{304.2} \text{ K} = 0.98 \]

From the compressibility chart, at these coordinates, \( z \approx 0.99 \)

\[ pV = nzRT \]

\[ n = \frac{200 \text{ kPa}}{1 \text{ atm}} = \frac{1.3 \text{ atm}}{0.008206(L)(\text{atm})} = 298 \text{ K} \]

\[ = 2.04 \text{ g mol} \]

\[ m = (2.04)(44) = 87.9 \text{ g} \quad \text{or} \quad 0.0879 \text{ kg} \]

**14.9**

**Basis:** 106 ft\(^3\) at 60°F and 14.7 psia

\[ pV = z_nRT \quad \text{at the reservoir} \]

\[ pV = nzRT \quad \text{at SC} \]

\[ T_i = \frac{T}{T_v} = \frac{120 + 460}{191(1.8)} = \frac{580}{344} = 1.69 \quad (\text{continued}) \]
Solutions Chapter 14

\[ p = \frac{P}{P_r} = \frac{1000}{1074} = 0.93 \]

\[ z = 0.95 \]

\[ V = V_r \left( \frac{T_r}{T} \right) \left( \frac{z}{z_r} \right) = 10^4 \cdot \left( \frac{14.7}{1000} \right) \left( \frac{120 + 460}{60 + 460} \right) \left( \frac{0.95}{1} \right) = 15.600 \text{ ft}^3 \]

14.10

Basis: 1 kg propane

For propane: \( T_r = 370 \text{ K} \quad p_r = 4255 \text{ kPa} \)

and \( R = 0.18855 \text{ (kPa)(m)}^3/(\text{kg})(\text{K}) \)

Reduced temperature \( T_r = \frac{T}{T_r} = \frac{230 + 273.2}{370} = 1.36 \)

Reduced pressure \( p_r = \frac{p}{p_r} = \frac{6000}{4255} = 1.408 \)

From a generalized compressibility chart

at \( p_r = 1.408 \) and \( T_r = 1.36 \), \( z = 0.80 \)

Since \( pV = znRT \), \( \dot{V} = \frac{zRT}{p} \)

\[ \dot{V} = 0.80 \cdot 0.18855 \cdot (503.2) \left( \frac{6000}{6000} \right) = 0.0127 \text{ m}^3/\text{kg} \]

14.11

(a) Yes

(g) No

(b) No

(h) No

(c) Yes

(d) No

(e) Yes

(f) No

14.12

Basis: 1 g mol \( \text{C}_4\text{H}_8\text{Cl} \) (MW = 112.56)

\( p_r = 4518 \text{ kPa} \quad T_r = 632.4 \text{ K} \)

\[ p_r = \frac{230}{4518} = 0.051 \quad T_r = \frac{380}{632.4} = 0.601 \]

These values fall below the gaseous region in the compressibility chart here \( \text{C}_4\text{H}_8\text{Cl} \) is not a gas. It is a liquid (sp.gr = 1.107), so that the volume is \( (1)(112.56)/1.107 = 102 \text{ cm}^3 \)

14.13

Basis: Data on gases cited in problem.

(a) The cubic feet associated with "165 ft\(^3\)" and "240 ft\(^3\)" probably means that the values are the respective volumes of an ideal gas at standard conditions, because the volumes calculated for the gases in part b. below are quite different than the stated values.

(continued)
Solutions Chapter 14

b. To find the amount of gas in the cylinder, first find the approximate volume in the cylinder.

\[ V_{\text{v}} = \frac{md^2h}{4} = \frac{(3.14)(9)^2(52)}{(4)(1728)} = 1.914 \text{ ft}^3 \]

Use the gas law as ratios:

\[ \frac{p_1 V_1}{p_2 V_2} = \frac{z_1 RT_1}{z_2 RT_2} \]

\[ V_2 = V_1 \left( \frac{p_2}{p_1} \right) \left( \frac{z_2}{z_1} \right) \]

For C_2H_4:

\[ T_1 = 283 \text{ K}, \quad p_1 = 50.5 \text{ atm} \]

Assume \( T_1 = 80^\circ \text{F} = 540^\circ \text{R} = 300^\circ \text{K} \)

\[ T_2 = \frac{300}{283} = 1.06 \]

\[ \frac{p_2}{(14.7)(50.5)} = 2.05 \]

\[ z_2 = 0.35 \]

(At standard conditions: \( z_2 = 1.00 \))

\[ V_2 = (1.914) \left( \frac{1515}{14.7} \right) \left( \frac{1}{0.35} \right) \left( \frac{492}{540} \right) = 514 \text{ ft}^3 \]

For CH_4:

\[ T_1 = 191 \text{ K}, \quad p_1 = 45.8 \text{ atm} \]

\[ T_2 = \frac{300}{191} = 1.57 \quad \frac{p_2}{(14.7)(45.8)} = 2.98 \]

\[ z_2 = 0.84 \]

\[ V_2 = (1914) \left( \frac{2015}{14.7} \right) \left( \frac{1}{0.84} \right) \left( \frac{492}{540} \right) = 285 \text{ ft}^3 \]

MW of C_2H_4 = 28 \quad MW of CH_4 = 16

\[ \text{wt of C}_2\text{H}_4 = \left( \frac{514}{(359)} \right) \frac{28}{16} = 40.1 \]

\[ \text{wt of CH}_4 = \left( \frac{285}{(359)} \right) \frac{16}{16} = 12.7 \]

Therefore \( \text{wt}_{\text{C}_2\text{H}_4} > \text{wt}_{\text{CH}_4} \)

c. For C_2H_4:

\[ pV = znRT = z \frac{m}{MW} RT \]

\[ m = \frac{PV(MW)}{zRT} = \frac{(1515)(1.91)(28)}{2(0.35)(10.73)(590)} = 40 \text{ lb C}_2\text{H}_4 \]

For CH_4:

\[ m = \frac{(2015)(1.91)(16)}{(0.84)(10.73)(540)} = 12.7 \text{ lb CH}_4 \]

Check with cylinder:

\[ 163 - 90 = 123 \text{ lb cylinder} \quad 105 - 9.5 = 135 \text{ lb cylinder} \]
14.14

The answer is it depends on the gas temperature and the pressure. If $pV = ZnRT$ applies, the ideal gas law is represented by $Z = 1$, and for a non-ideal gas, $Z$ can be greater or less than 1. The pressure is $p = \frac{ZnRT}{V}$. So $p_{real} = p_{ideal} Z$, for fixed $V$ and for a fixed number of moles and temperature (the volume of cylinder is fixed). The pressure prediction by the ideal gas law will be conservative (higher than the true pressure) for $Z < 1$, and lower than the true pressure for $Z > 1$.

14.15

a) $p_1 V_1 = Zn_1 n_1 RT \quad R = \text{constant}$

$p_2 V_2 = Z_2 n_2 RT_2 \quad V_1 = \text{constant, the vol. of cylinder}$

$\frac{p_1}{p_2} = \frac{Z_1}{Z_2} \quad T_2 = 133.0 \text{ K}$

$T_1 = \frac{T_2}{Z_1} \frac{24.44 + 273}{133} = 2.24 \quad p_1 = 34.5 \text{ atm}$

$p_2 = 3.80$

$Z_1 = 1.0, \quad Z_2 = 1.0 \quad \text{Ideal gas behavior}$

$p_1 = \frac{n_1}{n_2} \left( \frac{1.0}{1.0} \right) \frac{n_1}{n_2}$

$p_2 = \frac{n_2}{n_1} \left( \frac{1.0}{1.0} \right) \frac{n_2}{n_1}$

\[
\begin{align*}
\text{n}_{CO} &= \frac{pV}{RT} = \frac{14.7 \text{ psia}}{175 \text{ ft}^3} = 0.447 \text{ lb mol} \\
&= \frac{14.7 \text{ psia}}{10.73 \left( \frac{\text{psia} \cdot \text{ft}^3}{\text{lb mol} \cdot \text{R}} \right)} = 0.447 \text{ lb mol} \\
V_{cylinder} &= \frac{n_{CO}RT_1}{p_1} \\
V_c &= \frac{0.447 \text{ lb mol}}{2014.7 \text{ psia}} \left( \frac{10.73 \left( \frac{\text{psia} \cdot \text{ft}^3}{\text{lb mol} \cdot \text{R}} \right)}{536 \text{ R}} \right) = 1.276 \text{ ft}^3 \\
\text{n}_{\text{real, CO}} &= \frac{p_2 V_2}{RT} = \frac{1924.7 \text{ psia}}{1.276 \text{ ft}^3} = 0.427 \text{ lb mol} \\
&= \frac{1924.7 \text{ psia}}{10.73 \left( \frac{\text{psia} \cdot \text{ft}^3}{\text{lb mol} \cdot \text{R}} \right)} = 0.427 \text{ lb mol} \\
\text{n}_{\text{CO, lost}} &= (0.447 - 0.427) \text{ lb mol} = 0.020 \text{ lb mol} \\
\text{rate of loss} &= \frac{0.020 \text{ lb mol}}{48 \text{ hr}} = \frac{4.167 \times 10^{-2} \text{ lb mol}}{\text{hr}} \\
\end{align*}
\]

b) $n_{air} = \frac{pV}{RT} = \frac{14.7 \text{ psia}}{1600 \text{ ft}^3} = 4.09 \text{ lb mol air}$

$100 \text{ ppm} = 100 \left( 10^{-6} \right)(4.09 \text{ lb mol}) = 4.09 \times 10^{-4} \text{ lb mol}$

$t = \frac{4.09 \times 10^{-4} \text{ lb mol}}{4.167 \times 10^{-4} \text{ lb mol/hr}} = 0.982 \text{ hr}$

(continued)
Solutions Chapter 14

c) \( t = 67 \text{ hr} \)

\[
\frac{n_{\text{CO}}}{1600 \text{ ft}^3} = \frac{4.167 \times 10^{-4} \text{ lb mol}}{67} = 0.0279 \text{ lb mol}
\]

\( C_{\text{CO}} = \frac{0.0279 \text{ lb mol}}{1600 \text{ ft}^3} = 1.75 \times 10^{-5} \text{ lb mol/ft}^3 \)

d) The CO alarms would go on to alert people in the building.

14.16

a) The density of the gas must be 2.0 g/m³. MW is Si is 28.086 so

\[
\bar{V} = \frac{(2/28.086)}{0.0712 \text{ g mol/cm}^3} = 0.728 \text{ ft}^3 \text{ mol}^{-1} \text{ m}^{-3}
\]

Let \( T = 298 \text{ K} \). Also \( z = 1 \) at \( T_f = 1.98 \) and \( V_f \) very large.

\[
p = \frac{zRT}{\bar{V}} = 1 \left[ \frac{8.314 \text{ (Pa)(mol/} K \text{)}(100 \text{ cm})^3}{\text{(g mol)/(K)(m)}} \right]^{\frac{298 K}{1 \text{ m}}} = 2.48 \times 10^5 \text{ Pa}
\]

b) For a lower pressure, use a less dense gas (lower MW).

c) At too high a temperature, you cannot get adequate density.

14.17

Basis: 240 ft³ methane at 80°F and 1964.7 psia. Assume the number of moles does not change.

\[
\frac{p_1 V_1}{p_2 V_2} = \frac{nRT_1}{nRT_2} z_1
\]

\[
T_2 = \frac{T_1 z_1 p_1}{p_2 z_2}
\]

Calculation of \( z_1 \)

Methane \( T_e = 190.7 \text{ K} \)

\( p_e = 45.8 \text{ atm} \)

\( T_1 = 80^\circ F = 299.82 \text{ K} \)

\( T_e = \frac{299.82 \text{ K}}{190.7 \text{ K}} = 1.572 \)

\( p_e = \frac{133.7 \text{ atm}}{45.8 \text{ atm}} = 2.919 \)

\( z_1 = 0.83 \)

Calculation of \( z_2 \)

\( p_1 = (1950 \text{ psig + 14.7 psia}) \left( \frac{\text{atm}}{14.7 \text{ psia}} \right) = 133.7 \text{ atm} \)

\( p_2 = (3000 \text{ psig + 14.7 psia}) \left( \frac{\text{atm}}{14.7 \text{ psia}} \right) = 205.08 \text{ atm} \)

\( p_e = \frac{205.08 \text{ atm}}{45.8 \text{ atm}} = 4.478 \)

\( V = 240 \text{ ft}^3 \left( \frac{6.832 \times 10^{-2} \text{ m}^3/1 \text{ ft}^3 \times 100 \text{ cm}^3/1 \text{ m}^3}{} \right) \)

\( = 6.797 \times 10^6 \text{ cm}^3 \) (continued)
Solutions Chapter 14

\[ \hat{V}_e = \frac{RT}{p_e} = \frac{82.06 \text{ cm}^3 \text{ atm}}{(g \text{ mol})(K)} \frac{(80.7 \text{ K})}{45.8 \text{ atm}} \]

\[ = 341.68 \frac{\text{ cm}^3}{\text{ g mol}} \]

\[ n = \frac{p_e \hat{V}_e}{R T} = \frac{(45.8 \text{ atm})(6.797 \times 10^6 \text{ cm}^3)}{(299.82 \text{ K}) (82.06)(0.83)} \]

\[ = 15244.5 \text{ g mol} \]

\[ \hat{V} = \frac{V}{n} = \frac{6.797 \times 10^6 \text{ cm}^3}{15244.5 \text{ g mol}} = 445.87 \frac{\text{ cm}^3}{\text{ g mol}} \]

\[ \hat{V}_e = \frac{V}{\hat{V}_e} = \frac{445.87}{341.68} = 1.305 \]

\[ z_2 = 1.06 \]

\[ T_2 = \frac{T e p_2}{z_2 p_1} = \frac{540^\circ R (0.83)(3014.7 \text{ psia})}{1.06(1664.7 \text{ psia})} \]

\[ T_2 = 649^\circ R \] (189°F)

14.18

Use \( pV = nRT \) \( p_e = 37.2 \text{ atm}, T_e = 132.5 \text{ K} \)

@ state 2 \( p_e = \frac{142.9}{37.2} = 3.84 \quad T_e = \frac{300}{132.5} = 2.26 \)

Solutions Chapter 14

\( \rho_e = 37.2 \text{ atm} \quad T_e = \frac{973}{132.5} = 7.34 \)

\[ z_1 = 0.99 \]

\[ z_2 = 1.05 \]

\[ \frac{\rho_1}{\rho_2} = \frac{1}{\sqrt{\frac{V_1}{V_2}}} = \sqrt{\frac{(300)(0.99)}{973 (1.05)}} = 0.29 \]

If you use the Zitzler isentropic factor, \( \omega \) for air is about 0.036

\[ z = z^* + z^* \omega \]

\[ z_2 = 0.999 + 0.22 (0.036) = 1.00 \]

\[ z_2 = 1.05 + 0.03 (0.036) = 1.05 \]

14.19

Basis: Gas at 50 atm and 600°F

From the compressibility charts:

\[ \rho_e = \frac{50}{14.3} = 3.5 \quad \quad T_e = \frac{600}{40.0 + 460} = 1.2 \]

\[ z = 0.58 \]

\[ Q = \frac{100,000 \text{ std ft}^3}{\text{hr}} \times \frac{1 \text{ lb mol}}{359 \text{ std ft}^3} \times \frac{359(0.58) \text{ std ft}^3}{1 \text{ lb mol}} \times \frac{600}{50492} = 1415 \text{ actual ft}^3/\text{hr} \]

or use \( pV = nRT \) twice

(continued)
\[ \frac{P_2 V_2}{P_1 V_1} = \frac{z_2 P_2 RT_2}{z_1 P_1 RT_1} \]

\[ V_2 = V_1 \left( \frac{T_2}{T_1} \right) \left( \frac{P_2}{P_1} \right) \left( \frac{z_2}{z_1} \right) \]

\[ = 100,000 \left( \frac{600}{492} \right) \left( \frac{1}{50} \right) \left( \frac{0.58}{1.00} \right) \]

\[ = 1415 \text{ actual ft}^3/\text{hr} \]

14.20

Basis: initial gas at 200 psig and final gas at 1000 psig

MW C\textsubscript{2}H\textsubscript{4} = 28

\[ \begin{align*}
\text{initial} & & \text{final} \\
p_1 = 214.7/14.7 & & p_f = 1015/14.7 \\
T_1 = 1.05 & & T_f = 1.05 \\
z_1 = 0.90 & & z_f = 0.35
\end{align*} \]

Use \( pV = znRT \)

\[ \frac{n_2}{n_1} = \frac{P_2 z_f}{P_1 z_1} = 1015 \left( \frac{0.35}{0.90} \right) = 12.14 \]

Alternate way to get \( z \) is to use the Pitzer ascentric factor.

\[ z = z^0 + z^1 \omega \]  
(continued)
\[
\begin{align*}
\text{mol} & \quad \text{mol wt.} & \quad \text{lb} \\
\text{CO}_2 & \quad 10 & \quad 44 & \quad 440 \\
\text{CH}_4 & \quad 40 & \quad 16 & \quad 640 & \quad \text{avg. mol wt.} & = \frac{2480}{100} = 24.8 \\
\text{C}_2\text{H}_4 & \quad 50 & \quad 28 & \quad 1400 & \quad \text{n} = \frac{33.6}{24.8} = 1.35 \text{ lb mol} \\
100 & & & 2560 \\
\end{align*}
\]

\[T^* = 0.10 \times 304.2 + 0.40 \times 190.7 + 0.50 \times 283.1 = 248.25 \text{ K}\]

\[p^* = 0.10 \times (72.9) + 0.40 \times (45.8) + 0.50 \times (50.5) = 50.86 \text{ atm}\]

\[p^* = \frac{V}{p_c} = \frac{2415}{50.86 \times 4.7} = 3.23\]

\[T^*_c = \frac{T}{T_c} = \frac{640}{(248.25)^{1.8}} = 1.43\]

From Fig. in text, \( z \approx 0.75 \)

\[V = \frac{z n R T}{p} = \frac{0.75 \times 1.35 \text{ lb mol} \times [10.73 \text{ (psia)} \times (\frac{\text{ft}^3}{\text{lb mol}}) \times 640^\circ \text{R}]}{2415 \text{ psia}}\]

\[= 2.88 \text{ ft}^3 \text{ at } 180 ^\circ \text{F}, \text{ 2415 psia of gas is cylinder volume}\]

---

14.22

\[0.20 \text{ EtOH} \quad \text{T} = 500 \text{K} \quad \text{V} = 180 \text{ cm}^3/\text{g mol} \]

\[0.80 \text{ CO}_2 \quad 1.00 \quad p = ?\]

Basis: gas as above

\[p^*_c = (0.20) (63.0) + (0.80) (72.9) = 70.92 \text{ atm}\]

\[T^*_c = (0.20) (516.3) + (0.80) (304.2) = 346.6 \text{ K}\]

\[p^*_c = \frac{p}{p_c} = \frac{70.92}{346.6} = 0.20\]

\[T^*_c = \frac{T}{T_c} = \frac{500}{346.6} = 1.44\]

\[V^*_c = \frac{RT^*_c}{p_c} = \frac{(1 \text{ atm} \times 22.4 \text{ L})}{(273 \text{ K} \times 1 \text{ g mol})} \times 1 \text{ L} \times 70.92 \text{ atm} = 401 \text{ cm}^3/\text{g mol}\]

\[V^*_c = \frac{189}{401} = 0.45\]

From the compressibility chart, \( p_c \approx 2.5, \text{ } p \approx [? \text{ atm}].\]
14.23

Basis: 540 kg gas @ 393 K, 3500 kPa absolute

<table>
<thead>
<tr>
<th>Component</th>
<th>kg</th>
<th>kg mol</th>
<th>mole fraction</th>
<th>p_c, atm</th>
<th>T_c, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>100</td>
<td>6.25</td>
<td>0.321</td>
<td>45.8</td>
<td>191</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>240</td>
<td>8.00</td>
<td>0.412</td>
<td>48.2</td>
<td>305</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>150</td>
<td>3.41</td>
<td>0.175</td>
<td>42.1</td>
<td>370</td>
</tr>
<tr>
<td>N₂</td>
<td>50</td>
<td>1.79</td>
<td>0.092</td>
<td>33.5</td>
<td>126</td>
</tr>
<tr>
<td>Total</td>
<td>540</td>
<td>19.45</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ T_c' = (0.321)(191) + (0.412)(305) + (0.175)(370) + (0.092)(126) = 262.8 K \]

\[ p_c' = (0.321)(45.8)+(0.412)(48.2)+(0.175)(42.1)+(0.092)(33.5) = 44.96 \text{ atm} \]

\[ T_i' = \frac{3.93}{262.8} = 1.50 \quad p_i' = \frac{3500}{44.96} = 77 \quad \text{atm} \]

From Nelson and Obert Chart, \( z' = 0.935 \)

\[ \text{MW (average)} = \frac{540}{19.45} = 27.8 \text{ kg/kg mol} \]

\[ \rho = \frac{3500 \text{ kPa}}{393 \text{ K}} = 27.8 \text{ kg (K) (kg mol)} \]

\[ = \frac{3.19 \text{ kg}}{393 \text{ K and 3500 kPa}} \]

14.24

Use Kay's Method

\[ \rho_c' = \Sigma n_i p_i' ; \quad T_c' = \Sigma n_i T_i' \]

<table>
<thead>
<tr>
<th>Component</th>
<th>( \Sigma n_i T_i' )</th>
<th>( \rho_c' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂H₆</td>
<td>283</td>
<td>61.2</td>
</tr>
<tr>
<td>A</td>
<td>150.7</td>
<td>60.2</td>
</tr>
<tr>
<td>He</td>
<td>13.19</td>
<td>0.392</td>
</tr>
</tbody>
</table>

\[ \Sigma n_i p_i' = 48.31 \quad \Sigma n_i T_i' = 221.8 \]

\[ p_i' = \frac{120}{48.3} = 2.49 \quad T_i' = \frac{298}{222} = 1.342 \quad z = 0.70 \]

\[ V = \frac{(0.70)(82.05)(298)}{(120)} = 428 \text{ cm}^3 / \text{g mol} \]

\[ \% \text{ diff} = \left( \frac{142.8 - 140}{140} \right) 100 = 2.00\% \]
14.25

Basis: 30ft³ mixture of 100 atm and 300°F

<table>
<thead>
<tr>
<th>Comp</th>
<th>Mol. frac</th>
<th>T*</th>
<th>p*</th>
<th>T**</th>
<th>p**</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₇H₈</td>
<td>0.60</td>
<td>283</td>
<td>50.5</td>
<td>170</td>
<td>30.3</td>
</tr>
<tr>
<td>A</td>
<td>0.40</td>
<td>150.7</td>
<td>48</td>
<td>60.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

\[
T'_* = \frac{T}{T'_*} = \frac{760}{(230.2)(1.8)} = 1.835
\]

\[
p'_* = \frac{p}{p'_*} = \frac{100}{49.5} = 2.02
\]

\[
z = 0.95
\]

Avg. Mol. wt. = (0.60)(28) + (0.40)(40) = 32.8 lb/lb mol

\[
pV = nzRT
\]

\[
n = \frac{pV}{zRT} = \frac{(100)(14.7)(300)}{(0.95)(10.71)(760)} = 57.0 \text{ lb mol}
\]

Assume capacities are given at storage conditions. Then type IA is selected because it is the cheapest.

Number of tanks required = \[
\frac{(57.0)(32.8)}{62} = 30
\]

---

14.26

Steps 2, 3, and 4:

Assume a continuous process although a batch process would be acceptable and give the same results.

Step 5: Basis: G at given conditions

Steps 6 and 7:

Unknowns: F, P

Balances: \( C_{7}H_{8}, N_{2}, \text{(total)} \) degrees of freedom = 0

Steps 8 and 9:

Calculate G:

\[
T_{*} = \frac{70 + 460}{508.3} = 1.044
\]

\[
p_{*} = \frac{1450 + 14.7}{735} = 1.992
\]

\[
z = 0.34
\]

\[
V = \frac{(359)(n)(14.7)(530)(0.34)}{(1465)(492)} = \frac{(2640)}{(1728)}
\]

(continued)
\[
\begin{align*}
n & = \frac{(2640)(1465)(492)}{(1728)(359)(14.7)(330)(0.34)} = 1.157 \text{ lb mol} \\
\text{Balances:} \\
C_3H_4 & \quad F(0.20) + 1.157 = P(0.50) \\
\text{Total} & \quad F + 1.157 = P \\
F & = 1.928 \text{ lb mol} \\
P & = 3.085 \text{ lb mol}
\end{align*}
\]

14.27

Step 5: Basis: 1 hr.

Steps 2, 3, and 4: Steady state, open system

\[
\text{Convert F to moles and then to mass:}
\]

\begin{align*}
\text{Component} & \quad \text{kg} & \quad \text{MW} & \quad \text{kg mol} & \quad \text{mol fr} & \quad T_r(\text{K}) & \quad p_r(\text{atm}) \\
\text{Bz} & \quad 50 & \quad 78.11 & \quad 0.640 & \quad 0.592 & \quad 562.6 & \quad 48.6 \\
\text{Tol} & \quad 30 & \quad 92.13 & \quad 0.324 & \quad 0.299 & \quad 593.9 & \quad 40.3 \\
\text{Xy} & \quad 20 & \quad 106.16 & \quad 0.118 & \quad 0.109 & \quad 619 & \quad 34.6 \\
& \quad 100 & & & & 1.082 & \quad 1.000
\end{align*}

Calculate the kg of F; get z:

\[
\begin{align*}
T_r' & = \frac{562.6 (0.592) + 593.9 (0.299) + 619 (0.109)}{3} = 578.1 \\
p_r' & = \frac{48.6 (0.592) + 40.3 (0.299) + 34.6 (0.109)}{3} = 44.6 \\
T_r & = \frac{607K}{578.1K} = 1.05 \\
p_r & = \frac{26.8 \text{ atm}}{44.6 \text{ atm}} = 0.60 \\
z & = 0.80
\end{align*}
\]

Together mass of feed:

\[
\begin{align*}
n & = \frac{p_rV}{zRT} = \frac{26.8 \text{ atm} (483 \text{ m}^3)}{0.80 \quad 1 \text{ atm} \quad 8.314(\text{kPa})(\text{m}^3)(\text{K})} = 324.7 \text{ kg mol} \\
F & = (324.7)(100)(1.082) = 30,017 \text{ kg, say 30,000 kg}
\end{align*}
\]

The material balances are in kg.

Step 6: Unknowns: \( P_1, P_2, m_{Bz}, m_{Tol}, m_{Xy} \)
Step 7: Balances:

Bz

\[ \text{Tol} \quad \frac{m_{Bz}}{m_{xy}} = \frac{3}{2} = 1.5 \]

Xy

\[ \Sigma m = 9,800 \]

Step 8: The balances in kg are (only 3 are independent mass balances)

(1) Bz: \[ 30,000 \times 0.50 = P_1 \times (0.895) + M_{Bz} + P_1 \times 0.06 \]

(2) Tol: \[ 30,000 \times 0.30 = P_1 \times (0.084) + M_{Tol} + P_1 \times 0.09 \]

(3) Xy: \[ 30,000 \times 0.20 = P_1 \times (0.021) + M_{Xy} + P_1 \times 0.85 \]

(4) Total: \[ 30,000 = P_1 + 9,800 + P_1 \]

(5) \[ M_{Bz} + M_{Tol} + M_{Xy} = 9800 \]

(6) \[ M_{Bz} = 1.5M_{xy} \]

---

Solution: Using (1), (2), (3), (5), and (6) via Polymath

<table>
<thead>
<tr>
<th>kg</th>
<th>mass fr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_1 = 5500 kg/hr</td>
<td>m_Bz = 1518</td>
</tr>
<tr>
<td>P_1 = 14,700 kg/hr</td>
<td>m_Tol = 7270</td>
</tr>
<tr>
<td>m_Xy = 1012</td>
<td>0.103</td>
</tr>
<tr>
<td>9800</td>
<td>1.00</td>
</tr>
</tbody>
</table>
15.1
1.a Immediate but approximate

2.e Exact but requires access to a handbook

3.b Good accuracy, needs calculation of $z$

4.c Good accuracy, more complicated calculation than b even in a program with a data base

5.e May require a long search to filter out a good value
For other answers, look at the answer to P15.1.

15.2
Will get the most accurate value, and be quick, assuming you have the handbook that contains the required data. For other answers, look at the answer to P15.1.

15.3
Some valid answers are
(1) continuous analytical functions, and these functions can be differentiated and integrated
(2) higher accuracy (with complex equations)

15.4
\[ z = 1 + \frac{B}{V} + \frac{C}{V^\alpha} + \frac{D}{V^\beta} \]

The results for $\frac{p\dot{V}}{RT} = z$ are shown in the Excel table below. You can decide how much accuracy is needed.

<table>
<thead>
<tr>
<th>$p$(atm)</th>
<th>4 terms</th>
<th>2 terms</th>
<th>1 term</th>
<th>2 from 4</th>
<th>1 from 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0.95</td>
<td>0.95</td>
<td>1.00</td>
<td>0</td>
<td>-4.9</td>
</tr>
<tr>
<td>50</td>
<td>0.88</td>
<td>0.88</td>
<td>1.00</td>
<td>0</td>
<td>-13.3</td>
</tr>
<tr>
<td>100</td>
<td>0.77</td>
<td>0.76</td>
<td>1.00</td>
<td>-0.8</td>
<td>-29.8</td>
</tr>
<tr>
<td>200</td>
<td>0.80</td>
<td>0.79</td>
<td>1.00</td>
<td>1.6</td>
<td>-25.1</td>
</tr>
<tr>
<td>500</td>
<td>0.90</td>
<td>0.90</td>
<td>1.00</td>
<td>0</td>
<td>-10.7</td>
</tr>
<tr>
<td>1000</td>
<td>0.95</td>
<td>0.95</td>
<td>1.00</td>
<td>0</td>
<td>-3.6</td>
</tr>
<tr>
<td>5000</td>
<td>0.99</td>
<td>0.99</td>
<td>1.00</td>
<td>0</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

15.5
Basis: 460 kg CO₂

a. RK Equation:
\[
\frac{460 \text{ kg CO}_2}{44 \text{ kg}} = \frac{1 \text{ kg mol}}{10.455 \text{ kg mol CO}_2}
\]

\[ T_e = 304.2 \text{K}, \quad p_e = 7385 \text{kPa} \]
\[ a = 6458 \text{(kPa)(m}^3\text{)(K}^{0.5}\text{)(kg mol})^2 \]
\[ b = 0.0297 \text{ m}^3/\text{kg mol} \]
\[ R = 8.314 \text{ (kPa(m}^3\text{))/(kg mol)(K)} \]
\[ \dot{V} = \frac{V}{n} = \frac{10.4 \text{ m}^3}{10.455 \text{ kg mol}} = 0.995 \text{ m}^3/\text{kg mol} \]
\[ p = \frac{(8.314)(290)}{0.995 - 0.0297} \cdot \frac{6458}{0.995(0.995 + 0.0297)(290)^{0.5}} \]
(continued)
b. SRK Equation:

Data as above: \( T/T_c = 290/304.2 = 0.953 \)

\[
a' = \frac{0.42748(8.314)^2(304.2)^2}{7358} = 179.2 \text{ (kPa)} \cdot (\text{m}^3)/(\text{kg mol})^2
\]

\[
b = \frac{0.08664(8.314)(304.2)}{7358 \times 10^3} = 0.0297 \text{ m}^3/\text{kg mol}
\]

\[
p = \frac{(8.314)(290)}{0.995 - 0.0297} \left( \frac{379.2 \times 1.040}{0.995(0.995 + 0.0297)} \right) = 0.995 \text{ atm}
\]

\[
\alpha = 0.480 + (1.574)(0.225) - 0.176(0.225)^2 = 0.843
\]

\[
\beta = (1 + 0.843(1 - 0.953))^2 = 1.040
\]

\[
p = 2.111 \times 10^5 \text{ kPa} \quad \text{No significant difference.}
\]

15.6

\[
a \Rightarrow (\text{atm}) \left( \frac{L}{\text{g mol}} \right)^2
\]

\[
b \Rightarrow \text{L/g mol}
\]

\[
\alpha \Rightarrow \text{dimensionless}
\]
\[
p = \frac{RT}{V - b} - \frac{a\alpha}{V(V + b) + b(V - b)}
\]

\[
\alpha = (1 + \kappa(1 - T_r^{1/2}))^2 = 0.9890
\]

\[
\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2 = 0.1276
\]

\[
a = 0.45724 \left( \frac{RT}{p_r} \right)^{1.7124}
\]

\[
b = 0.07780 \left( \frac{RT}{p_r} \right)^{0.3722}
\]

From Polymath:

\[
\dot{V} = 29.9 \text{ ft}^3/\text{lb mol}
\]

\[
\frac{100}{29.9} = 3.34 \text{ lb mol NH}_3 \rightarrow 56.8 \text{ lb NH}_3
\]

Part II: Calculate the final pressure

Final \(\dot{V} = \frac{5}{3.34 \text{ lb mol}} = 1.497 \text{ ft}^3/\text{lb mol}\)

350°F \(\rightarrow\) 810°F

Introduce \(\dot{V}\) into the PR equation. From Polymath

\[
p = \frac{(10.73)(810)}{1.497 - 0.3722} - \frac{17,124(0.984)}{1.497(1.497 + 0.3722) + 0.3722(1.497 - 0.3722)}
\]

\[
= 2462 \text{ psia}
\]

15.9

Basis: CO\(_2\) at 81 psig and 25°C

Pressure in can (81.0 psig + 14.7 psia) (1 atm/14.7 psia) = 6.51 atm

Temperature 25°C \(\Rightarrow\) 298.15K \(\Rightarrow\) T\(_r\) = 304.2 K

\[
V = \pi(4.05 \text{ cm})^2(17.0 \text{ cm}) = 876 \text{ cm}^3
\]

\[
p_r = 72.9 \text{ atm}
\]

\[
n = ? \text{ CO}_2
\]

\[
\omega = 0.225
\]

\[
\text{C}_4\text{H}_8\text{O}_5 + \text{NaHCO}_3 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{NaC}_4\text{H}_4\text{O}_7
\]

Using Peng-Robinson equation

\[
n^2(b'an - b'RT - b'^2p) - n^2(V(\alpha - 2bRT - 3b^2p)) - n(V^2)(bp - RT) - V^3p = 0
\]

Equations \(\Rightarrow\)

\[
f(n) = n^3q - n^2V(\alpha) - n(V^2)(bp - RT) - V^3p = 0
\]

\[
q = b'an - b'^2RT - b'^2p
\]

\[
z = \alpha - 2bRT - 2b^2p
\]

\[
a = 0.45724 \left( \frac{RT}{p_r} \right)^{1.7124} = 3.908 \times 10^6
\]

\[
b = 0.07780(\text{RT}/p_r) = 0.07780(298.15/304.2) = 0.26985
\]

\[
(\text{T}_r)^{1/2} = 0.990
\]

\[
\alpha = \left[ 1 + \kappa(1 - (T_r)^{1/2}) \right] = 1.007
\]

\[
\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2 = 0.7080
\]

(continued)
Solutions Chapter 15

The ideal gas law gives 0.233 mol CO₂

T = 298.18 K

p = 6.51 atm

Introduce the values into the PR equation to get n = 0.2420 mol CO₂

\[
\begin{align*}
0.2420 \text{ mol CO}_2 & \times \frac{1 \text{ mol NaHCO}_3}{1 \text{ mol CO}_2} \times \frac{84.00 \text{ g NaHCO}_3}{1 \text{ mol NaHCO}_3} = \frac{20.3 \text{ g NaHCO}_3}{1000} = 0.0203 \text{ mol NaHCO}_3 \\
\end{align*}
\]

15.10

Basis: 1 min

\[
\begin{align*}
\text{CO}_2 & \quad \left(1\right) \quad \left(2\right) \\
2000 \text{ m}^3/\text{min} & \quad 20^\circ \text{C} \quad \text{2000 atm} \\
20^\circ \text{C} & \quad 4800 \text{ kPa} \quad 110^\circ \text{C} \\
\end{align*}
\]

Calculate the moles entering the compressor:

\[
\begin{align*}
\frac{500}{72.9} \text{ atm} & = 0.68 \\
\frac{4800}{72.9} \text{ atm} & = 0.650 \\
\end{align*}
\]

\[
\begin{align*}
T_i = \frac{20 + 273}{304.2} \text{ K} = 0.96 \\
T_a = \frac{110 + 273}{304.2} \text{ K} = 1.26 \\
\end{align*}
\]

\[
\begin{align*}
s = 3.6 \times 10^4 \text{ atm} \left(\frac{\text{cm}^3}{\text{g mol}}\right) & = 364.68 \text{ kPa} \left(\frac{\text{m}^3}{\text{kg mol}}\right) \\
\end{align*}
\]

Solutions Chapter 15

\[
\begin{align*}
b = 42.8 \frac{\text{cm}^3}{\text{g mol}} = 0.0428 \frac{\text{m}^3}{\text{kg mol}}, \quad R = 8.314 \frac{(\text{kJ})(\text{mol})(K)}{\text{mol}^2} \\
\end{align*}
\]

Use Van der Waals' equation:

\[
\left(p + \frac{n^2 a}{V^2}\right)(V - nb) = nRT \\
\]

As the initial guess for the number of moles in State 1 use the ideal gas law

\[
n_i = \frac{p_i V_i}{RT_i} = \frac{500(2000)}{8.314(293)} = 410.5 \text{ kg mol} \\
\]

The number of moles at condition (1) is obtained from

\[
\left(\frac{200 + \frac{n_i^2 (364.68)}{2000}}{2000 - 0.0428 n_i}\right) = \frac{8.314(293)}{n_i} \\
\]

From Polymath (on the CD)

\[
n_i = 420 \text{ kg mol} \\
\]

Calculate the m³ exiting the compressor:

Insert into Vander Waals' equation new parameters:

\[
p = 4800 \text{ kPa} \quad T = 383 \text{ K} \quad n = 420 \text{ kg mol} \\
\]

Solve for V

\[
V = 246 \text{ m}^3 \text{ at } 383 \text{K and } 4800 \text{ kPa} \\
\]
15.11

\[ p_{\text{abs}} = p_g + \text{barometric pressure} \quad \text{T} = 273 - 50 = 223 \text{ K} \]

\[ p_{\text{abs}} = 39 + 1 = 40 \text{ atm} \]

Basis: \( 1 \text{ g mol H}_2 \)

H\(_2\) Coefficients

\[
\begin{array}{cc}
\text{Van der Waals} & 0.246 \times 10^6 (\text{atm/cm}^3)/(\text{g mol})^2 \\
\text{Redlich-Kwong} & 1.439 \times 10^4 (\text{atm K}_{12}^3)/(\text{cm}^3)/(\text{g mol})^2
\end{array}
\]

(Continued)

\[ \alpha = [1 + 0.60283(1 - 1.00686)]^2 = 0.992 \]

Propane Coefficients

\[
\begin{array}{ccc}
\text{Prop} & \text{a} & \text{b} \\
\text{RK} & 180.5 \times 10^6 (\text{atm K}_{12}^3)/(\text{cm}^3)/(\text{g mol})^2 & 62.7 \text{ cm}^3/\text{g mol} \\
\text{PR} & 10.04 \times 10^4 (\text{atm cm}^3)/(\text{g mol})^2 & 56.3 \text{ cm}^3/\text{g mol}
\end{array}
\]

Computer results:

Redlich-Kwong: \(1193.14 \text{ cm}^3/\text{g mol}\)

Peng-Robinson: \(1168.91 \text{ cm}^3/\text{g mol}\)

Determine the volume at condition of state 2 (383 K, 4800 kPa)

\[
\left(4800 + \frac{(419.9)^2(136.68)}{V^3}\right)(V - 0.0428(419.9)) = (419.9)(8.314)(383)
\]

\[ V = 246 \text{ m}^3 \text{ at state 2} \]

15.13

For \( \text{CO}_2 \), \( \omega = 0.225 \) and \( T_e = 304.2 \text{ K}, \ p_e = 72.9 \text{ atm} \)

\[ a = 62.75 \times 10^6 (\text{atm K}_{12}^3)/(\text{cm}^3)/(\text{g mol})^2 \]

\[ b = 29.9 \text{ cm}^3/\text{g mol} \]

Computer results:

Redlich-Kwong: \(1559.6 \text{ cm}^3/\text{g mol}\)
## Solutions Chapter 15

### 15.14
For CO₂, \( \omega = 0.225 \) and \( T_a = 304 \, \text{K} \), \( p_a = 72.9 \, \text{atm} \) or 7385 kPa

\[
R = 8.314 \, \text{(kJ)}/(\text{mol} \cdot \text{K}) \quad \text{and} \quad \frac{a}{R} = 6458 \, \text{(kJ)}/(\text{mol} \cdot \text{K})^2
\]

\[
b = 0.0297 \, \text{m}^3/(\text{kg mol})
\]

\[
1200 = \frac{(8.314)(290)}{(V - 2.97 \times 10^2)} - \frac{6458}{V(V+2.97 \times 10^2)(290)^2}
\]

\[\hat{V} = 1.876 \, \text{m}^3/\text{kg mol from Polymath}\]

\[
n_{CO_2} = \frac{V}{\hat{V}} = 10.4 \quad V = 5.54 \, \text{kg mol}
\]

\[
n_{CO_2} = \frac{48 \, \text{kg}}{1 \, \text{kg mol}} = 266 \, \text{kg CO}_2
\]

### 15.15

\[
p = \frac{nRT}{V - nb} - \frac{n^2a}{V^2}
\]

\[T = 492.0^\circ \text{R}
\]

\[
a = \left(\frac{p - nRT}{V - nb}\right) - \frac{V^2}{n^2} \quad R = 0.7302 \frac{\text{ft}^3}{(\text{lb mol})^2 \text{R}}
\]

Basis: 1.0 lb mol

### Solutions Chapter 15

<table>
<thead>
<tr>
<th>1.0 lb mol</th>
<th>( \frac{(\text{ft}^3)\text{atm}}{(\text{lb mol})^2\text{R}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 atm</td>
<td>( \frac{1.806 , \text{ft}^3 - (1.0 , \text{lb mol})b}{(1.860 , \text{ft}^3)^2} )</td>
</tr>
</tbody>
</table>

\[200 = \frac{359.3(\text{ft}^3)\text{atm}}{(1.860 \, \text{ft}^3)^2 - 0.2891 \, a}
\]

\[
similartly \quad 1000 = \frac{359.3(\text{ft}^3)\text{atm}}{(0.741 \, \text{ft}^3)^2 - 1.82a}
\]

\[
a = \left(\frac{1000 - 359.3}{0.741 - b}\right)(-\frac{1}{1.82})
\]

\[200 = \frac{359.3}{(1.860 - b)} - 0.289 \left(\frac{1}{1.82}\right)\left(1000 - \frac{359.3}{0.741 - b}\right)
\]

\[200 = \frac{359.3}{(1.860 - b)} + 158.8 - \frac{57.07}{(0.741 - b)}
\]

\[41.20 = \frac{359.3}{(1.860 - b)} - \frac{57.07}{(0.741 - b)}
\]

\[
b = 0.4808 \frac{\text{ft}^3}{\text{lb mol}}
\]

\[
a = 209.3(\text{atm})(\frac{\text{ft}^3}{\text{lb mol}})^2
\]
15.16

a. Solution by compressibility factor method:

Basis: 80 lb water at 900°F

\[ V = \frac{10 \text{ ft}^3}{80 \text{ lb}} \times \frac{16 \text{ lb}}{1 \text{ cm}^3 / \text{g mol}} = 140.8 \text{ cm}^3 / \text{g mol} \]

\[ p_c = 218.3 \text{ atm} \text{ from Appendix D1 (217.6 atm for the CD)} \]

\[ V'_o = \frac{RT}{p_c} = \frac{82.06 \text{ (cm}^3 / \text{atm})}{243 \text{ cm}^3 / \text{g mol}} = 243 \text{ cm}^3 / \text{g mol} \]

\[ T_e = 647.4 \text{ K} \]

\[ \frac{V'}{V_o} = \frac{140.8}{243} = 0.579; \quad \frac{T}{T_e} = \frac{900}{647.4} = 1.39 \]

From the compressibility charts, \( p_c = 1.9 \)

\[ p = p_c (1.9) (218.3) = 415 \text{ atm} \]

b. Solution using the Redlich-Kwong equation of state:

\[ p = \frac{RT}{(V-b)} \quad \text{where} \quad a = 0.4278 \frac{RT^{2.5}}{p_c} \]

\[ b = 0.0867 \frac{RT}{p_c} \]

\[ a = \frac{82.06 \text{ (cm}^3 / \text{atm})}{(647.4 \text{ K})^{2.5}} \]

\[ 218.3 \text{ atm} = 1.407 \times 10^8 \text{ (cm}^3 / \text{atm})(\text{K})^{2.5} \]

\[ n = \left( \frac{bV}{V^2} - n \right) + n(pb + RT) - \frac{p}{nV} = 0 \]

\[ n^3 - 0.962n^2 + 0.376n - 0.0936 = 0 \]

Iterate to find value of \( n \).

Use Excel to solve this cubic equation to obtain a positive, real answer. (continued)
Solutions Chapter 15

n = 0.594 lb mol or [17.8 lb ethane]

b. Use the compressibility factor method.

\[
\begin{array}{cccc}
P_r & T_r & P_r & T_r \\
709 \text{ psia} & 549^\circ \text{R} & 2.84 & 1.02 & 0.43 \\
\text{mass} & = & 1(\text{ft}^3) & 2014.7 \text{ psia} & 10.73 \text{ (lb mol)} \\
560^\circ \text{R} & 0.43 & 10.73 \text{ (psia) (R)} & 1 \text{ mol} & = 23.4 \text{ lb ethane}
\end{array}
\]

15.18

a. Van der Waals equation

\[
a = \frac{(27) R T_r}{64 P_r}, \quad b = \frac{(1) R T_r}{8 P_r}
\]

Methane: \( T_r = 190.7 \text{K}, \quad P_r = 45.8 \text{ atm} \)
Propane: \( T_r = 369.9 \text{K}, \quad P_r = 42.0 \text{ atm} \)

\[
\begin{array}{c}
\text{Methane:} \quad 190.7 = 4.16 \\
45.8 = 8.81 \\
\text{Propane:} \quad 369.9 = 42.0
\end{array}
\]

Propane will be higher for both coefficients

b. SRK equation:

\[
a' = \frac{0.42748 R^2 T_r}{P_r}, \quad b = \frac{0.08664 R T_r}{P_r}
\]

15.19

Steps 2, 3, and 4:

System: Mixer plus engine, open, steady state

\[
\begin{array}{c}
100\% \ \text{C}_4\text{H}_{10} \quad \text{Mix} \\
100\% \ \text{N}_2 \quad \text{Engine} \\
\end{array}
\]

\[
\begin{array}{c}
\text{A: Air} \quad 100\% \text{ xs} \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{Component} & \% \\
\text{O}_2 & 0.21 \\
\text{N}_2 & 0.29 \\
\text{CO}_2 & 1.00 \\
\text{CO} & 0.63 \\
\text{H}_2\text{O} & 9.42 \\
\end{array}
\]

\[
\begin{array}{c}
\text{mol br} \\
22.415
\end{array}
\]

Step 5: Basis: \( 1 \text{ hr} = 2593 \text{ m}^3 \text{ at SC} \)

\[
\frac{259}{22.415} = 11.68 \text{ kg mol in P}
\]

Steps 6 and 7:

Unknowns: \( n_{\text{C}_4\text{H}_{10}}, n_{\text{N}_2}, A \) degrees of freedom = 0 - 1; one

Element balances: C, N, H, O \quad \text{equation is redundant if the equations are independent}

(continued)
Solutions Chapter 15

C: \[ n_{C,\text{H}_2}(2) = 115.68(0.0565 + 0.0063) = 7.265 \quad n_{C,\text{H}_4} = 3.632 \ \text{kg mol} \]

2N: \[ A(0.79) = 115.68(0.7441) \quad A = 108.96 \ \text{kg mol} \]

2O: \[ n_{C,\text{H}_4} + (108.96)(0.21) = 115.68 \left( \frac{0.0989 + 0.0565 + 0.0063 + 0.0942}{2} \right) \]

\[ n_{C,\text{H}_4} = 0.908 \ \text{kg mol} \]

\[ T = -18\degree C = 255.6 \ \text{K} \quad V = 0.190 \ \text{m}^3 \quad (0.190 \times 10^6 \ \text{cm}^3) \]

Use Van der Waals' equation:

\[ p = \frac{nRT}{V-nb} \quad a = \frac{1.36 \times 10^9}{(\text{atm})(\text{cm}^3)} \quad (\text{g mol})^2 \rightarrow 1.377 \times 10^7 \quad \frac{(\text{kgPa})(\text{m}^3)}{(\text{kg mol})^2} \]

\[ b = \frac{31.9 \ \text{cm}^3}{\text{g mol}} \rightarrow 0.0319 \ \text{m}^3/\text{kg mol} \]

Solution: \[ p = 1.013 \times 10^5 \ \text{kPa} \]

Use Redlich-Kwong equation:

\[ p = \frac{RT}{V-b} \quad a = \frac{15.65 \times 10^6}{(\text{atm})(\text{K})(\text{cm}^3)/\text{g mol})^2} \]

\[ b = \frac{25.3 \ \text{cm}^3}{\text{g mol}} \]

\[ V = \frac{0.190 \ \text{m}^3}{0.9086 \ \text{kg mol}} = 0.209 \ \text{m}^3/\text{kg mol} \]

Solution using Polymath \[ p = 1.01 \times 10^5 \ \text{kPa} \]

15.20

Assume a continuous process although a batch process would be acceptable and give the same results.

Steps 2, 3, and 4:

\[ \begin{array}{ccc}
F = ? & \text{Mixer} & F = ? \\
\text{mol fr.} & \text{mol fr.} & \text{MW} \\
C_2H_4 & 0.50 & 28 \\
N_2 & 0.50 & 28 \\
\text{G} & 100\% C_2H_4 @ 1450 \text{ psig and 70°F} & 1.00 \\
\end{array} \]

Step 5: Basis: G at given conditions

Steps 6 and 7:

Unknowns: \( F, P \)

Balances: \( C_2H_4, N_2 \) (or total) \( \) degrees of freedom = 0

Steps 8 and 9:

Calculate G: Use Van der Waals’ equation

\[ p = \frac{1465}{14.7} = 99.8 \ \text{atm} \quad R = 82.06 \frac{\text{atm cm}^3}{(\text{g mol})} \]

\[ T = \frac{530}{1.8} = 294.5 \ \text{K} \quad C_2H_4: \\
\quad a = 4.48 \times 10^6 \ \text{atm cm}^3/(\text{g mol})^2 \\
b = 57.2 \ \text{cm}^3/\text{g mol} \]

\[ N_2: \\
\quad a = 1.347 \times 10^6 \\
b = 38.6 \]
\( V = \frac{2640 \cdot (2.54)}{1} = 43,262 \text{ cm}^3 \)

\[
\left( p + \frac{n_a}{V^3}\right)\left( \frac{V}{n} - b \right) = RT
\]

\[
\left[ 99.8 + \frac{n^4 (4.48 \times 10^4)}{(43,262)^3} \right] \left[ \frac{43,262}{n} - 57.2 \right] = (82.06)(294.5) = 24,167
\]

Start with \( n = 550 \text{ cm}^3 \).

**Polymath Results**

**NLE Solution**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>f(x)</th>
<th>Ini Guess</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>756.04046</td>
<td>-4.776E-06</td>
<td>550</td>
</tr>
</tbody>
</table>

**NLE Report (safernewt)**

Nonlinear equations

\( f(n) = (99.8^n + 0.00239^n - 0.003^n)(43262 - 57.2n) - 24167n = 0 \)

Settings

Max iterations = 150
Tolerance F = 0.00000001
Tolerance X = 0.00000001
Tolerance min = 0.00000001

\[
\frac{756 \text{ g mol}}{454 \text{ g}} = 1.665 \text{ lb mol}
\]

**Balances**

Let \( P \) be the lb mol of gas in the feed, and \( F \) be the lb mol of gas with 20% \( \text{C}_2\text{H}_4 \).

\[
\text{C}_2\text{H}_4: \quad F (0.20) + 1.665 = P (0.50)
\]

Total: 

\[
F + 1.665 = P
\]

\[
F = 2.78 \text{ lb mol} \quad P = 4.40 \text{ lb mol}
\]
16.1
1. (1); 2. (2); 3. (3); 4. (4); 5. (3); 6. (1)

16.2
(a) 40°C; (b) 190°C; (c) 60°C; (d) Compound B

16.3
(a) afgcb is the saturated curve  
(b) afe is the saturated liquid curve  
(c) cgh is the saturated vapor curve  
(d) hfa to the left is the liquid phase  
(e) hfcgb to the right is the vapor phase  
(f) afgcb below is the liquid vapor-region  
(g) e is the critical point

16.4

16.5 (e)

16.6 All true

16.7
(a) higher; (b) lower; (c) higher; (d) lower; (e) no change; (f) lower;  
(g) higher; (b) lower; (i) higher; (j) lower; (k) lower; (l) higher

16.8
From the p-T diagram for water you can see that raising the pressure by a large amount on ice at constant temperature causes the water to go from the solid phase to the liquid phase.
The vapor pressure of methanol is less than that of gasoline so that at lower temperatures the fuel-to-air mixture is insufficient for combustion.

Automotive parts can be made of alcohol tolerant materials such as stainless steel or other corrosion resistant materials and additives to the methanol, such as 15% gasoline, can help solve the problem of difficult cold-weather engine starts.

### Appendix Q (T is in K)

<table>
<thead>
<tr>
<th>Compound</th>
<th>p* (mm Hg)</th>
<th>ln (p*)</th>
<th>log_{10} (p*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Acetone at 0°C</td>
<td>p* = 70.51</td>
<td>16.6513</td>
<td>7.2316</td>
</tr>
<tr>
<td></td>
<td>p* = 70.55</td>
<td>T = 35.93</td>
<td>T + 237.23</td>
</tr>
<tr>
<td>(b) Benzene at 80°F</td>
<td>p* = 102.73</td>
<td>15.9008</td>
<td>6.90565</td>
</tr>
<tr>
<td></td>
<td>p* = 102.74</td>
<td>T = 52.36</td>
<td>T + 220.79</td>
</tr>
<tr>
<td>(c) Carbon tetrachloride at 300 K</td>
<td>p* = 123.81</td>
<td>15.8742</td>
<td>6.8941</td>
</tr>
<tr>
<td></td>
<td>p* = 122.89</td>
<td>T = 45.99</td>
<td>T + 227.17</td>
</tr>
</tbody>
</table>

### Solution 16.11

Fit the Antoine Equation using the three data points to get A, B, and C. In mm Hg

<table>
<thead>
<tr>
<th>kPa</th>
<th>mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.53</td>
<td>18.98</td>
</tr>
<tr>
<td>15.0</td>
<td>112.54</td>
</tr>
<tr>
<td>58.9</td>
<td>441.90</td>
</tr>
</tbody>
</table>

\[
\ln(18.98) = A - \frac{B}{C + (40 + 273)} = 2.9434
\]

\[
\ln(112.54) = A - \frac{B}{C + (10 + 273)} = 4.7233
\]

\[
\ln(441.90) = A - \frac{B}{C + (20 + 273)} = 6.0911
\]

The solution from Polymath is

\[
A = 16.5386 \quad B = 2707.43 \quad C = -33.8541
\]

At 40°C, \[ \ln (p*) = 16.538 - \frac{2707.43}{-33.85 + (40 + 273)} \]

\[ p* = 939 \text{ mm Hg (125 kPa)} \]

### Solution 16.12

At the triple point, all the phases (solid, liquid and vapor) exist in equilibrium. Therefore, the vapor pressure of liquid ammonia = the vapor pressure of solid ammonia

\[
15.16 - 3053/T = 18.7 - 3754/T
\]

\[ T = 195 \text{ K} \]

### Solution 16.13

No. It is a typo. Probably the number was 98.8°C because if you equate the pressures from the two equations, \[ T = 371.75K, \text{ or } 98.7°C \].
16.14
For benzene \((p^* \text{ is in mm Hg and } T \text{ in K})\)

\[ \ln(p^*) = 15.9008 \frac{278.51}{T - 52.36} \quad p^* = 760 \text{ mm Hg} \quad \ln(p^*) = 6.6331 \]

\(T = 353 \text{K} \) agrees with data base on CD

For toluene

\[ \ln(p^*) = 16.0137 \frac{309.62}{T - 53.67} \quad p^* = 760 \text{ mm Hg} \]

\(T = 383.7 \) agrees with data base on CD

16.15
Merge the two equations \((A1 \text{ MW} = 27)\)

\[ W = 10^4 = 5.83 \times 10^2 \frac{(p,v0^2)^{1/3}}{T^{1/2}} \quad \text{where} \quad p_v = \frac{10^{(8.73+1.92\ln T)}}{T^{0.7}} \]

The solution from Polymath is

\[ T = 1492 \text{K} \]

16.16

<table>
<thead>
<tr>
<th>( \log(T) )</th>
<th>( (\log(T))^2 )</th>
<th>( \log(T)^3 )</th>
<th>( \ln p^* = a + b \ln T + c(\ln T)^2 )</th>
<th>( \text{VP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6101</td>
<td>31.4727</td>
<td>176.5329</td>
<td>0.61130</td>
<td></td>
</tr>
<tr>
<td>5.7038</td>
<td>32.5331</td>
<td>185.5619</td>
<td>3.53600</td>
<td></td>
</tr>
<tr>
<td>5.7991</td>
<td>33.6295</td>
<td>195.0204</td>
<td>17.21000</td>
<td></td>
</tr>
<tr>
<td>5.8861</td>
<td>34.6462</td>
<td>203.9313</td>
<td>62.15000</td>
<td></td>
</tr>
<tr>
<td>5.9402</td>
<td>35.2856</td>
<td>209.6027</td>
<td>128.80000</td>
<td></td>
</tr>
<tr>
<td>5.9915</td>
<td>35.8976</td>
<td>215.0795</td>
<td>245.60000</td>
<td></td>
</tr>
<tr>
<td>6.0403</td>
<td>36.4847</td>
<td>220.3767</td>
<td>437.00000</td>
<td></td>
</tr>
<tr>
<td>6.0868</td>
<td>37.0488</td>
<td>225.5079</td>
<td>733.20000</td>
<td></td>
</tr>
<tr>
<td>6.1257</td>
<td>37.8561</td>
<td>232.9186</td>
<td>1454.00000</td>
<td></td>
</tr>
<tr>
<td>6.2146</td>
<td>38.6214</td>
<td>240.0166</td>
<td>2637.00000</td>
<td></td>
</tr>
</tbody>
</table>

THE COEFFICIENTS ARE

\(-1199.2548 \quad a \quad -79.0261 \quad c\)

\(532.2715 \quad b \quad 3.9638 \quad d\)

16.17
Based on data from the steam tables:

\textbf{State 1: liquid} \quad \textbf{State 3: solid} \quad \textbf{State 5: liquid (saturated)}

\textbf{State 2: superheated vapor} \quad \textbf{State 4: saturated vapor} \quad \textbf{State 6: vapor (saturated)}

You can calculate the properties of a mixture of vapor and liquid in equilibrium (for a single component) from the individual properties of the saturated vapor and saturated liquid by averaging the properties of the two saturated phases. The weights are the respective amounts of each phase.
16.18 Based on data from the steam tables:

State 1: saturated vapor  State 3: two phase (saturated liquid and vapor)
State 2: saturated liquid  State 4: superheated vapor

16.19

All of the values of specific volume are obtained using 
\[ \hat{V} = x_{\text{vapor}} \hat{V}_{\text{vapor}} + (1-x_{\text{vapor}}) \hat{V}_{\text{liquid}} \]
with \( \hat{V} \) data from the steam tables.

(a) \( \hat{V} = 0.5 \times 1.673 + 0.5 \times 0.001043 = 0.837 \text{ m}^3/\text{kg} \)

(b) \( \hat{V} = 0.5 \times 0.6058 + 0.5 \times 0.001073 = 0.303 \text{ m}^3/\text{kg} \)

(c) \( \hat{V} = 0.3 \times 350.8 + 0.7 \times 0.01613 = 105.25 \text{ ft}^3/\text{lb} \)

(d) \( \hat{V} = 0.7 \times 1.8431 + 0.3 \times 0.0187 = 1.296 \text{ ft}^3/\text{lb} \)

16.20

(a) T; (b) F; (c) T; (d) T; (e) F; (f) T

16.21

Use data from the steam tables at the initial condition of \( p = 101.33 \text{ kPa} \) and saturated water (i.e., two phases):

\[ \hat{V}_L = 1.044 \text{ cm}^3/\text{g} \] and \[ \hat{V}_\text{vapor} = 1673.0 \text{ cm}^3/\text{g} \].

Then the mass of both phases in the container can be calculated:

\[ m_L = 0.03 \text{ m}^3 (100 \text{ cm/m})^3 / 1.044 \text{ cm}^3/\text{g} = 28.376 \text{ g} \]

\[ m_{\text{vapor}} = 2.97 \text{ m}^3 (100 \text{ cm/m})^3 / 1673.0 \text{ cm}^3/\text{g} = 1.775 \text{ g} \]

\[ m_{\text{total}} = 30.511 \text{ g} \]

At the final conditions all of the liquid has been evaporated, and only saturated vapor will exist having a specific volume of:

\[ \hat{V}_\text{vapor} = (3.00 \text{ m}^3) (100 \text{ cm/m})^3 / 30.511 \text{ g} = 98.3 \text{ cm}^3/\text{g} \]

Interpolating in the steam tables

\( (212-\text{T}) ^\circ \text{C} / (212-214) ^\circ \text{C} = (99.09-98.3) \text{ cm}^3/\text{g} (99.09-95.28) \text{ cm}^3/\text{g} \)

\( T = 212 ^\circ \text{C} \)

\( (1985.2-p) \text{kPa} / (1985.2-2065.1) \text{kPa} = (99.09-98.3) \text{ cm}^3/\text{g} (99.09-95.28) \text{ cm}^3/\text{g} \)

\( p = 2002 \text{kPa} \)

16.22

Basis: 10 lb of water

Specific volume:

\[ \hat{V} = \frac{10.0}{2.01} = 4.975 \text{ ft}^3/\text{lb} \]

From the paper steam tables (in ft³/lb) at 80 psia:

\[ \hat{V}_L = 0.0176 \] \[ \hat{V}_\text{vapor} = 5.476 \]

Mass balance:

\[ m_L + m_{\text{vapor}} = 2.01 \]

(continued)
Volume balance

\[ 10.0 = m_L(0.0176) + m_v(5.476) \]

Mass of liquid is

0.184 lb

Mass of vapor is

1.826 lb

The volume of liquid is

\[ V_{liq} = m_{liq} \dot{V}_{liq} = (0.184)(0.0176) = 3.28 \times 10^{-3} \text{ ft}^3 \]

The volume of vapor is

\[ V_{vap} = m_{vap} \dot{V}_{vap} = 10.0 - 3.28 \times 10^{-3} = 9.997 \text{ ft}^3 \]

Quality is: \(\frac{1.826}{2.01} = 0.908\)

16.23

Basis: 2.10 lb water

Specific volume: \(\dot{V} = (1-x) \dot{V}_v + x \dot{V}_l\)

Specific volume of water = \(\dot{V}_l = \frac{0.35}{2} = 0.175 \text{ m}^3/\text{kg}\)

From the steam tables:

Specific volume of saturated liquid,

\(\dot{V}_l = 0.001\ 088 \text{ m}^3/\text{kg}\)

specific volume of saturated vapor =

\(\dot{V}_v = 0.414 \text{ m}^3/\text{kg}\)

Then, \(0.175 = (1-x)(0.001\ 088 + x (0.414))\)

The quality = \(x = 0.23\)

16.24

Since the two phases coexist in equilibrium, we have a saturated mixture, and the pressure must be the saturation pressure at the given temperature:

\[ p = p^* @ 90^\circ \text{C} = 70.14 \text{ kPa} \]

At 90^\circ \text{C}, \(\dot{V}_v\) and \(\dot{V}_l\) values are \(\dot{V}_v = 0.001\ 036 \text{ m}^3/\text{kg}\) and \(\dot{V}_l = 2.361 \text{ m}^3/\text{kg}\)

Add the volume occupied by each phase:

\[ v = V_v + V_l = m_v \dot{V}_v + m_l \dot{V}_l = (8 \text{ kg})(0.001\ 036 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.361 \text{ m}^3/\text{kg}) = 4.73 \text{ m}^3 \]

16.25

\[ v = \frac{Q}{A} = \frac{m \dot{V}}{A} \]

where

\(v\) = velocity, ft/s
\(\dot{V}\) = specific volume of the fluid, ft\(^3\)/lb
\(A\) = pipe cross sectional area, ft\(^2\)
The value can be obtained from the steam tables: \( \dot{V} = 0.9633 \text{ ft}^3/\text{lb} \)

The area is \( A = \pi d^2/4 = \pi \left( \frac{2.9}{12} \right)^2 = 0.046 \text{ ft}^2 \)

\[ v = \frac{25,000 \text{ lb}}{\text{hr}} \cdot \frac{0.9633 \text{ ft}^3}{\text{lb}} \cdot \frac{1}{0.046 \text{ ft}^2} = 5.24 \times 10^4 \frac{\text{ft}}{\text{hr}} \text{ or } [145 \text{ ft/s}] \]

16.26

The hot oil vaporized the water, and the increase in volume in the system caused the damage.

16.27

Prepare a Cox chart as described in the text. Use semi-log paper with the horizontal axis \( \log_{10} \). Obtain vertical scale rules by use of steam properties at even integers for the temperature. Or you can use Antoine Equation, Appendix G, to get 2 points and draw a line between them.

\begin{table}
\begin{tabular}{|c|c|c|}
\hline
& \( T_{\text{min}} (^{\circ} \text{F}) \) & \( p_{\text{max \ steam}} (\text{psia}) \) & \( p_{\text{max}} (\text{psia}) \) \\
\hline
(a) Acetone & 454 & 670 & 691 \\
(b) Heptane & 512 & 700 & 397 \\
(c) Ammonia & 270 & 1500 & 1636 \\
(d) Ethane & 89.7 & 750 & 708 \\
\hline
\end{tabular}
\end{table}

16.28

Steps for preparing a Cox Chart (using water as the reference substance):

1. On logarithmic paper, set up the pressure scale on one axis. The other axis will be a nonlinear temperature scale which will be set up by the following method.

2. Draw a diagonal line from the origin to the opposite corner of the graph.

3. From the steam tables, obtain values for the vapor pressure of water at evenly spaced temperature increments. (continued)
4. Plot these vapor pressures along the diagonal line.

5. Now, beginning with the first point on the diagonal, draw a line extending from that point to the temperature axis and label the intersection as the corresponding temperature for that vapor pressure.

6. Repeat step five for every point on the diagonal line. This process will establish the temperature scale.

7. Using the established temperature scale, plot the data for benzene and draw a line through the points.

8. From this line, obtain the vapor pressure for benzene at 125°F.

The vapor pressure for benzene at 125°C (257°F) is estimated to be 3.3 atm.

---

**16.29**

The procedure is the same as outlined for P16.28. The result from the Cox chart is that the vapor pressure for aniline at 250°F is 22 atm.

---

**16.30**

From the CD that accompanies the text the respective vapor pressures at 300K are in increasing value

<table>
<thead>
<tr>
<th>Substance</th>
<th>p* in mm Hg</th>
<th>PEL (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>65.8</td>
<td>1000</td>
</tr>
<tr>
<td>Methanol</td>
<td>139.7</td>
<td>200</td>
</tr>
<tr>
<td>MTBE</td>
<td>294</td>
<td>100</td>
</tr>
</tbody>
</table>

The relative values of p* are about the same as the inverse of the relative values of the PEL.
17.1

Basis: Data given in problem statement

\[ \text{H}_2\text{O} \quad \text{dry N}_2 \]

27°C
27°C

\[ p' = 3.536 \text{kPa} \quad p = 101.3 \text{kPa} \]

(a) \[ p_T = p_{\text{N}_2} + p_{\text{H}_2\text{O}} = (101.3 + 3.536) \text{ kPa} = 104.8 \text{ kPa} \]

(b) \[ \frac{n_{\text{H}_2\text{O}}}{n_{\text{N}_2}} = \frac{3.536 \text{ kPa}}{101.3 \text{ kPa}} = 0.0349 \]

17.2

\[ T = -20°C \]

\[ p' = 14.1 \text{ mm Hg} \]

\[ \begin{array}{c|c|c}
\text{O}_2 & \text{N}_2 & \text{C}_6\text{H}_{14} \\
59.6 & 79 & \end{array} \]

\[ p_{\text{N}_2} = 760 \text{ mm Hg} \quad p_{\text{O}_2} = 760 - 14.1 = 745.9 \text{ mm Hg} \]

\[ p_{\text{C}_6\text{H}_{14}} = p_{\text{C}_6\cdot \text{H}_{14}} = 14.1 \text{ mm Hg} \]

Basis: 760 mol saturated gas (or use 100 mol)

\[ p \rightarrow \text{mole} \]

\[ \begin{array}{c|c|c}
\text{O}_2 & 21 (745.9) & 156.6 \\
\text{N}_2 & 79 (745.9) & 589.3 \\
\text{C}_6\text{H}_{14} & 14.1 & 760 \\
\end{array} \]

For complete combustion

\[ \text{C}_6\text{H}_{14} + 9.5/2 \text{O}_2 \rightarrow 6 \text{CO}_2 + 7 \text{H}_2\text{O} \]

156.6 - 134 = 22.60 mol O_2 excess

\[ \frac{22.60}{734} \times 100 = 3.06\% \]

17.3 (a) Volume increases (b) Pressure increases

17.4

mol wt. \text{CCL}_3\text{NO}_2 = 164.5

Basis: 1 mol saturated gas

\[ \begin{array}{c|c}
\text{mol fr.} & \text{CCl}_3\text{NO}_2 \\
0.02 & \text{air} \\
0.98 & 1.00 \\
\end{array} \]

\[ \begin{array}{c|c|c|c}
\text{100 kPa} & \text{0.02 mol CCl}_3\text{NO}_2 & 760 \text{ mm Hg} & 15.0 \text{ mm Hg} \\
1 \text{ mol gas} & 101.3 \text{ kPa} & & \\
\end{array} \]

(a) Using linear interpolation, which may introduce a slight error, 15.0 mm Hg corresponds to

\[ \frac{(15.0-13.8)}{18.3-13.8} \times (5) = 1.3 + 15 = 16°C \]

(289.5K)

(a) Basis: 100 m³ at 100 kPa and 16.5°C

\[ \begin{array}{c|c|c|c}
100 \text{ m}^3 & 100 \text{ kPa} & 273 \text{ K} & 1 \text{ kg mol air} \\
101.3 \text{ kPa} & 289.5 \text{ K} & 22.4 \text{ m}^3 \text{ air at SC} & \\
\end{array} \]

(continued)
17.5
Basis: 1 mol air

\[ y = 0.12 \]
\[ P_{H_2O} = p_T(0.12) = 101.3 \text{ kPa (0.12)} \]
\[ = 12.2 \text{ kPa} \]

The dewpoint is the temperature at which \( P_{H_2O} = 12.2 \text{ kPa} \), or from the steam tables 323K or 50°C.

17.6
Assume the tank with air fills with the hazardous liquid vapor at 80°F. The pressure in the tank with air will become after the transfer \((10 + 14.7) + 13 = 37.7 \text{ psia}\) hence the seal will possibly rupture during the transfer.

17.7
At 60°F, \( P_{H_2O} = 0.52 \text{ in Hg} \) at 75°F, \( p^* = 0.87 \text{ in Hg} \)

Basis: 12,000 ft³ air at 75°F and 29.7 in Hg absolute

\[
\begin{align*}
0.52 \text{ in Hg} & \quad 1 \text{ lb mol} \\
0.52 \text{ in Hg} & \quad 18 \text{ lb H}_2\text{O} \\
& 359 \text{ ft}^3 \text{ at SC} \\
& 29.92 \text{ in Hg total} \\
& 535^\circ \text{R / lb mol} \\
& 9.62 \text{ lb H}_2\text{O}
\end{align*}
\]

17.8
Basis: 1 gal benzene (sp. gr. 0.879, MW 78.1) at 750 mm Hg, 70°F

Moles of air = \( \frac{(3600 \text{ ft}^3)}{10.73} \times (14.7) = 9.18 \text{ lb mol} \)

Moles of benzene = \( \frac{(1) \times (10.73)(0.879)(62.4)}{7.48} = 0.094 \text{ mol} \)

\[ n_{Total} = 9.18 + 0.094 = 9.274 \text{ mol} \]

\[ y_B = \frac{0.094}{9.274} = 0.0101 \]

mol % = \( 0.01\% \) therefore beneath explosive limit

17.9
Basis: 350 ft³ \( \text{C}_2\text{H}_4 - \text{O}_2 \) mixture at 25°C, 745 mm Hg

\[ n_1 = \frac{P \cdot V}{R \cdot T} = \frac{745 \times 14.7 \times 350}{760 \times 10.73 \times 298(1.8)} = 0.874 \text{ lb mol} \]

\[ n_2 = \frac{745}{760} \times 14.7 \times \frac{300}{333} \times \frac{1}{1.8} = 0.671 \text{ lb mol} \]

\[ P_{H_2O} = 149.4 \text{ mm Hg} \]

\[ y_{H_2O} = \frac{149.4}{745} = 0.201 \]

\[ n_{H_2O} = (0.201)(0.671) = 0.135 \text{ lb mol} \]

(continued)
C₆H₁₃ + \( \frac{5}{2} \) O₂ \rightarrow 2CO₂ + H₂O

You get 1 mol H₂O/mol C₆H₁₃ on reaction

Therefore moles C₆H₁₃ = 0.135

mol O₂ = 0.874 - 0.135 = 0.739 lb mol

\[ \frac{V_{0, ai}}{V_{0, a}} = \frac{0.739}{0.874} = 0.845 \]

\[ V_{0, a} = 0.845(350) = 298.1 \text{ ft}^3 \text{ at 745 mm and 25°C} \]

\[ V_{C6H13} = 350 - 276 = 74 \text{ ft}^3 \text{ at 745 mm and 25°C} \]

17.10

Elephant seals have an average body temperature several degrees higher than ours. That means their breath can hold a bit more moisture than ours, and on that day, that extra moisture could have been just enough for condensation to occur.

But there are other reasons the elephant seals' breath may have been easier to see. It could be that it was a few degrees colder on the beach than where the observer was sited. And, as you know if you have ever experimented with seeing your breath, the bigger the volume of air, the more moisture available to condense out and so the condensed moisture was more visible.

17.11

(a) \( p_{sat} \) exists if saturation occurs. Then, with \( p_{sat} = 100 \text{ kPa} \)

\[ p_{sat} = 100 (0.014) = 1.4 \text{ kPa} \]

which corresponds to

\(-11°C \) from Perry
17.13

At equilibrium, the pressure of Hg is its vapor pressure

\[ p_{Hg} = p_{Hg}' = \frac{1.729 \times 10^{-4} \text{ g mol Hg}}{99.5 \text{ g mol air}} \]

Note: \( p_{Hg} = p_{Hg}' = p_{Hg} \) for all purposes so

\[ \frac{1.729 \times 10^{-4} \text{ g mol Hg}}{99.5 \text{ g mol total gas}} \]

Basis: \( 1.729 \times 10^{-4} \text{ g mol Hg} \)

\[ \frac{1.729 \times 10^{-4} \text{ g mol Hg}}{99.5 \text{ g mol air}} = \frac{1000 \text{ mg}}{1000 \text{ g}} = 0.3814 \text{ mg Hg} \]

\[ V = \frac{nRT}{p} = \frac{99.5 \text{ g mol air}}{99.5 \text{ g mol air}} \left( \frac{293.15 \text{ K}}{1000 \text{ g}} \right) \left( \frac{8.314 \text{ (kPa)(m)}^3}{1000 \text{ g}} \right) \]

\[ = 2.44 \text{ m}^3 \text{ at } 20^\circ \text{C and 99.5 kPa} \]

\[ 15.65 \text{ mg m}^2 \text{ at } 20^\circ \text{C and 99.5 kPa}. \]

Level is not acceptable.

A mercury spill can be cleaned up reasonably effectively by dusting with sulfur, then vacuuming with a vacuum cleaner specifically designed for mercury pick-up, which prevents the escape of mercury vapor.

The instructor should point out to the student that the assumption of the "no ventilation" is not a very good approximation unless the surface of the mercury is rather large or there is truly no ventilation in the storeroom.

17.14

Step 5: Basis: 1 min

Steps 2, 3, and 4: System is loading plus water seal, steady state, open

\[ C_4 \rightarrow \text{Loading} \rightarrow \text{Water seal} \rightarrow P \]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol fr.</th>
<th>kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>(H_2)(C)(sat)\</td>
<td>2.34 |</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>120</td>
</tr>
</tbody>
</table>

\( p_{H_2O} \) at 20°C = 2.34 kPa

\[ n_e = \frac{pV}{RT} = \frac{100.0 \text{ kPa}}{293.15 \text{ K}} \left( \frac{100 \text{ cm}^3}{1 \text{ m}} \right) \left( \frac{1 \text{ kg mol(K)}}{293.15 \text{ K}} \right) \left( \frac{8.314 \text{ (kPa)(m)}^3}{100 \text{ cm}^3} \right) \]

\[ = 1.231 \times 10^3 \text{ kg mol} = 1.231 \times 10^2 \text{ g mol } C_4 \]

Steps 6, 7, 8, and 9:

At P, the mole fraction of water is 2.34/120 = \( x_{H_2O} = 0.0195 \)

The moles of P come from a \( C_4 \) balance (\( C_4 \) is a tie element)

\[ 1.231 \times 10^2 = 0.015P \]

Then the air in is

\[ 0.821 (1-0.0195 - 0.015) = 0.793 \text{ g mol} \]

\[ V = \frac{nRT}{p} = \frac{0.793 \times 10^2 \text{ kg mol}}{293.15 \text{ K}} \left( \frac{8.314 \text{ (kPa)(m)}^3}{100 \text{ kPa}} \right) \]

(continued)
17.15

Assume equilibrium.

At 75°F, from the Antoine equation, the vapor pressure of benzene is 90 mmHg.
Assume the barometer is 760 mm Hg abs.

\[
\frac{\text{mol Bz}}{\text{mol air}} = \frac{p_{\text{a}} - p_{0}}{p_{0}} = \frac{90}{760 - 90} = 0.13 \frac{\text{mol Bz}}{\text{mol air}}
\]

a) The OSHA limit is 1 ppm over 8 hours. The above greatly exceeds this limit.

b) No, because the garage is probably not well ventilated, and also if a water heater is in the garage, the LEL (Lower Explosive Limit) may be exceeded.

17.16

Basis: 50 ft³ air at 29.92 in. Hg and 70°F

\[p_{Hg} = 0.36 \text{ in. Hg}\]

The amount of water per hour is

\[
\begin{array}{c|c|c|c|c}
\text{50 ft}^3/60 \text{ min} & 1 \text{ lb mol} & 429°F & 0.36 \text{ in. Hg of H}_2\text{O} & 18 \text{ lb} \\
\text{1 hr} & \text{29.92 in. Hg} & \text{lb mol} & \text{1.68 lb H}_2\text{O} \\
\end{array}
\]

Alternate solution: make air and water balances.

17.17

Basis: 1 hr

The question really is: does the Hg condense at 150°F, or is it still a vapor (and thus not collected).

The moles of Hg are: \(40,000 \times 0.023 \times 10^{-2}\) lb Hg/1 lb mol Hg = 0.046 lb mol/200 lb Hg

The moles of gas are (ignoring the Hg):

\[
\frac{40,000 \text{ lb gas}}{32 \text{ lb gas}} = 1250 \frac{\text{lb gas}}{\text{lb gas}}
\]

\[
\gamma_{Hg} = \frac{0.046}{0.046 + 1250} = 3.68 \times 10^{-5}
\]

The partial pressure of the Hg in the gas is \(\gamma_{Hg}\)

\[
(3.68 \times 10^{-5}) \times (14.7) = 5.4 \times 10^{-4} \text{ psia}
\]

The Hg will remain a vapor and not condense.
17.19

Steps 1-4:

\[
\begin{align*}
&\text{air} & F(\text{mol}) & \text{remove 50\%} & H_2O & P(\text{saturated}) & \text{mol fr} \\
& H_2O & 25^\circ C & 100 \text{ kPa} & H_2O & 100 \text{ kPa} & 100-p^*p/100 \\
& & & & & & p^*/100 \\
\end{align*}
\]

At 16°C

\[
0.57 \text{ in Hg} \
0.28 \text{ psia}
\]

\[
p^* = 13.6 \text{ mm Hg} = 1.81 \text{ kPa} \quad \text{From steam tables} \quad p^* = 1.92 \text{ kPa}
\]

\[
\text{Thus } p_{\text{ar}} = 100 - 1.81 = 98.18 \text{ kPa} \quad p_{\text{ar}} = 100 - 1.92 = 98.08
\]

Step 5: Basis is 100 Mol F

Step 6: Unknowns: W, P

Step 7: Balances: H_2O, air

Steps 8 & 9: Balances around process in mol

\[
\begin{align*}
\text{Air} & & 100 \left( \frac{98.08}{100} \right) = W(0) + p \left( \frac{100 - p_n}{100} \right) & \text{in P} \\
\text{H}_2\text{O} & & 100 \left( \frac{1.92}{100} \right) = W(1) + p \left( \frac{p_{n,\text{H}_2\text{O}}}{100} \right) & \text{in P} \\
\text{Total} & & 100 = W + P
\end{align*}
\]

Also, \( p^* = f(T) \) vapor pressure relation

(continued)
Solutions Chapter 17

- The exit gas has one-half the entering H$_2$O, or ½ (1.92) = 0.96 mol thus W = ½ (1.92) = 0.96 mol H$_2$O.

- The exit air has 98.08 mol dry air.

- At the exit $p_{w,o} = p_{w} = y_{H_2O}(100) = \frac{0.96}{0.96 + 98.08}$ = 0.097 kPa

- From the steam tables, this corresponds to about 280 K (7°C), or use Antoine Eq.

Note: Taking ½ of (1.92) = 0.96 and dividing by 100 instead of $(p_{w,o} + p_{w})$ is wrong. The answer is close to correct because of the very small amount of water.

17.20

Basis: 1000 m$^3$ sat. air at 99 kPa and 30°C

$p_{w,o}$ at 30°C = 0.6155 psia = 31.8 mm Hg = 4.24 kPa

\[
\begin{align*}
1000 \text{ m}^3 & \times 1 \text{ kg mol} \times 99 \text{ kPa} \times 273 \text{ K} \\
22415 \text{ m}^2 \times \text{ 15C} \times 101.3 \text{ kPa} \times 303 \text{ K}
\end{align*}
\]

or \[ n = \frac{99 \text{ kPa} \times 1000 \text{ m}^3}{303 \text{ K} \times 8.314 \text{ (kPa)(m$^3$)/mol}} = 39.3 \text{ kg mol}

Initial:

Initial mol H$_2$O = 39.3 \left(4.24 \frac{99}{99}\right) = 1.68 kg mol H$_2$O

Initial mol air = 39.3 \left(\frac{99 - 4.24}{99}\right) = 39.3 - 1.68 = 37.62 kg mol air

Final:

At 14°C and 133 kPa, the air is still saturated, and $n_{H_2O} = 37.62 \text{ kg mol}$

\[ \frac{p_{w,o}}{p_w} = \frac{n_{H_2O}}{n_w}; \text{ so } \frac{1.59}{(133 - 1.59)} = \frac{n_{H_2O}}{n_w} \]

There is the same as

an H$_2$O material balance

\[ n_{H_2O} = 0.46 \text{ kg mol} \]

1.68 - 0.46 = 1.22 kg mol or 22 kg

17.21

Steps 2, 3, and 4:

\[ \text{C}_2\text{H}_6 \xrightarrow{\text{Combustion chamber}} \begin{array}{c} \text{CO}_2 \\ \text{H}_2\text{O} \\ \text{O}_2 \\ \text{N}_2 \end{array} \]

Assume combustion is complete and the gases are ideal. The process is open, steady state with reaction. The first objective is to make material balances.

\[ \text{C}_2\text{H}_6 + 3.5\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O} \]

Step 5:

Basis: 100 mol C$_2$H$_6$

Step 6:

The entering O$_2$ is 350 mol

The excess O$_2$ is (0.20) (3.50) = 70 mol

Total O$_2$ is 420 mol

The N$_2$ is 420 \left(\frac{0.79}{0.21}\right) = 1580 mol

Steps 6 and 7:

Unknowns: 4 (The components of the flue gas) (continued)
Solutions Chapter 17

Balances: C, H, O, N, total of 4
Degrees of freedom = 0

Steps 8 and 9 (balances in moles, in = out):

C: \( 2(100) = n_{\text{CO}} \), \( n_{\text{CO}} = 200 \text{ mol} \)
2N: \( 1580 = n_{\text{N}} \), \( n_{\text{N}} = 1580 \text{ mol} \)
H: \( 6(100) = 2n_{\text{H}_2}\text{O} \), \( n_{\text{H}_2}\text{O} = 300 \text{ mol} \)
O: \( 420(2) = 2n_{\text{CO}} + n_{\text{H}_2}\text{O} + 2n_{\text{O}_2} \), \( n_{\text{O}_2} = 700 \text{ mol} \)
Total: \( 2150 \text{ mol} \)

The dewpoint is the temperature at which the flue gas is saturated

\[ p^*_{\text{H}_2\text{O}} = y^*_{\text{H}_2\text{O}} P_{\text{sat}} = \frac{300}{2150} (100 \text{ kPa}) = 14.0 \text{ kPa} \]

This pressure of \( \text{H}_2\text{O} \) corresponds (from the steam tables) to \( 325.7 \text{ K} \) (52.6°C)

17.22

Step 5: Basis: 100 lb mol flue gas

Steps 2, 3, and 4:

---

Solutions Chapter 17

---

Steps 6 and 7:

Unknowns: F, A, W
Equations: Material balances: C, H, O (the ash is ignored)

Steps 8 and 9 (balances are in moles; in = out)

To get F:
\[ C: (0.80F)(1/12) = (0.140 + 0.004) 100 \quad F = 216 \text{ lb or 18.0 lb mol} \]

To get A:
\[ \text{N}_2: 80 = A(0.79) \quad A = 101.27 \text{ lb mol} \]

H: Hydrogen from the dry coal plus the water in the coal is (MW H = 1.008):

\[ \begin{array}{ccc}
216 & 2.5 & 1 \\
97.5 & 18.016 & 2 \\
6.74 & \text{lb mol H}_2\text{O} \\
\end{array} \]

In A:
\[ p^*_{\text{H}_2\text{O}} = 0.3624 = y^*_{\text{H}_2\text{O}} P_{\text{sat}} = y^*_{\text{H}_2\text{O}} (29.90) \]

\[ y^*_{\text{H}_2\text{O}} = 0.0121 \]

The water in A is (0.0121) (101.27) = 1.23 lb mol

Total \( \text{H}_2\text{O} \) in P: \( W = 7.97 \text{ lb mol} \) (continued)
The dew point is 

\[
\frac{7.97}{187.97} = 2.21 \text{ in. Hg equivalent to } 102^\circ F
\]

17.23

<table>
<thead>
<tr>
<th>mo. %</th>
<th>P</th>
<th>(P_t = 98 \text{ kPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 CO₂</td>
<td>P</td>
<td>( P_t = 98 \text{ kPa} )</td>
</tr>
<tr>
<td>26.0 CO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.0 H₂O</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 CH₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55.0 N₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Air 10% excess

\( O₂ = \frac{22.55}{84.83} \) mol

Step 4: Calculate the x's air and add total air to the diagram

Step 5: Basis: 100 mol synthesis gas

Step 6: Unknowns: \( n_c, n_o, n_{H₂O}, n_N, P \) (5 total)

Step 7: Balances C, O, H, N, \( \Sigma n_i = P \) (5 independent equations)

Steps 8, 9: Use element balances

\[
\begin{align*}
\text{C:} & \quad 4.5 + 26.0 + 0.5 = n_{CO₂} \quad n_{CO₂} = 31.0 \\
\text{H:} & \quad 0.5 (4) + 13 (2) = n_{H₂O} (2) \quad n_{H₂O} = \frac{28}{2}
\end{align*}
\]

Solutions Chapter 17

O₂: \[
4.5 + \frac{26.0}{2} + 22.55 = n_{CO₂} \quad n_{CO₂} = 2.05
\]

N₂: \[
56.0 + 84.83 = n_{N₂} \quad n_{N₂} = \frac{140.8}{187.9}
\]

\[
Y_{H₂O} = \frac{28/2}{187.9} = \frac{14}{187.9}
\]

\( P_{H₂O} = 98 \left( \frac{14}{187.9} \right) = 7.3 \text{ kPa} \) (or 1.06 psia)

This is equivalent to a temperature of 104°F from the steam tables (40°C)

17.24

Basis: 100 mol gases leaving absorber

\[
\text{CH₄} + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}
\]

\[
0.8335 \text{ mol N}_2, 0.21 \text{ mol O}_2, 1 \text{ mol CO}_2, 0.1108 \text{ mol CO}_2
\]

\[
0.79 \text{ mol N}_2, 2 \text{ mol O}_2
\]

\[
1.0 - 0.8335 - 0.1108 = 0.0557 \text{ mol H}_2\text{O}; 0.0557 \times 20 = 1.114 \text{ psia}
\]

Dew point = 105°F at 1.114 psia

b) At constant temperature of 130°F, the gas must be compressed until the partial pressure increases and becomes equal to the vapor pressure in order to reach the point of condensation.

From Steam tables, the vapor pressure of water at 130°F is 2.223 psia.

The total pressure at which the partial pressure of water (mol fraction = 0.0557) will be 2.223 psia is

\[
P_{H₂O} = P_{H₂O}
\]

\[
\frac{2.223}{0.0557} = 40.1 \text{ psia}
\]
17.25

Basis: 1 lb mol of benzene free air

Barometric Pressure = \( 742 \) mm Hg

\( p^* \) benzene at 40°C = 181

Partial pressure of air = 561

Partial pressure of benzene = 181 \( \Rightarrow \) 0.323 lb mol benzene

At 25 psig total pressure or = 2052

\( p^* \) benzene at 10°C = 45.4

Partial pressure of air = 2066.6

Final partial pressure of benzene in air = \( 45.4 \Rightarrow 0.023 \) lb mol benzene

\( 0.323 - 0.023 = 0.3 \) lb mol \( C_6H_6 \) recovered

a. \( \frac{(0.3)(100)}{(0.323)} = 92.9\% \) recovery

b. 2 psig is 103 + 742 = 845 mm Hg

\( \frac{(0.023)(845)}{(1.023)} = 18.9 \) mm Hg partial pressure of benzene in the recycled air.

17.26

Steps 2, 3, and 4:

The dewpoint of 140°F gives \( p^*_{w,o} = 149.3 \) mm Hg

Step 5:

Basis: 100 lb wet solids in (BDS is bone dry solids)

Step 8 and 9:

BDS balance: 60 lb BDS = 0.90 (wet solids out)

\[ \text{wet solids out} = 66.7 \text{ lb} \]

From a total balance \( 100 - 66.7 = 33.3 \) lb \( H_2O \) evaporated = 1.85 lb mol \( H_2O \) evaporated

For the air,

Assume the air exits at 1.0 atm

Composition in: \( \frac{H_2O}{800} \) (100) = 1.25%

\( \frac{\text{Air}}{800} \) (100) = 98.75%

Composition out: \( \frac{H_2O}{800} \) (100) = 18.7% (continued)
Solutions Chapter 17

Overall balance (mol) on the gas phase

\[ \text{Air} = 81.3\% \]

Air balance (mol) on the gas phase

\[ A_{\text{in}} + 1.85 = A_{\text{out}} \]

Air balance (mol) on the gas phase

\[ 0.9875 \cdot A_{\text{in}} = 0.813 \cdot A_{\text{out}} \]

\[ A_{\text{in}} = 8.619 \text{ lb moles wet air in} \]

\[ \frac{8.619 \text{ lb mol}}{359 \text{ ft}^3/1660^\circ \text{R}} = \frac{0.9440 \text{ ft}^3}{800 \text{ lb mol}} \]

of wet air @ 800 mm Hg and 200°F

(continued)

17.27

Basis: 1 hr

Calculate the amounts of the various components in the gas phase:

Water

\[ \text{H}_2\text{O in} = 0 \text{ (by specification)} \]

\[ \text{H}_2\text{O out (saturated):} \]

\[ p^s \text{ at } 300 \text{ K} = 3.51 \text{ kPa} = p_{\text{H}_2\text{O}} \]

\[ y_{\text{H}_2\text{O}} = \frac{3.51 \text{ kPa}}{110 \text{ kPa}} = 0.0319 \]

\[ \text{CO}_2 \]

\[ \text{CO}_2 \text{ in: } y_{\text{CO}_2} = 0.00055 \]

\[ \text{CO}_2 \text{ out: } y_{\text{CO}_2} = 0.125 \]

O

\[ \text{O}_2 \text{ in: } y_{\text{O}_2} = 0.21 \]

\[ \text{O}_2 \text{ out: } y_{\text{O}_2} = 0.0804 \]

Assume the other gas in and out is \( \text{N}_2 \).

The entering gas is

\[ \frac{600 \text{ m}^3}{120 \text{ kPa}} \cdot \frac{\text{(kg mol)/(K)}}{300 K \cdot 8.314(\text{kJ/Kmol})(\text{m}^3)} = 28.87 \text{ kg mol} \]

The exit gas can be obtained from a \( \text{N}_2 \) balance

\[ 28.87(I - 0 - 0.00055 - 0.21) = n_{\text{in}}(I - 0.0319 - 0.125 - 0.0804) \]

\[ n_{\text{in}} = 29.89 \text{ kg mol} \]

In one hour in the steady state the moles of \( \text{CO}_2 \) produced were

\[ 29.89(0.125) - 28.87(0.00055) = 3.72 \text{ kg mol} \]

The mole of \( \text{O}_2 \) consumed were

\[ 28.87(0.21) - 30.14(0.0804) = 3.64 \text{ kg mol} \]

\[ RQ = \frac{3.72}{3.64} = 1.02 \]
18.1

Basis: gas as given in problem statement

(a) \( \frac{P_{\text{H}_2\text{O}}}{P_{\text{tot}} - P_{\text{H}_2\text{O}}} = \frac{P_{\text{H}_2\text{O}}}{101.6 - P_{\text{H}_2\text{O}}} \) so, \( P_{\text{H}_2\text{O}} = 2.96 \) kPa

\( P_{\text{H}_2\text{O}} \) at 60 °C = 19.9 kPa

% humidity = \( 100 \left( \frac{2.96}{19.9} \right) \left( \frac{101.6 - 19.9}{101.6 - 2.96} \right) \) = 12.2%

(b) Relative humidity

\( \frac{100 \times 2.96}{19.9} = 14.9\% \)

(c) Dewpoint occurs where \( P_{\text{H}_2\text{O}} = 2.96 \) kPa, or \( T = 24^\circ \text{C} \) from the steam tables.

18.2

At 27 °C, \( P_{\text{H}_2\text{O}} = 3.52 \) kPa. The actual pressure of the water vapor is obtained from

\[
p = \frac{nRT}{V} = \left( \frac{0.636}{18.01} \right) \left( \frac{8.314}{28.0} \right) \left( \frac{300 K}{28.0} \right) = 3.15 \text{ kPa}
\]

\( 100 \left( \frac{3.15}{3.52} \right) = 89\% \text{ RH} \)

18.3

At 50 °F, \( P_{\text{H}_2\text{O}} = 0.5067 \) psia from the steam tables.

At 40 °F, \( P_{\text{H}_2\text{O}} = 0.1217 \) psia

At 58 °F, \( P_{\text{H}_2\text{O}} = 0.2384 \) psia

(a) \( 100 \left( \frac{0.1217 \text{ psia}}{0.5067 \text{ psia}} \right) = 24\% \)

(b) The mol fraction of \( \text{H}_2\text{O} \) vapor is constant on compression unless saturation is reached. At the initial conditions

\[
y_{\text{H}_2\text{O}} = \frac{0.1217}{14.696} = 8.28 \times 10^{-3}
\]

At 2 atm, \( P_{\text{H}_2\text{O}} = P_{\text{tot}} y_{\text{H}_2\text{O}} = (14.692)(2) \left( \frac{0.1217}{14.696} \right) = 0.2437 \) psia

\( 0.2437 > 1 \) hence water condenses and the relative humidity is 100%
Solutions Chapter 18

18.4

\[ T = 140^\circ F \]
\[ p^* = 5.878 \text{ in Hg} \]

\[ p = 30 \text{ in Hg} \]

\[ H = 0.03 \text{ mol H}_2\text{O/mol BDA} \Rightarrow \text{Basis: 1 mol BDA} \]

\[ \frac{\text{mol H}_2\text{O}}{\text{mol H}_2\text{O} + \text{BDA}} = 0.03 \]
\[ = 0.0291 = y_{H_2O} \]

\[ P_{H_2O} = 30 \times 0.0291 = 0.874 \text{ in Hg} \]

\[ P_{\text{air}} = 30 \times (1 - 0.0291) = 29.13 \text{ in Hg} \]

\[ (a) \quad \% \text{ rel. humidity} = 100 \frac{P_{H_2O}}{p^*_{H_2O}} = 100 \left( \frac{0.874}{5.878} \right) = 14.9\% \]

\[ (b) \quad \text{Dew point is the temperature at which vapor first condenses on cooling at constant humidity, hence} \quad p^* = 0.874 \text{ in Hg} \approx 75^\circ \text{F} \]

18.5

From steam tables, \( p^*_{w90^\circ F} = 0.6982 \text{ psia} \). Assume constant pressure during the process.

Partial pressure of water, \( P_w = (0.85) \times p^*_{w90^\circ F} = 0.593 \text{ psia} \)

Partial pressure of dry air, \( P_{\text{dry air}} = \text{Total pressure} - P_w = 14.696 - 0.593 = 14.103 \text{ psia} \)

(a) Molar humidity

\[ \text{mol of water vapor} \quad \text{mol of dry air} \]
\[ = \frac{P_w}{P_{\text{dry air}}} = \frac{P_w}{P_{\text{dry air}}} = \frac{0.593}{14.013} = 0.042 \]

(b) Humidity

\[ \frac{\text{lb of water vapor}}{\text{lb of dry air}} = \frac{0.042 \text{ lb mol H}_2\text{O}}{18 \text{ lb mol H}_2\text{O}/\text{lb mol H}_2\text{O}} = 0.026 \]

(c) Saturation temperature or the dew point is the temperature at which the vapor pressure of water will become equal to the existing partial pressure of 0.593 psia.

By interpolation, dew point \( = 84.8^\circ \text{F} \)

(d) Number of degrees of superheat

\( = 90^\circ \text{F} - 85^\circ \text{F} = 5^\circ \text{F} \)

(e) At 105°F and 14.696 psia, all the water is still present as vapor, i.e., the gas phase composition and hence the partial pressures are unchanged from those at 90°F. The molar humidity and dew point are the same as at 90°F.

(f) At 60°F and 14.696 psia, the air is cooled below its original dew point of 85°C. Hence, water will condense, and the resulting air will be saturated with water vapor.

\[ \therefore \quad \text{The dew point} = 60^\circ \text{F} \]

To find the molar humidity, find the partial pressures:

\[ P_w = P^*_{w90^\circ F} = 0.2563 \text{ psi} \]

\[ P_{\text{dry air}} = 14.696 - 0.2563 = 14.44 \text{ psi} \]

Molar humidity (continued)
Solutions Chapter 18

\[
= \frac{\text{mol water}}{\text{mol dry air}} = 0.0177 \text{ mol water / mol dry air}
\]

(g) Water condensed:

<table>
<thead>
<tr>
<th>Basis: 1.0 mol of dry air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial water in air, at 90°F, 1 atm = 0.042 mol water/mol dry air</td>
</tr>
<tr>
<td>Final water in air, at 69°F, 1 atm = 0.0177 mol water/mol dry air</td>
</tr>
<tr>
<td>Water condensed = 0.042 - 0.0177 = 0.0243 mol water/mol dry air</td>
</tr>
<tr>
<td>Fraction of the original water condensed = ( \frac{0.0243}{0.042} = 0.58 )</td>
</tr>
</tbody>
</table>

Alternate solution:

Make (1) a total balance, (2) an H₂O balance, (3) an air balance. Two are independent.

Use as a basis: 1 mole wet air

18.6

\[ T = 25°C, p_Bz = 2.20 \text{ mm Hg}, p_i = 800 \text{ mm Hg}, \text{ hence } p_{air} = 797.8 \text{ mm Hg} \]

(a) \[ \frac{n_Bz}{n_i} = \frac{p_{Bz}}{p_i} \Rightarrow \frac{n_{Bz}}{n_i} = \frac{2.20}{800} = 2.75 \times 10^{-3} \text{ mol Bz/mol gas} \]

(b) \[ \frac{n_{Bz}}{n_{air}} = \frac{p_{Bz}}{p_{air}} \Rightarrow \frac{n_{Bz}}{n_{air}} = \frac{2.20}{797.8} = 2.7576 \times 10^{-3} \text{ mol Bz/mol Bz free gas} \]

(c) \[ \frac{g_{Bz}}{g_{Bz\ free\ gas}} = \frac{2.7576 \times 10^{-3} \text{ mol Bz}}{1 \text{ mol air}} \Rightarrow \frac{78 \text{ g Bz}}{1 \text{ g mol air}} = 0.0074 \]

(d) Relative Saturation = \[ \frac{p_{Bz}}{p^{*}_{Bz\ at\ 25°C}} \]

\[ p^{*}_{Bz\ at\ 25°C} = 95.6 \text{ mm Hg} \Rightarrow \text{ Rel. Saturation} = \frac{2.20}{95.6} = 0.023 \]

(e) \[ \mu g_{Bz} = \frac{2.20 \text{ g mol Bz}}{800 \text{ g mol gas}} \Rightarrow \frac{78 \text{ g Bz}}{1 \text{ g mol Bz}} \Rightarrow \frac{10 \mu g}{1 \text{ g}} \Rightarrow 122.4 \text{ L at SC} \]

\[
\frac{760 \text{ mm Hg}}{800 \text{ mm Hg}} = \frac{298 \text{ K}}{273 \text{ K}} = 9.96 \times 10^5 \text{ mg} / \text{m}^3 \text{ Exceeds the standard}
\]

(f) \[ \frac{g_{Bz}}{\text{ft}^3} = \frac{9.96 \times 10^5 \mu g}{1 \text{ g}} \Rightarrow \frac{0.028 \text{ m}^3}{1 \text{ ft}^3} = 0.278 \text{ g Bz/ft}^3 \]
Solutions Chapter 18

18.7

(a) Initial

\[ p_{air, V} = \frac{n_{air} \cdot RT}{n_{air} \cdot T} \]

Final

Assume all of the water evaporates, and check later on to see if the assumption is true.

\[ p_{air, f} + p_{H_2O} = p_1 \text{ so } p_{air, f} = p_1 - p_{H_2O} \]

\[ V_{air, f} = \frac{n_{air} \cdot RT}{n_{air} \cdot T} \]

The material balance is simple: all the initial air = final air.

\[ \frac{p_{H_2O, f}}{p_1 - p_{H_2O}} = \frac{66 + 460}{180 + 460} = \frac{526}{640} = 0.212 \]

Since \( p^* = 7.51 \text{ psia} \), all of the water can evaporate and the air will not be saturated.

(b) Basis: 1 lb H_2O (0.0555 lb mol H_2O)

At the final condition

So \( n = 0.254 \text{ lb mol} \)

\[ V = \frac{nRT}{p} = \left( \frac{0.254}{33.0} \right) \left( \frac{10.73 \cdot 640}{33.0} \right) = 53.0 \text{ R}^3 \]

(c) \( n_{air} = 0.254 - 0.0555 = 0.1985 \text{ lb mol} \)

\[ \frac{1 \text{ lb H}_2\text{O}}{0.1985(29)} = 0.17 \text{ lb H}_2\text{O} \text{ lb air} \]

Solutions Chapter 18

18.8

The vapor pressure of ethyl acetate at 30 °C is 122.5 mm Hg.

% relative saturation = 50 = \( \frac{P_{\text{vap}}}{P_{\text{vap}}} \)

\[ P_{\text{vap}} = 0.50 (122.5) = 61.2 \text{ mm Hg} \]

Basis: 740 mol EA

(a) \[ \frac{n_{\text{vap}}}{n_1} = \frac{61.2}{740} = 0.0828 \]

Hence the vapor analyzes 8.28% EtAc and 91.72% air.

(b) Molal saturation is

\[ \frac{n_{\text{vap}}}{n_{\text{air}}} = \frac{P_{\text{vap}}}{P_{\text{air}}} = \frac{61.2}{740 - 61.2} = 0.090 \text{ mol EtAc} \text{ mol air} \]
18.9

Basis: 0.0083 lb mol H₂O vapor/lb mol CH₄

(a) \( p^*_{\text{H₂O}} \) at 80°F = 26 mm Hg (steam tables)

\[
\frac{p_{\text{H₂O}}}{P_{\text{total}}} = \frac{n_{\text{H₂O}}}{n_{\text{total}}}
\]

\[
y_{\text{H₂O}} = \frac{0.0083}{1.0083} = 0.0083
\]

\[
y_{\text{H₂O}} P_{\text{total}} = p_{\text{H₂O}}
\]

\[
\frac{0.0083 \times 1520}{1.0083} = 12.5 \text{ mm Hg} = p_{\text{H₂O}}
\]

\[
\frac{12.5}{26} = 0.48
\]

(b) \( \frac{P_{\text{total}}}{P_{\text{H₂O}}} = \frac{12.5}{p_{\text{H₂O}}} = 0.20 \)

When \( p^*_{\text{H₂O}} = 62.5 \text{ mm Hg} \), the temperature is 109°F.

---

18.10

Steps 1, 2, 3, and 4:

\[
F(\text{kg mol})
\]

\[
P(\text{kg mol})
\]

\[
\text{Air: 22°C, RH = 50%}
\]

\[
\text{W = 200 kg mol H₂O}
\]

Data for \( p^* \) from the steam tables:

- 22°C (295K) = 2.622
- 72°C (345K) = 33.77

These calculations provide the composition of \( F \) and \( P \):

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{H₂O}} ) = 0.50 (2.60)</td>
<td>( P_{\text{H₂O}} ) = 0.80 (33.77) = 27.02</td>
</tr>
<tr>
<td>( p_{\text{air}} ) = 103.0 ( \times ) 1.31</td>
<td>( p_{\text{air}} ) = 102.0 - 27.0 = 76.0</td>
</tr>
<tr>
<td>( P_t ) = 103.0</td>
<td>( P_t ) = 103.0</td>
</tr>
</tbody>
</table>

Step 5: Basis:

\( W = 200 \text{ kg H₂O} \) (1 hour)

Steps 6 and 7: Unknowns are: \( F, P \)
Balances are: H₂O, air

Steps 8 and 9: This is a steady state process without a reaction

(continued)
Solutions Chapter 18

### Balances

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2O$</td>
<td>$F\left(\gamma_{\text{m}}\right) + \gamma_{\text{m}}(1.00) = P\left(\gamma_{\text{m}}\right)$</td>
</tr>
<tr>
<td>air</td>
<td>$F\left(\gamma_{\text{m}}\right) = P(\gamma_{\text{m}})$</td>
</tr>
<tr>
<td>$F = 32.86 \text{ kg mol}$</td>
<td>$P = 43.95 \text{ kg mol}$</td>
</tr>
</tbody>
</table>

### Bone dry air:

$F\left(\gamma_{\text{m}}\right) = 32.45 \text{ kg mol}$  
$P\left(\gamma_{\text{m}}\right) = 32.43 \text{ kg mol}$

**Step 10:** Check using total balance

Weight in kg of dry air used $= 32.45 \times 29 = 941 \text{ kg}$

18.11

**Steps 1, 2, 3, and 4:** This is a steady state process without reaction.

---

**Solutions Chapter 18**

<table>
<thead>
<tr>
<th></th>
<th>mass fr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>0.015 kg $H_2O$</td>
</tr>
<tr>
<td></td>
<td>0.01477</td>
</tr>
<tr>
<td>1.000 kg air</td>
<td>0.98523</td>
</tr>
<tr>
<td>1.015 kg total</td>
<td>1.00000</td>
</tr>
<tr>
<td>$P$</td>
<td>9.09 kg $H_2O$</td>
</tr>
<tr>
<td></td>
<td>0.08339</td>
</tr>
<tr>
<td>100.00 kg CaCO$_3$</td>
<td>0.91661</td>
</tr>
<tr>
<td>109.00 kg total</td>
<td>1.00000</td>
</tr>
<tr>
<td>$A$</td>
<td>0.005 kg $H_2O$</td>
</tr>
<tr>
<td></td>
<td>0.004975</td>
</tr>
<tr>
<td>1.000 kg air</td>
<td>0.995025</td>
</tr>
<tr>
<td>1.005 kg total</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

**Step 5:** System is the filter. Basis: $F = 1000 \text{ kg}$

**Step 6:** Unknowns: $T$, $W$

**Steps 7, 8, and 9:**

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO$_3$ balance:</td>
<td>1000 (0.10) = $T$ (0.40)</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>1000 (0.90) = $T$ (0.60) + $W$ (1.00)</td>
</tr>
<tr>
<td>Total</td>
<td>1000 = $T + W$</td>
</tr>
</tbody>
</table>

The balances are not independent; only 2 are independent.

All we need is the CaCO$_3$ balance as CaCO$_3$ is a tie component.

a. $T = 250 \text{ kg}$
   
   $W = 1000 - 250 = 750 \text{ kg}$

b. System is the dryer; same basis.

(continued)
Step 6: The unknowns are G, P, and A

Steps 7, 8, and 9: We have 3 balances: \( \text{H}_2\text{O}, \text{air}, \text{CaCO}_3 \)

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO(_3):</td>
<td>250 (.40)</td>
</tr>
<tr>
<td>( \text{P} = 109.09 \text{ kg} )</td>
<td></td>
</tr>
</tbody>
</table>

(From an overall system balance on CaCO\(_3\) with 100 kg CaCO\(_3\) in and out in P the water out in P = 9.09 kg.)

\[
\text{air: } \begin{pmatrix} 1.005 \\ 1.015 \end{pmatrix} = \begin{pmatrix} 1.000 \\ 1.015 \end{pmatrix} - \begin{pmatrix} 0.005 \\ 1.015 \end{pmatrix} = \begin{pmatrix} 0.005 \\ 0.015 \end{pmatrix} + \begin{pmatrix} 9.09 \\ 109.09 \end{pmatrix}
\]

\( A = 14,400 \text{ kg} \)

18.12

Step 5: Basis: 1 mol F

Steps 2, 3, and 4:

\[
\begin{align*}
\text{T} &= 300K \\
p &= 750 \text{ mm Hg} \\
\text{HC} &\rightarrow 100\% \text{ RS} \\
\text{HC} &\rightarrow \text{N}_2 \\
\text{W} &\rightarrow \text{100\% of HC in F}
\end{align*}
\]

\[
\begin{align*}
\text{HC balance: } l &\left( \frac{3.94}{750} \right) = W(1.0) + \text{P} x_{\text{HC}}^* \\
p &= 1 - 0.00473 = 0.99527 \text{ mol}
\end{align*}
\]

\[
\begin{align*}
x_{\text{HC}}^* &= \frac{3.94}{750} (0.1) = 0.00053 \\
p_{\text{HC}} &= p_T (0.00053) \\
p_{\text{HC}} &= 0.00053 (750) = 0.396 \text{ mm Hg} = p^*_\text{HC} \\
\text{ln} (0.396) &= 15.9008 - \frac{2788.51}{750 - 52.36} \to T = 218 \text{ K}
\end{align*}
\]
18.13

Steps 1, 2, 3, and 4:

Air
30°C
100 kPa
RH = 75.0%

F (mol)

Compressor
275 kPa

\( \rho_m = 275 \text{ kPa} \)

Air
Saturated
20°C
RH = 100%

Cooler

P(mol)

\( \rho_{H_2O} = 0.6153 \text{ psia} \)

\( \rho_{H_2O} = 0.3388 \text{ psia} \)

\( \rho_{H_2O} = 4.241 \text{ kPa} \)

\( \rho_{H_2O} = 2.34 \text{ kPa} \)

System: overall

Step 5: Basis: 0.341 kg H2O (0.341/18) kg mol

Step 6 and 7: Unknowns: F, P

Balances: air, \( H_2O \)

Steps 8 and 9: Balances are in kg mol

Total: \( F = \frac{0.341}{18} \)

Air: \( F \left( \frac{100 - 3.18}{100} \right) = P \left( \frac{275 - 2.34}{275} \right) \)

Solve any two together

Total: \( F = 0.804 \) kg mol

18.14

Steps 1, 2, 3, and 4:

\( F = 0.804 \text{ kg mol} \)

\( 8.314 \text{ J mol}^{-1} \text{ K}^{-1} \)

\( 303 \text{ K} \)

\( 20.3 \text{ m}^3 \text{ at 30C and 100 kPa} \)

Steps 5: Basis: \( P = 100 \) mol

Steps 6 and 7: Unknowns are \( F, B, n_{Bz}, n_{CS_2} \)

Balances are \( CS_2, Bz, Air \)

Steps 8 and 9:

\( CS_2: F(0.12) = n_{CS_2} + 100 \text{ (0.03)} \)

\( Bz: B = n_{Bz} + 100 \text{ (0.03)} \)

Air: \( F (0.88) = 100 \text{ (0.94)} \)

\( F = 106.8 \) mol

\( n_{CS_2} = 9.82 \text{ mol} \)

(continued)
Fraction CS₂ recovered = \frac{9.82}{12.82} = 0.77

18.15
Pick a closed system in which the octane lost to the surroundings is part of the system rather than an open system.

During the day, the vapor space is saturated and expands so that the air-hydrocarbon mixture escapes through the vent. At night, the gas mixture contracts, and fresh air enters so that more liquid will vaporize.

The volume change of the mixture due just to the temperature change (assumption pₑₓₜₐₜ is constant) is

\frac{dV}{V₀} = \frac{dT}{T}

using the ideal gas law

where V₀ is the volume of the free space. As T increases, the vapor pressure of the octane increases and the number of moles of octane increases. The volume change due to the vaporization is

\frac{dV'}{V₀} = \frac{\partial V V}{n_w} \frac{dp}{p_i}

where y is the mole fraction of octane in the vapor space, p* is the vapor pressure of the octane, and p_i is the total pressure in the vapor space.

Thus, the total volume change is approximately

\frac{dV}{V₀} = \left( \frac{dT}{T} + \frac{dp}{p_i} \right)

Introduce pV = nRT to get

\frac{dn}{nRT} = \frac{V_p dT}{RT^2} + \frac{V_p dp}{pRT}

Introduce the equation

ln(p') = A - \frac{B}{T}

to get

\frac{dn}{nRT} = \frac{V_p dt}{RT^2} - \frac{V_p dp}{pRT} \left[ A - \ln p' \right] \frac{dp}{p'}

Integrate between T₁ and T₂ to get N, the octane in lost in a day

\begin{align*}
N &= \frac{V_p}{RB} \left[ \exp \left[ A - \left( \frac{B}{T₂} \right) \right] - \exp \left[ A - \left( \frac{B}{T₁} \right) \right] \right] \\
&\quad - \frac{A}{2p_i} \left[ \frac{p_i'}{p_i} - 1 \right] \left[ \frac{1}{p_i} \frac{\ln p_i}{2} - \frac{1}{4} \right] \left[ \frac{1}{p_i} \frac{\ln p_i}{2} - \frac{1}{4} \right]
\end{align*}

For octane p_i = 44 mm Hg abs, p_i = 222 mm Hg.

A = 7.30, \quad B = 1.600

If V₀ = 1 m³, \quad N = 3.40 mol for 1 day.

18.16
(a) Entering Leaving

80°F = 26.8°C \quad 70°F = 21.0°C

(continued)
(b) **Entering**

\[ \text{Vol fr. } = \frac{V}{V_{\text{tot}}} = \frac{p}{P_{\text{tot}}} \]

\[ \text{H}_2\text{O} : 5 \text{ mm Hg} \quad \text{740 mm Hg} \quad (100) = 0.676\% \]

\[ \text{H}_2\text{O} : 18 \text{ mm Hg} \quad \text{740 mm Hg} \quad (100) = 2.43\% \]

**Air:** 100 - 0.676 = 99.324\%  

2.43 = 97.57\%

(c) **Entering**

**Basis:** 1 lb mol at 80°F, 740 mm Hg  
**Vol % = mol %**

<table>
<thead>
<tr>
<th>lb</th>
<th>wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_2O: (0.00676)(18)</td>
<td>0.12</td>
</tr>
<tr>
<td>Air: (99.324)(29)</td>
<td>28.80</td>
</tr>
</tbody>
</table>

28.92 | 100.0 |

**Leaving**

**Basis:** 1 lb mol at 70°F, 740 mm Hg

<table>
<thead>
<tr>
<th>lb</th>
<th>wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_2O: (0.0243)(18)</td>
<td>0.44</td>
</tr>
<tr>
<td>Air: (0.9757)(29)</td>
<td>28.30</td>
</tr>
</tbody>
</table>

28.74 | 100.0 |

(d) **Entering**

**Basis:** 1 lb mol at 80°F, 740 mm Hg  
**Actual:** p_vap = 5 mm Hg

**Leaving**

**Basis:** 1 lb mol at 70°F, 740 mm Hg  
**Actual:** p_vap = 18 mm Hg

---

**Solutions Chapter 18**

\[ p^* \text{ at } 26.8^\circ\text{C} = 26 \text{ mm Hg} \quad p^* \text{ at } 21.0^\circ\text{C} = 19 \text{ mm Hg} \]

\[ \text{Rel. Humidity } = \frac{p}{p^*} = \frac{5 \text{ mm Hg}}{26 \text{ mm Hg}} = 19.2\% \]

\[ \text{Rel. Humidity } = \frac{p}{p^*} = \frac{18 \text{ mm Hg}}{19 \text{ mm Hg}} = 94.8\% \]

\[ p_{\text{vap}} \]
Solutions Chapter 18

\[
\text{Entering} \quad \text{Leaving} \\
\begin{align*}
\text{Vol} \ % \ & \text{air} = 99.324 \ % \\
\text{Vol dry air} & = (800,000)(0.99324) = 794,600 \text{ ft}^3 \\
\text{Total vol} & = \frac{779,900}{0.9757} = 799,300 \text{ ft}^3 \\
\text{Vol} \ H_2O \ & \text{vapor} = (800,000)(0.00676) = 5400 \text{ ft}^3 \text{ at } 80^\circ \text{F, 740 mm Hg} \\
\text{Vol} \ H_2O \ \text{vap} & = 799,300 - 779,900 = 19,400 \text{ ft}^3 \text{ at } 70^\circ \text{F, 740 mm Hg} \\
\text{Water evaporated} & = 17,535 - 4,790 = 12,745 \text{ ft}^3 \text{ at SC}
\end{align*}
\]

18.17

\[
\begin{align*}
\text{Vol} \ H_2O & = 794,600 \text{ lb } H_2O \text{/1000 ft}^3 \text{ dry air (see f)} \\
\text{Vol} \ H_2O & = 779,900 \text{ lb } H_2O \text{/1000 ft}^3 \text{ dry air (see f)}
\end{align*}
\]

Water evaporated = 879 - 240 = 639 lb H_2O/day

Part g could also be worked using part f and the volume of dry air:

\[
\begin{align*}
\text{Entering} & \quad \text{Leaving} \\
\text{794,600 ft}^3 \text{ dry air} & \quad \text{779,900 ft}^3 \text{ dry air}
\end{align*}
\]
18.18

Basis: 1000 ft³ wet air at 30°C and 740 mm Hg

\[ p_{H_2O} = 1.253 \text{ in Hg} \]
\[ = 31.9 \text{ mm Hg} \]

\[ p_{ar} = 740 - 31.9 = 708.1 \text{ mm Hg} \]

(a) \[ \frac{1000 \times 31.8}{740} = \frac{760}{503} \times 0.946 \text{ lb H}_2\text{O} \]

(b) \[ \frac{1000 \times (740 - 31.8)}{740} = 958 \text{ ft}^3 \text{ dry air at 740 mm Hg and 30°C} \]

or 1000 ft³ at 708.1 mm Hg and 30 °C

18.19

\[ p^*_{25°C} = 23.8 \text{ mm Hg (3.17 kPa)} \]

\[ p^*_{19.5°C} = 17.0 \text{ mm Hg (2.27 kPa)} \]

Assume a constant total pressure process for (1).

(1) At 100 kPa, \( p_{H_2O} \) is constant and the saturation temperature is the temperature at which the water vapor starts to condense, namely 19.5°C.

---

Solutions Chapter 18

Solutions Chapter 18

(2) At 25°C, compression increases \( p^* \) (volume changes), but \( y_{H_2O} \) is constant.

\[ \begin{align*}
\text{liquid} & \quad \uparrow \quad \text{vapor} \\
23.8 & \quad \uparrow \quad 25 \quad 17.0
\end{align*} \]

\[ p_{H_2O} = p_{ar} \cdot y_{H_2O} \text{ so that } \frac{p_{sat}}{p_{ar}} = \frac{(p_{H_2O})_2}{(p_{H_2O})_1} = \frac{p^*_{25°C}}{p^*_{19.5°C}} \]

\[ p_{sat} = 100 \text{ kPa} \left( \frac{23.8}{17.0} \right) = 140 \text{ kPa} \]

(3) Basis: 100 mol wet vapor

\[ p^*_{(H_2O)_1} = p^*_{(H_2O)_2} \]

(continued)
$\frac{n_{H_2O}}{n_{air}} = \frac{p_{H_2O}}{p_{air}} = y_{H_2O}$

Exit composition

<table>
<thead>
<tr>
<th>mol fr</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>97.73</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>0.009205</td>
</tr>
</tbody>
</table>

98.683 1.0000

The material balances:

Initial |
\begin{align*}
\text{mol or kPa} & \\
\text{Air: } & 100 - 2.27 = 97.73 \\
\text{H}_2\text{O: } & 2.27 = \frac{.27}{100.00}
\end{align*}

Final:

<table>
<thead>
<tr>
<th>\text{mol or kPa}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{To remove 60% of water vapor (40% is left):}</td>
</tr>
<tr>
<td>\text{n}_2 = 0.4 (2.27) = 0.908 \text{ mol}</td>
</tr>
<tr>
<td>\text{All of the air is left, } n_{\text{air}} = 97.73</td>
</tr>
</tbody>
</table>

\[ p^*_{H_2O} = 100 \left( \frac{0.908}{97.73 + 0.908} \right) = 0.9205 \text{ kPa} \]

\[ (6.906 \text{ mm Hg}) \]

(a) 6.91 mm Hg corresponds to 62.22°C

(b) At constant temperature, the pressure increases until

\[ y_{(H_2O)} = 0.9205/100 = 0.009205 \text{ (saturation at 25°C and p)} \]

(b) $p_{\text{at}25^\circ C} = p_y y_{(H_2O)} p_y = 3.17 \text{ kPa}$ $0.009205 = 344 \text{ kPa}$

(c) Process (1) is probably more economical because the 344 kPa requires higher cost equipment.

Basis: 1 mol P

Unknowns: x, F, A, y, W

Balances: C, H, O, N plus dew point for $H_2O$ is given so mol fraction $H_2O$ is known

All balances are in moles.

C: $F_x = P (0.10) \quad W = 10.54 \quad \frac{P}{105.46}$

H: $F (1-x) = W (2)$

N2: $A (0.79) = P (0.9 - y_{N2})$

O2: $A (0.21) = P (0.10 + y_{O2}) + \frac{W}{2}$

$x = 0.33 \quad \frac{1-x}{x} = \frac{H}{C} \quad 0.667 \quad 0.333 = 2.00$
18.21 Note: This problem will give different results depending on the source of the vapor pressure data (steam tables, Antoine Eq., CD, Perry, etc.)

\[ H_2O \]

\[ \text{DRYER} \]

\[ 32^\circ C (355K) \]

\[ 95 \text{ kPa} \]

\[ \text{C} \]

\[ \text{CONDENSER} \]

\[ 42^\circ C (315K) \]

\[ 91 \text{ kg mol H}_2\text{O/hr} \]

\[ 100 \text{ kPa} \]

\[ \text{HEATER} \]

\[ 17^\circ C (290K) \]

\[ W \]

\[ 5000 \text{ kg mol/hr} \]

\[ \text{Humid air} \]

\[ 90\% \text{ RH} \]

\[ 105 \text{ kPa} \]

\[ 42^\circ C (315K) \]

\[ 91 \text{ kg mol H}_2\text{O/hr} \]

\[ 17^\circ C (290K) \]

\[ W \]

\[ 100 \text{ kPa} \]

(steam tables \( p^* = 8.214 \); paper steam tables \( p^* = 8.143 \); CD \( p^* = 8.181 \))

Basis: 5000 kg mol air

\[ RH = \frac{P_{H_2O}(100)}{P_{H_2O}} \quad ; \quad 90 = \frac{P_{H_2O}(100)}{8.143} \]

\[ P_{H_2O} = 7.329 \text{ kPa} \]

\[ Y_{H_2O} = \frac{P_{H_2O}}{P_{atm}} \quad ; \quad Y_{H_2O} = \frac{7.329}{105} = 0.0698 \text{ entering} \]

(a) The mol \( H_2O \) entering = (5000)(0.0698) = 349 kg mol \( H_2O / \text{hr} \)

\( H_2O \) balance on condenser:

18.22 Basis: 100 m$^3$ air

(b) \( W = 349 - 91 = 258 \text{ kg mol H}_2\text{O/hr} \)

\[ W = \frac{258 \text{ kg mol H}_2\text{O}}{18 \text{ kg mol H}_2\text{O}} = \frac{4644 \text{ kg H}_2\text{O/hr condenses}}{\text{hr condenses}} \]

(c) dry air enters the condenser = 5000 - 349 = 4651 kg mol

Stream B:

\[ \begin{align*}
\text{H}_2\text{O} & \quad 91 \text{ kg mol} \\
\text{dry air} & \quad 4651 \text{ kg mol} \\
& \quad 4742 \text{ kg mol}
\end{align*} \]

The air leaving the condenser in B is saturated.

\[ P_{H_2O} = P_{atm} \quad Y_{H_2O} = 100 \left( \frac{91}{4742} \right) = 1.919 \text{ kPa corresponding to 17}^\circ C \]

(d) In C \( Y_{H_2O} \) is still (91/4742); 95 (91/4742) = 1.82 kPa \( \rightarrow 17^\circ C \)

18.22

Basis: 100 m$^3$ air

(a) \( p^*_{H_2O} \) at 21°C = 0.3628 psia = \( p_{H_2O} \)

\[ P_{H_2O}/p_t = \frac{V_{H_2O}}{V_t} = 0.01 \]

\[ p_t = 0.3628/0.01 = 36.28 \text{ psia} \]

(b) \( s = (p)^{1.4} + (350 - T)^{1.9} \)

Also \( p \) and \( T \) are related by the vapor pressure curve for water since the gas has to be saturated for condensation to take place. From Lange's Handbook,

\[ \log_{10} p^* = 8.10765 - \frac{1750.286}{235.0 + T} \quad \text{for} \ T < 60^\circ C \]

(continued)
Solutions Chapter 18

For minimum cost:

\[
\frac{dS}{dT} = \left[ \frac{d}{dT} \left( p^{1.4} + (350 - T)^{1.9} \right) \right]_p + \left[ \frac{d}{dT} \left( p^{1.4} + (350 - T)^{1.9} \right) \right]_T \frac{dp}{dT}
\]

where \( \frac{dp}{dT} = (2.3)(175.28)(p)/(T - 38)^2 \). Solving the equations simultaneously, economical values are 5.8 psia, 76°C.

18.23

For dry air leaking:

Basis: 100 kg mol dry gas to absorber

CO₂ Balance:

\[
\begin{align*}
100 \text{ kg mol at B} & \quad 16.7 \text{ kg mol CO}_2 = 1.144 \text{ mol gas at B/mol gas at A} \\
14.6 \text{ kg mol CO}_2 & \quad 100 \text{ kg mol at A} \\
1.144 - 1.00 & = 0.144 \text{ mol air leaking in/mol gas at A}
\end{align*}
\]

You can calculate the same result using C, O, and N balances.
Less centrifuge removal = 100.0

Wet water remaining (goes into air) = 77.8 lb/hr

\[
\begin{align*}
70^\circ F & \quad p^* = 0.363 \text{ psi} = 18.6 \text{ mm Hg} \\
50\% \text{RH} & \quad p_{H_2O} = (0.5)(8.6) = 0.0124 \text{ mol H}_2\text{O} \quad \text{[BDA = bone dry air]} \\
760 \text{ mmHg} & \quad \text{pair} 750.7 \text{ mol BDA}
\end{align*}
\]

\[
\begin{align*}
100^\circ F & \quad p^* = 0.790 \text{ psi} = 40.8 \text{ mm Hg} \\
94^\circ F & \quad p_{H_2O} = 40.8 = 0.0577 \text{ mol H}_2\text{O} \\
750 \text{ mmHg} & \quad \text{pair} 709 \text{ mol BDA}
\end{align*}
\]

\[
0.0575 - 0.0124 = 0.0451 \text{ mol H}_2\text{O} \text{ gained/mol BDA}
\]

\[
\begin{align*}
1 \text{ mol BDA} & \quad \frac{77.8 \text{ lb H}_2\text{O}}{1 \text{ hr}} \quad \frac{18 \text{ lb H}_2\text{O}}{18 \text{ lb H}_2\text{O}} = 95.7 \text{ lb mol BDA/hr}
\end{align*}
\]

Volume of moist air req'd is: 95.7 (1.024) \( \frac{330}{492} \) (359) = 37,920 ft\(^3\) at 70°F, 760 mm Hg

Basis: 100 lb mol dry air in fresh feed

\[
\begin{align*}
F = 600 \\
p = 40^\circ F \\
\text{RH} = 70\% @ 75^\circ F \\
\text{Dried Product} \quad w/d \text{ salt, W}
\end{align*}
\]

Assume \( p = 14.7 \) psia

System: mixing point (A)

\[
\begin{align*}
R & \quad p^*_{H_2O} = 0.3628 \text{ psi (0.7387 in Hg)} \\
& \quad p_{H_2O} = 14.7 \quad P_{air} = 0.345 \\
& \quad P_{air} = 14.7 - 0.345 = 14.355
\end{align*}
\]

\[
\begin{align*}
F & \quad p_f = 0.1217 \text{ psi (0.2478 in Hg)} \\
& \quad p_{H_2O} = 0.4296 \text{ psi (0.8748 in Hg)}
\end{align*}
\]

\[
\begin{align*}
P_{H_2O} = 0.1217 \\
P_{H_2O} = 0.4296(0.70) = 0.300
\end{align*}
\]

\[
\begin{align*}
p_{ar} = 14.7 - 0.1217 = 14.58 \\
p_{ar} = 14.4
\end{align*}
\]

Total: \( F + R = P_1 \)

\[
\begin{align*}
H_2O: & \frac{0.1217}{14.7} + \frac{0.345}{14.7} = \frac{P_1}{14.7}
\end{align*}
\]

solve with \( F = 100 \) or another basis

\[
\begin{align*}
R = 396.2 \text{ lb mol} \\
P_1 = 496.2 \text{ lb mol}
\end{align*}
\]

outside air = 100/496.2 = 0.2 recycle = 396.2/496.2 = 0.8
18.26

**Data about compositions**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>P and R</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{H}_2\text{O}}$</td>
<td>0.3628</td>
<td>0.9487</td>
</tr>
<tr>
<td>$P_{\text{H}_2\text{O}}$</td>
<td>0.1814</td>
<td>0.9487</td>
</tr>
<tr>
<td>$P_{\text{dew}}$</td>
<td>14.62</td>
<td>14.77 (assumed)</td>
</tr>
<tr>
<td>$P_{\text{air}}$</td>
<td>14.4386</td>
<td>13.8213</td>
</tr>
</tbody>
</table>

Basis: 1 hr (better than F or P = 100)

Overall: Balances 2, unknowns 2 (F, P)
18.27

Steps 1-4:

\[
\text{Exit air} \quad 69^\circ \text{C} \quad \text{P}_{\text{air}} = 765 \text{ mm Hg Abs} \\
\text{RH} = 0.70 \quad \text{mm Hg} \\
\text{P}_{\text{Bz}} = 329.7 \\
\text{P}_{\text{F}} = 435.3 \quad (8.08 \text{ lb mol}) \\
\text{P}_{\text{tot}} = 765 \\
\frac{\text{F Feed}}{781 \text{ lb/hr}} = 31.4 \text{ lb} \\
\begin{array}{c}
\text{S} \\
60% \text{ Bz} \\
100% \\
\text{MW Bz} = 78.11 \\
\end{array}
\]

Dry air

\[
\text{A}_1 (\text{lb mol}) \quad 75^\circ \text{C} \\
100\% \text{ air} \\
0.25 \text{ lb Bz} \quad (60.5 \text{ lb}) \\
1.25 \text{ lb S} \quad (242 \text{ lb}) \\
\text{W (lb)} \quad \text{wet crystals}
\]

\[
\text{P}_{\text{tot}} = \text{P}_{\text{air}} = 770 \text{ mm Hg Abs}
\]

Step 5: Basis: 1 hr

Step 4 cont’d: Calculate composition of A₂

\[
\frac{\text{p}^* \text{ Bz at } 65^\circ \text{C}}{471 \text{ mm Hg abs.}} \\
\text{P}_{\text{Bz}} = 0.70 \quad (471) = 329.7 \quad \text{mm Hg abs} \\
\text{P}_{\text{tot}} = 765 - 329.7 = 435.3 \quad \text{mm Hg abs}
\]

Data: Vapor Pressure of Bz.

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>p* (mm Hg abs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.0</td>
<td>396</td>
</tr>
<tr>
<td>65.0</td>
<td>471</td>
</tr>
<tr>
<td>70.0</td>
<td>553</td>
</tr>
<tr>
<td>75.0</td>
<td>650</td>
</tr>
</tbody>
</table>

80.0 760

Steps 6 and 7:

Overall system:

Balances: air, Bz, S (Total balance not convenient – don’t mix lb and lb mol)

Unknowns: A₁, A₂ W

\[
\begin{align*}
\text{S (lb)}: & \\
781 (0.31) & = W (1/1.25) \\
W & = 302.6 \text{ lb}
\end{align*}
\]

\[
\begin{align*}
\text{air (lb mol)}: & \\
A_1 (1.00) & = A_2 \left(\frac{143.3}{765}\right)
\end{align*}
\]

\[
\begin{align*}
\text{Bz (lb mol)}: & \\
A_1 (0.69) + & = 302.6(0.25/1.25) + A_2 329.7 \\
78.11 & 78.11 + 78.11 & 78.11
\end{align*}
\]

Solution: A₂ = 14.21 lb mol

A₁ = 809 lb mol

(a)

\[
\frac{8.09 \text{ lb mol air}}{[1 \text{ lb mol at SC}]} - \frac{1}{273} - \frac{273}{770} = 3654 \text{ lb}^2 \text{ at } 75^\circ \text{C and 770 mm Hg abs.}
\]

(b) With the present design, A will either (a) build up in the system, or (b) exit with the crystals, or (c) both.

To remove the A from the S in the product, a separator of some sort must be placed (a) before the feed, (b) after the feed but before the column, or (c) after the column but before the filter.
18.28

System: the reactor

Basis: 1 mol pure benzene feed to reactor

(a) 

\[
\text{feed } N_2: \quad \frac{18 \text{ mol O}_2}{21 \text{ mol } N_2} = \frac{79 \text{ mol N}_2}{67.7 \text{ mol } N_2}
\]

\[
\text{total output mol: } \frac{67.7 \text{ mol } N_2}{0.80 \text{ mol } N_2} = 84.6 \text{ mol (dry)}
\]

output \( C_8H_8O_4 \) \( (84.6 \text{ mol}) \times 0.0076 \) \( = 0.643 \text{ mol} \)

From stoichiometric Equation (1): moles benzene reacted \( = 0.643 \text{ mol} \)

H\(_2\)O entering with benzene: benzene is accompanied by \( H_2O \) vapor; benzene and \( H_2O \) are at their respective vapor pressures.

<table>
<thead>
<tr>
<th>( T )</th>
<th>( P_{H_2O} ) (psia)</th>
<th>( P_{H_2} ) (psia)</th>
<th>( P_{total} ) (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180°F</td>
<td>15.681</td>
<td>7.510</td>
<td>23.191</td>
</tr>
</tbody>
</table>

\[
\frac{n_{H_2O}}{n_{benzene}} = \frac{P_{H_2O}}{P_{benzene}} = \frac{7.510}{15.68} = 0.48
\]

1 mol benzene in \( 7.510 \text{ moles } H_2O \) \( = 0.48 \text{ mol } H_2 \) enter the reactor

H\(_2\)O entering with air:

\[
\frac{P_{H_2O}}{P^*_{H_2O}} = 0.5 \quad p^*_{H_2O} \text{ at } 150°F \text{ = 3.718 psia}
\]

\[
p_{H_2O} = (0.5)(3.718) = 1.86 \text{ psia}
\]

\[
p_{air} = 14.7 - 1.86 = 12.84 \text{ psia}
\]

\[
\frac{n_{H_2O}}{n_{air}} = \frac{1.86}{12.84} \text{ mol } H_2O = \frac{84.6 \text{ mol air}}{12.84 \text{ mol air}} = 6.67
\]

Total mol H\(_2\)O entering reactor \( = 0.48 + 6.67 = 7.15 \text{ mol } H_2O \)

Element Balances about the reactor

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2O )</td>
<td>( C_8H_8 )</td>
</tr>
</tbody>
</table>

\[\begin{align*}
2O \text{ Balance:} \\
\frac{12.75}{2} + 1(0) + 18 + 0 &= \frac{x}{2} + 0 + y + z + 0 + 2(0.643)
\end{align*}\]

\[\begin{align*}
2H \text{ balance:} \\
12.75 + 3(1) + 0 + 0 &= x + 0 + 0 + 0 + 0 + 3w + 2(0.643)
\end{align*}\]

\[\begin{align*}
C \text{ balance:} \\
0 + 6(1) + 0 + 0 &= 0 + 0 + 0 + 0 + z + 6w + 4(0.643)
\end{align*}\]

Total mol balance is not possible but we know from extra information given (\( N_2 = 80\% \)) that the total exit mol are \( = 84.6 \). Four equations and four unknowns exist so the degrees of freedom are zero. Consequently, on dry basis: (continued)
Solutions Chapter 18

84.6 = 67.7 + y + z + w + 0.641

Solving simultaneously (the answers are sensitive to round off in the previous computations):

\[ x = 13.98 \quad y = 13.62 \quad z = 2.48 \quad w = 0.16 \]

Moles of benzene undergoing reaction by Reaction (2) = 1.0 - 0.16 - 0.643 = 0.20 mol per mol Bz feed

Another approach is to use the extent of reaction: \( \xi = 0.0164 \).

Balances around Dehydrator

\[
\text{mol H}_2\text{O with } C_6H_4\text{O}_4: \frac{0.643}{12} = 4.72 \text{ mo} \\
\text{mol H}_2\text{O by reaction: } 0.643 \times 1 = 0.643 \text{ mol} \\
\text{Total} \quad 5.36 \text{ mol}
\]

(b) \[
\frac{\text{lb H}_2\text{O}}{\text{lb mol benzene}} = \frac{5.36 \text{ mol}}{18 \text{ lb H}_2\text{O}} = \frac{96.5 \text{ lb H}_2\text{O}}{1 \text{ lb mol}}
\]

(c) Exit gases from scrubber are

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\textsubscript{2}</td>
<td>67.7</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>13.62</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>2.48</td>
</tr>
<tr>
<td>C\textsubscript{6}H\textsubscript{4}</td>
<td>0.16</td>
</tr>
<tr>
<td>Total</td>
<td>83.96</td>
</tr>
</tbody>
</table>

\| H\textsubscript{2}O | 21.9 |
| Total | 105.9 |

Calculation for H\textsubscript{2}O vapor

Gas is saturated at 142°F

\[ P_{\text{H}_2\text{O}} = 3.04 \text{ psia} \quad P_{\text{gas}} = 14.7 - 3.04 = 11.66 \text{ psia} \]

\[ \frac{P_{\text{H}_2\text{O}}}{P_{\text{gas}}} = \frac{3.04}{11.66} = 0.261 \quad n_{\text{H}_2\text{O}} = 0.261(83.96) = 21.9 \]

(d) Water Balance about Scrubber:

mol H\textsubscript{2}O added = 21.90 + 4.70 - 13.70 = 12.90 mol

\[
\frac{\text{lb H}_2\text{O added}}{\text{lb mol benzene fed}} = \frac{12.90 \text{ mol}}{1 \text{ lb mol}} = \frac{232 \text{ lb H}_2\text{O}}{1 \text{ lb mol}}
\]
19.1

\( F = 2 - P + C = 2 - 2 + 2 = \boxed{2} \)

19.2

\( F = 2 - P + C \)

(a) \( F = 2 - 2 + 1 = \boxed{1} \)

(b) \( F = 2 - 3 + 2 = \boxed{1} \)

19.3

a. \( F = 2 - P + C \)
   
   \( C = 3 \)
   
   \( P = 2 \)  (assume that \( p \) is not unreasonably high)

\( F = 2 - 2 + 3 = \boxed{3} \)

b. Possible variables are: pressure
   
   mol or mass fraction of
   
   \( H_2O \)
   
   acetic acid
   
   only 2 are independent
   
   ethyl alcohol

19.4

(a) \( F = 2 - P + C = 2 - P + 2 \)

if \( F = 0 \)

\( P = 4 - F \)

Max \( P = 4 \)

(b) \( F = 2 - P + C \)

\( 3 = 2 - 2 + C \) \( C = 3 \)

19.5

\( C = 1 \)

\( P = 2 \)

\( F = 2 - 2 + 1 = 1 \)

19.6

\( C = 3 \) (\( O_2, N_2, H_2O \))

\( P = 2 \)

\( F = 2 - 2 + 3 = \boxed{3} \)

19.7

The number of components is 3, but one independent reaction exists among them so that

\( C = 2 \)

\( NH_4Cl(s) \rightleftharpoons NH_3(g) + HCl(g) \)

\( P = 2 \)

\( F = 2 - 2 + 2 = \boxed{2} \)

19.8

(1) \( F = 2 - P + C \)

(continued)
The rank of
\[
\begin{array}{ccc}
\text{Ca} & \text{CaCO}_3(s) & \text{CaO(s)} & \text{CO}_2(g) \\
1 & 1 & 1 & 0 \\
C & 1 & 0 & 1 \\
O & 3 & 1 & 2 \\
\end{array}
\]

is only 2 so \( C = 2 \)

\[ P = 3 \text{ hence } F = 2 - 3 + 2 = 1 \]

19.9

(a) F; (b) F; (c) F; (d) T; (e) T; (f) T

19.10

Henry's Law is \( p = Hx \), a straight line with no intercept. A plot of the data indicates Henry's law fits the data well.

19.11

Use Henry's law \( p = Hx \). The MW of CHCl₃ is 119.4. The total pressure is 1 atm.

\[ x = \frac{p}{H} = \frac{0.024(l)}{170} = 1.41 \times 10^{-4} \text{ mol fraction} \]

The concentration in mg/L is

Water: \( \frac{1000}{18} = 55.6 \text{ g mol/L} \)

The number of moles of CHCl₃ is

\[ (55.6)(1.41 \times 10^{-4}) = 7.84 \times 10^{-3} \text{ g mol/L} \]

Concentration = \( \frac{119.4 \text{ g mol}}{1 \text{ L}} \times \frac{7.84 \times 10^{-3} \text{ g mol}}{1 \text{ g}} = 940 \text{ mg/L} \)
19.12

\( p = H_x \) where \( p \) is in kPa and \( x \) is mol fraction

The mole fraction of \( O_2 \) in the gas phase is \( y_{O_2} \)

\[
y_{O_2} = \frac{P_{O_2}}{P_{total}} = H_x_{O_2}
\]

The moles of \( O_2 \) and \( H_2O \) are:

\[
\begin{align*}
O_2: & \quad 6 \text{ mg} = 1\text{ g} = 10^3 \text{ L} = 32 \text{ g} \text{ mol } O_2 = 0.1875 \text{ g mol/m}^3 \text{ in water} \\
H_2O: & \quad \frac{10^3 \times 10^3}{18} = 55.6 \times 10^3 \text{ g mol/m}^3
\end{align*}
\]

\[
K_{O_2} = \frac{0.1875}{55.6 \times 10^3 + 0.1875} = 3.37 \times 10^{-5}
\]

\[
P_{\text{total}} = 1 \text{ atm}
\]

\[
y_{O_2} = \frac{4.02 \times 10^8 \text{ kPa}}{101.3 \text{ kPa}} \times 1 \text{ mol fr.} = \frac{3.77 \times 10^8 \text{ mol fr.}}{101.3 \text{ kPa}} = 0.134
\]

Basis: 1 L gas

\[
n = \frac{P_{\text{total}}}{RT} = \frac{(101.3 \text{ kPa} \times 0.134)}{101.3 \text{ kPa}} \times 1 \text{ L} \times (\text{ g mol kK}) = 18 \text{ g} \times 1000 \text{ mg} = \frac{0.101 \text{ mg}}{\text{ per L}}
\]

19.13

Steps 2, 3, and 4:

SO₂

\[ y_1 = 0.03 \]

SO₂

Air

\[ G = 84.9 \text{ m}^3 \]

293 K

\[ P_{\text{total}} = 1 \text{ atm} \]

H₂O

\[ n_{H₂O} = ? \]

SO₂

Air

\[ y_2 = 0.003 \]

SO₂

Air

290 K

\[ P_{\text{total}} = 1 \text{ atm} \]

Step 5: Basis: 1 min (85 m³ entering gas)

Steps 6 and 7:

Unknowns: \( n_{SO₂}, n_{H₂O}, \) Air

Equations. Material balances:

\[ H₂O, SO₂, \text{ Air} \]

\[ y_i > H_x_i \]

Steps 8 and 9:

The liquid and vapor are assumed to be in equilibrium at the exit, and the water is saturated with \( SO₂ \) so that

\[ y_i = H_x_i \]

\[ 0.03 = (43) x_{SO₂} \text{ so that } x_{SO₂} = 0.00070 \text{ mol fraction} \]

(continued)
Solutions Chapter 19

Material balance SO₂ (moles):

\[ G \times (0.03 - 0.003) = L \times (0.00070 - 0) \]

b. \[ \frac{L}{G} = \frac{38.6 \text{ g mol H₂O}}{\text{g mol air}} \]

The respective flow rates are

\[ G = \frac{85 \text{ m}^3}{1 \text{ g mol gas}} = 3540 \text{ g mol gas} \]

\[ L = (3540) (38.4) = 137 \times 10^3 \text{ g mol water} \]

In terms of kg

a. \[ \frac{L}{(136)} (18) = \frac{2450}{\text{kg/min}} \]

19.14

Steps 2, 3, and 4

\[ p_{\text{real}} = 1 \text{ atm} \quad \text{and at 60°F the vapor pressures are:} \]

\[ p'_{\text{toluene}} = 16 \text{ mm Hg} \]

\[ p'_{\text{benzine}} = 60 \text{ mm Hg} \]

Assume the mixture to be ideal so that Raoults Law applies

Step 5: Basis: 1 mol liquid

Steps 6-9:

\[ y_{i} = \frac{P_{i}}{P_{\text{real}}} \]

For toluene:

\[ y_{\text{tol}} = \frac{(16)(0.60)}{760} - 0.0126 \]

For benzene:

\[ y_{\text{benz}} = \frac{(60)(0.40)}{760} - 0.0316 \]

The balance is air.

\[ \begin{array}{ccc}
0.0126 & \text{Toluene} \\
0.0316 & \text{Benzene} & \text{The vapor is flammable.} \\
0.0442 & \text{Total} \\
\end{array} \]

19.15

Use Raoults Law.

\[ p_{\text{total}} = p'_{i} (1 - x_{i}) + p_{a} x_{i} \]

From Perry the vapor pressures are:

\[ \begin{array}{cc}
\text{p'}_{\text{toluene}} = 16.8 \text{ atm} \\
\text{p'}_{\text{benzene}} = 4.8 \text{ atm} \\
\text{p}_{\text{total}} = \frac{(100/14.7) \text{ atm}}{} = 6.80 \text{ atm} \\
\text{6.80} = 16.8 (1 - x_{i}) + 4.8 x_{i} \\
x_{\text{benz}} = 0.83 \quad \text{assuming the liquid phase is essentially all of the mixture.} \\
\end{array} \]

19.16

Mole fraction in the liquid phase is given by solving the following equations for \( x_{i} \):

\[ y_{i} = \frac{p'_{i} x_{i}}{p_{\text{real}}} \quad \text{and} \quad y_{\text{tol}} = \frac{p'_{\text{toluene}} x_{\text{tol}}}{p_{\text{real}}} \quad \text{to get} \quad x_{\text{tol}} = \frac{(p_{\text{real}} - p'_{\text{tol}})}{(p_{\text{real}} - p'_{\text{down}})} \]

The corresponding equilibrium mole fraction in vapor phase (y) is, (continued)
Solutions Chapter 19

\( y = \frac{p_y}{p_{total}} \)

Using these equations for the various temperatures given, the following data for \( x \) and \( y \) are obtained for the total pressure of 1 atm:

<table>
<thead>
<tr>
<th>( T(\text{C}) )</th>
<th>( x_{y_1} )</th>
<th>( y_{y_1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>92</td>
<td>0.508</td>
<td>0.720</td>
</tr>
<tr>
<td>100</td>
<td>0.256</td>
<td>0.453</td>
</tr>
<tr>
<td>110.4</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

From the above-calculated data, the following T-x diagram can be drawn.

![T-x diagram](image)

19.17

Use the Antoine equation or the physical property package on the CD to get the vapor pressure of pentane (P) and heptane (H). Assume ideal liquid and vapor.

**Basis:** Data given in problem statement

\[
\ln p_{\text{P}}(\text{mm}) = 15.8333 - \frac{2477.07}{T - 39.94} \quad p'_P = 283.6 \text{ mm Hg (3.48 psia)}
\]

\[
\ln p_{\text{H}}(\text{mm}) = 15.8737 - \frac{2911.32}{T - 56.51} \quad p'_H = 20.6 \text{ mm Hg (0.40 psia)}
\]

Convert mass fractions to mole fractions:

(continued)
### Solutions Chapter 19

**Basis: 100 g liquid**

<table>
<thead>
<tr>
<th></th>
<th>g</th>
<th>MW</th>
<th>g mol</th>
<th>mol ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>20</td>
<td>72.15</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>H</td>
<td>80</td>
<td>86.17</td>
<td>0.93</td>
<td>0.77</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td>1.21</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Equations to use, \( i = P \) and \( H \)

\[ \sum y_i = 1 \]

\[ y_i = \frac{p_i x_i}{p_{total}} \]

a. \[ \frac{p_H \cdot x_H}{p_{total}} + \frac{p_P \cdot x_P}{p_{total}} = 1 \]

\[ p_{total} = (283.6)(0.23) + 20.6(0.77) = 60.95 \text{ mm Hg} \]

3.19 in Hg

10.8 kPa

1.57 psia

\[ y_P = \frac{16}{4.07} (0.23) = 0.40 \]

\[ y_H = \frac{0.5}{4.07} (0.77) = 0.10 \]

b. \[ y_P = \frac{p_P}{p_{total}} \]

\[ y_H = \frac{p_H}{p_{total}} \]

\[ y_P = \frac{62}{122} = 0.51 \]

\[ y_H = \frac{60.95}{122} = 0.50 \]

19.19

The mole fractions of each component are needed to apply Raoult's law. Assuming a basis of 100 g of solution, we can construct the following:

<table>
<thead>
<tr>
<th></th>
<th>Mol. weight</th>
<th>Mol</th>
<th>Mol. fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>25</td>
<td>1.8</td>
<td>0.37</td>
</tr>
<tr>
<td>Methanol</td>
<td>75</td>
<td>3.2</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Raoult's law is used to compute the vapor pressure (\( p^* \)) of pure methanol based on the partial pressure required to flash:

\[ p = xp^* \]

\[ p^* = \frac{p}{x} = \frac{62}{0.63} = 98.4 \text{ mm Hg} \]

Use the Antoine equation to get \( T \)

\[ \ln(p^*) = 18.5875 - \frac{3626.55}{293 + T} \]

\( T = 293 \text{ K} \) (20°C)

19.20

Data:

- Benzene (B) \( MW \) 78.1 \( p^* \) at 60°C 51.3 kPa
- Toluene (T) \( MW \) 92.1 \( T \) 18.5 kPa


b. \[ x_B = \frac{1}{1} - \frac{0.541}{78.1} = 0.459 \]

\[ x_T = \frac{1}{1} - \frac{0.541}{92.1} = 0.459 \]

\[ x_B = \frac{1}{1} - \frac{0.541}{78.1} = 0.459 \]

\[ x_T = \frac{1}{1} - \frac{0.541}{92.1} = 0.459 \]

a. The equations to use are

\[ x_B p_B = x_B p^* \]

\[ x_T p_T = x_B p^* \]

\[ y_B + y_T = 1 \]

\[ y_B + y_T = 1 \]

(continued)
Solutions Chapter 19

\[
(1-y_b)p_w = x_p y_p \gamma_p \\
(1-x_p y_p) p_w = x_p y_p \gamma_p \\
p_w = x_p \gamma_p y_p + y_p \gamma_p (0.541)(51.3) + (0.459)(18.5) = 36.2 \text{ kPa}
\]

(b) What will be the composition of this first bubble?
\[
y_b = \frac{x_p \gamma_p y_p}{p_w} = \frac{0.541 \times 51.3}{36.2} = 0.766 \\
y_r = 1 - y_b = 0.234
\]

19.21

Data:

\[p^* \text{ at } -31.2^\circ \text{C (kPa)}
\]

Propane (P) 160.0
n-butane (B) 27.6

Assume ideal solution and vapor. Use Raoult's law

(a) \[y_P p_w = x_P y_P \gamma_P \]
\[y_B p_w = x_B y_B \gamma_B \]
\[y_P = \frac{x_P y_P \gamma_P}{p_w} \]
\[y_B = \frac{x_B y_B \gamma_B}{p_w} \]

More manipulations give
\[x_P \frac{p_w - p^*_P}{p^*_P - p_w} = 101.3 - 26.7 = 0.56 \]

(b) \[y_P = \frac{(0.56)(160.0)}{101.3} = 0.884 \]
\[y_B = 1 - 0.884 = 0.116
\]

(c) For propane

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-16.3</td>
<td>0.196</td>
<td>0.577</td>
</tr>
<tr>
<td>-31.2</td>
<td>0.560</td>
<td>0.884</td>
</tr>
<tr>
<td>-42.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

19.22

Basis: 1.0 lb mol of mixture @ 200°C

Data: (continued)
Solutions Chapter 19

\[ p_c, \text{ @ } 200^\circ F = 14.7 \text{ psia} \]
\[ p'_c, \text{ @ } 200^\circ F = 5.5 \text{ psia} \]

Mole fraction \( C_7 \)

<table>
<thead>
<tr>
<th>Mole fraction ( C_7 )</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
</table>

Partial Press \( C_7 \)

<table>
<thead>
<tr>
<th>Partial Press ( C_7 )</th>
<th>0</th>
<th>2.94</th>
<th>5.88</th>
<th>8.82</th>
<th>11.75</th>
<th>14.7</th>
</tr>
</thead>
</table>

Partial Press \( C_8 \)

<table>
<thead>
<tr>
<th>Partial Press ( C_8 )</th>
<th>5.5</th>
<th>4.40</th>
<th>3.30</th>
<th>2.20</th>
<th>1.10</th>
<th>0</th>
</tr>
</thead>
</table>

\[ 5.5 | 7.34 | 9.18 | 11.02 | 12.75 | 14.7 |

\[ p' \text{ is mm Hg and } T \text{ is in K} \]

Solve Equation (1) to get from Polymath \( T = \text{447 K} \)

19.24 Assume ideal solution

For the dewpoint

\[ \frac{1}{p_{\text{total}}} = \frac{y_1}{p_1} + \frac{y_2}{p_2} \]

\[ p_{\text{total}} = 100 \text{ psia or } 5, 171 \text{ mm Hg} \]

\[ y_i \text{ (mol fr.)} \]

\[ 0.20 \text{ n-pentane} \quad p'_1 = \exp \left[ \frac{15.8333 - 2477.07}{(-39.94 + T)} \right] \quad (2) \]

\[ 0.80 \text{ n-hexane} \quad p'_2 = \exp \left[ \frac{15.8366 - 2697.55}{(-48.78 + T)} \right] \quad (3) \]

19.23 Assume ideal solution.

For the bubblepoint

\[ p_{\text{total}} = p'_1(T) x_1 + p'_2(T) x_2 \]

\[ p_{\text{total}} = 200 \text{ psia or } 10,342 \text{ mm Hg} \]

\[ y_i \text{ (mol fr.)} \]

\[ 0.20 \text{ n-pentane} \quad p'_1 = \exp \left[ \frac{15.8333 - 2477.07}{(-39.94 + T)} \right] \quad (2) \]

\[ 0.80 \text{ n-hexane} \quad p'_2 = \exp \left[ \frac{15.8366 - 2697.55}{(-48.78 + T)} \right] \quad (3) \]

\[ p'_i \text{ is mm Hg and } T \text{ is in K} \]

Solve Equation (1) to get from Polymath \( T = \text{413 K} \)
19.25

Calculate the bubble point and dew point temperatures at 39.36 in. Hg = 1000 mm Hg. Use the Antoine equations to get $p^*$ based on the assumption the solution is ideal.

$$\ln p^* = A - \frac{B}{C + T}$$

1 = Benzene

2 = Toluene

$$K_i = \frac{\bar{p}_i}{p_i}$$

$$\ln(K_i) = \ln(p'_i) - \ln(p_i) = \ln(p'_i) - 6.9078$$

Calculate $1 \ln K_1$ and $1 \ln K_2$. Solve the bubble point equation and the dew point equation by a computer code (or Newton's method) starting with $T = 365$K (slightly above $p^*$ for benzene).

a. Bubble point temperature

$$\sum y_i = 1 = \sum K_i x_i$$

If solution is ideal

$$K_i x_i = \frac{p'_i}{p_i}$$

and $0.5 \frac{\bar{p}_i}{p_i} + 0.5 \frac{\bar{p}_i}{p_i} - 1 = 0 \quad (1)$

Use the Antoine equation to get $p^*$.

Benzene: $p'_1 = 15.9008 - \frac{2788.51}{-52.36 + T}$

Toluene: $p'_2 = 16.0137 - \frac{3096.52}{-53.67 + T}$

Solution of Equation (1) using Polymath: Bubble point temperature is 375 K

b. Dew point temperature

$$\sum x_i = 1 = \sum \frac{x_i}{K_i} = 0.5 \cdot \frac{x_i}{K_i} + 0.5 \cdot \frac{x_i}{K_i}$$

Solution of Equation (2): Dewpoint temperature is 381.5 K

19.26

Assume ideal liquid and vapor exist. Vapor pressure data at 121°C from the Antoine equation (refer to problem P19.23 for the equations)

<table>
<thead>
<tr>
<th>p* (atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentane (P)</td>
</tr>
<tr>
<td>Hexane (H)</td>
</tr>
</tbody>
</table>

$$P_r = \frac{p^* x_r}{9.07 x_r}$$

$$P_l = p^* (1 - x_r) = 4.03(1 - x_r)$$

$$P_{true} = 5.45 = p_r + p_l = 9.07x_r + 4.03(1 - x_r)$$

b. $x_r = 0.282$ (0.718 hexane)

$$\frac{P_r}{P_{true}} = \frac{9.07(0.282)}{5.45} = 0.469 \quad (0.531 \text{ hexane})$$

(continued)
Solutions Chapter 19

a. Basis:  \( F = 1 \) mol

\[
F = L + V
\]

\[
L = 1 - V
\]

\[
F(x_f) = Lx + Vy
\]

\[
F(x_f) = L(0.40) = (1 - V)(0.282) + V(0.469)
\]

\[
L = 0.37 \text{ mol} \quad V = 0.63 \text{ mol}
\]

Solve for \( y_1 \) in (1):

\[
y_1 = \frac{F_x}{V} - \left( \frac{L}{V} \right) x_1
\]

(4)

Introduce in (2):

\[
\left[ \frac{F_x}{V} - \left( \frac{L}{V} \right) x_1 \right] \rho_{\text{rned}} = x_1 \rho^i
\]

Basis: 1 minute

Introduce the given values

\[
\rho^i = 10 \text{ kPa} \quad \rho^* = 100 \text{ kPa}
\]

\[
F^i = 100 \text{ mol} \quad L^i = 50 \text{ mol}
\]

\[
V^i = 50 \text{ mol} \quad V^a = 25 \text{ mol}
\]

\[
L^a = 25 \text{ mol}
\]

\[
x_1 = 0.50
\]

The solution is

\[
p^*_1 = 10 kPa \quad p^*_1 = 100 kPa
\]

\[
p^*_2 = 100 kPa \quad p^*_2 = 1000 kPa
\]

(continued)
19.28
Assume pentane is the major contributor to the gas-phase composition.

\[ y_i = \frac{P_i}{P_{tot}} \]

For Raoult's law,

\[ p_i = p^* x_i \]

so

\[ P_{tot} \frac{y_i P_{sat}}{x_i} = \frac{(0.018)(100)}{0.05} \approx 36 \text{ kPa} \]

Using the Antoine equation,

\[ \ln \left( \frac{2477.07}{39.94 + T} \right) = 15.8333 \]

\[ T = 242 \text{ K} \]

19.29
Basis:

\[ p_{\text{H}_2} @ 180 ^\circ \text{F} = 460 \text{ mm Hg} \]

\[ p_{\text{H}_2,0} @ 180 ^\circ \text{F} = 388 \text{ mm Hg} \]

\[ P_{\text{sat}} = P_{\text{H}_2,0} = 460 + 388 = 848 \text{ mm Hg} \]

19.30
Assume that the pressure at the bottom of the lake = \( P_{\text{CO}_2} \)

\[ p = \rho g h \text{ varies with height} \]

Avg. depth = 225 m

\[ P_{\text{CO}_2} = \frac{1000 \text{ kg}}{9.8 \text{ m/s}^2} \times \frac{225 \text{ m}}{1 \text{ m}} = 2.21 \times 10^3 \text{ kPa} + 1.01 \times 10^2 \text{ kPa} \]

= 23 Atm

\[ P_{\text{CO}_2} = H_{\text{CO}_2} \Rightarrow x_{\text{CO}_2} = \frac{23 \text{ atm}}{1.7 \times 10^5 \text{ atm} \text{ mol}^{-1}} = 0.0134 \]

If the entire 200,000 tons were saturated at \( P_{\text{CO}_2} \) but not supersaturated

\[ \frac{200,000 \text{ ton H}_2 \text{O}}{1000 \text{ kg}} \times \frac{1 \text{ kg mol}}{18 \text{ kg}} = 1.11 \times 10^3 \text{ kg mol} \]
0.0134 = \frac{n_{\text{CO}_2}}{1.11 \times 10^9 + n_{\text{CO}_2}} \quad n_{\text{CO}_2} \text{ is mol of CO}_2

n_{\text{CO}_2} = 1.51 \times 10^9 \text{ kg mol}

\frac{nRT}{p} = V_{\text{CO}_2} = \frac{(1.5 \times 10^9)(8.314)(273)}{101.3 \text{kPa}} = 5.39 \times 10^4 \text{ m}^3

Above would be the worst case. The CO\text{2} would be less; \rho_{\text{CO}_2} average might be a better choice to use in which case \ V_{\text{CO}_2} would be, say \frac{1}{2} the calculated amount.

19.31

For multiple components, the vapor pressure varies with composition as well as with temperature, and to be precise the composition should be stated.

19.32

a. Apply Henry’s law to solve the problem.

\[ p = Hx \quad x = \frac{p}{H} \]

From the internet, \( H = 43,600 \) where \( x \) is the mole fraction in the liquid and \( p \) is in bars.

**Enriched gas**

\[ x_0 = \frac{(110)(0.397) \text{ kPa}}{1 \text{ bar}} = \frac{100 \text{ kPa}}{43,600 \text{ bar}} = 1.00 \times 10^{-5} \text{ mol fr.} \]

b. To compare enriched gas with nonenriched gas

\[ \frac{x_{\text{enriched}}}{x_{\text{nonenriched}}} = \frac{(p_H)_{\text{enriched}}}{(p_H)_{\text{nonenriched}}} = \frac{(110)(0.397)}{(110)(0.21)} = 1.89 \]

percent excess is: \[ \frac{1.89 - 1}{1} (100) = 89\% \]

19.33

Apply K values to solve the problem. Get the mole fraction of the compound in the liquid phase.

**Basis:** 100 g water (5.555 g mol)

<table>
<thead>
<tr>
<th>liquid</th>
<th>liquid</th>
<th>vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{g} )</td>
<td>( \text{MW} )</td>
<td>( g_{\text{mol}} )</td>
</tr>
<tr>
<td>H\text{O}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glycerol</td>
<td>5.5</td>
<td>92.08</td>
</tr>
<tr>
<td>MEK</td>
<td>1.1</td>
<td>72.10</td>
</tr>
<tr>
<td>Phenol</td>
<td>2.1</td>
<td>94.11</td>
</tr>
</tbody>
</table>

The mole fractions in the gas phase are in the far right hand column. Glycerol and phenol have the lowest concentrations. If volatilization is proportional to the vapor phase concentration, only MEK might be a problem.
20.1

The Langmuir equation is

\[ y = \frac{(1 + A)p}{1 + Bp} \]

\[ y = kp^n \]

The Freundlich isotherm for a gas

\[ y = \frac{(1 + A)p}{1 + Bp} \]

\[ y = kp^n \]

\( y \) = uptake in mg mol/g adsorbent and \( p \) is the partial pressure of the SO\(_2\). A, B, k, and n are coefficients in the respective equations.

Fit the data using Polymath. The results are:

Freundlich:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ini. guess</th>
<th>Value</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k )</td>
<td>100</td>
<td>1.3807316</td>
<td>0.1692861</td>
</tr>
<tr>
<td>( n )</td>
<td>3</td>
<td>0.197042</td>
<td>0.0345842</td>
</tr>
</tbody>
</table>

\( R^2 = 0.9676593 \) Fit is reasonably good.

Langmuir:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ini. guess</th>
<th>Value</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>100</td>
<td>-0.2169352</td>
<td>3.775E-06</td>
</tr>
<tr>
<td>( B )</td>
<td>100</td>
<td>0.2098918</td>
<td>1.357E-06</td>
</tr>
</tbody>
</table>

\( R^2 = 0.9850928 \)

(continued)
20.2

Refer to Problem 20.1 for the equations. Transformation of the uptake to mg mol/g gel is

<table>
<thead>
<tr>
<th>mg mol</th>
<th>mg mol/g gel</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.456</td>
<td>4.053</td>
</tr>
<tr>
<td>3.247</td>
<td>5.358</td>
</tr>
<tr>
<td>3.571</td>
<td>5.893</td>
</tr>
<tr>
<td>4.762</td>
<td>7.858</td>
</tr>
<tr>
<td>5.248</td>
<td>8.660</td>
</tr>
<tr>
<td>6.168</td>
<td>10.178</td>
</tr>
<tr>
<td>7.413</td>
<td>12.233</td>
</tr>
</tbody>
</table>

Results from Polymath:

**Freundlich**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ini. guess</th>
<th>Value</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>1</td>
<td>2.2075306</td>
<td>0.2616611</td>
</tr>
<tr>
<td>n</td>
<td>1</td>
<td>0.6259709</td>
<td>0.2086725</td>
</tr>
</tbody>
</table>

**Langmuir**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ini. guess</th>
<th>Value</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>-0.961996</td>
<td>4.453E-05</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>0.001727</td>
<td>4.674E-06</td>
</tr>
</tbody>
</table>

R² = 0.9446851

(continued)
20.3

Refer to Problem 20.1 for the equations. Transformation of the uptake to mg mol/g is

0.0026
0.0142
0.0731
0.1613
1.0859
1.5301
1.7114
1.8649
1.9657
2.0396

Results from Polymath are:

Freundlich

Langmuir

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ini. guess</th>
<th>Value</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>-0.9831</td>
<td>3.794E-06</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>0.0065856</td>
<td>2.08E-06</td>
</tr>
</tbody>
</table>

$R^2 = 0.9998068$

(continued)
Let \( c_{i1} = 0 \). Then \( c_{i} = 1.06 c_{i}^{0.465} \).

20.5  
Basis: 1 L solution

The material balance in mg is 12-0.001 = 12 mg/L removed from the solution. The equilibrium relation gives:

\[
y = 100 (0.001)^{0.465} = 12.6 \text{ mg adsorbate/g adsorbent taken up}
\]

\[
\frac{12 \text{ mg adsorbate}}{1 \text{ L solution}} = \frac{1 \text{ g charcoal}}{12.6 \text{ mg adsorbate/L solution}} = 0.95 \text{ g charcoal/L solution}
\]

20.6  
Step 5: Steady State open process.

Basis: 1 minute (100 lb moist air)

Steps 2, 3, and 4:

Assume \( p = 760 \text{ mm Hg} \)

Exit air is: 99 lb dry air and \( 99 \times 10^{-3} \text{ lb H}_2\text{O} \)

Calculate moles of water in the entering air to use in calculating the partial pressure of the water in the air.

\[
\begin{array}{c|c|c|c|c}
\text{lb} & \text{H}_2\text{O} & \text{BD air} & \text{lb} & \text{H}_2\text{O} \\
1 & . & . & . & . \\
99 & . & . & . & . \\
100 & . & . & . & . \\
\end{array}
\]

\[
\begin{array}{c|c|c}
\text{lb} & \text{BD air} & \text{Air} \\
. & . & . \\
. & . & . \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\text{lb} & \text{H}_2\text{O} & \text{lb} & \text{BD air} & \text{Moist Gel} \\
. & . & . & . & . \\
. & . & . & . & . \\
X & . & . & . & . \\
10^2 & \text{lb H}_2\text{O} & \text{lb G} & . & . \\
9.1 & \text{lb H}_2\text{O} & \text{lb G} & . & . \\
\end{array}
\]

Steps 6 and 7:

Unknowns: Dry gel (G) and \( X \)

Equations: \( \text{H}_2\text{O}, \text{dry air, gel balances plus equilibrium relation} \)
Steps 8 and 9:

Material balance on H₂O (in lb) on the humidifier:

\[
\frac{\text{Out}}{(10^3)(99) + XG} - \frac{\text{In}}{1} = 0
\]

Equilibrium relation:

\[
X = \frac{\text{lb} \text{ H₂O}}{\text{lb} \text{ G}} = 0.0375 \left[ \frac{760 (0.0556)}{3.469} \right]^{0.63} = 0.190
\]

\[1 - 0.099 = 0.190 \text{ G} \quad \text{G} = 4.72 \text{ lb/min}.

20.7

Step 5: Basis: 1 minute (2 kg activated carbon)

Steps 2, 3, and 4:

BDA is bone dry air and AC is activated carbon. The dew point of the feed is 12°C, and the barometer is 770 mm Hg. MW of DE = 98.97 and MW of BDA is 29.

The entering concentration of DE in F is determined from the dewpoint

At 12°C, \( p_{\text{de}} = 127.95 \) mm Hg

\[
Y_{\text{de}} = \frac{n_{\text{de}}}{n_{\text{BDA}}} = \frac{p_{\text{de}}}{p_{\text{BDA}}} = \frac{127.95}{770 - 127.95} = 0.199 \quad \text{g mol DE} \quad \text{g mol BDA}
\]

\[
\frac{0.199 \text{ g mol DE}}{198.97 \text{ g DE}} \times \frac{1 \text{ g mol BDA}}{29 \text{ g BDA}} = \frac{0.679 \text{ g DE}}{\text{g BDA}}
\]

Steps 6 and 7:

Unknowns: DE in P and BDA in P

Material balances: DE and BDA

Steps 8 and 9:

DE balance (g of DE):

\[
\frac{9.7 \text{ g DE}}{1 \text{ g mol BDA}} + \frac{50 \text{ g DE}}{1 \text{ kg AC}} = \frac{2 \text{ kg AC}}{1 \text{ kg AC}}
\]

\[
\frac{n_{\text{de}}}{\text{g mol BDA}} + \frac{300 \text{ g DE}}{1 \text{ kg AC}} = \frac{2 \text{ kg AC}}{1 \text{ kg AC}}
\]

The amount of DE in the exit AC is

\[
300 \text{ g DE} \times \frac{1 \text{ kg AC}}{1000 \text{ g AC}} = 0.300 \text{ g DE/AC}
\]

(continued)
The amount of DE in the exit air is

\[
\frac{10.83}{770-10.83} = 0.0143 \text{ g mol DE} \quad \text{g mol BDA}
\]

or

\[
\frac{0.0143 \text{ g mol DE}}{1 \text{ g mol BDA}} = \frac{98.97 \text{ g DE}}{1 \text{ g mol DE}} = 1.412 \text{ g DE} \quad \text{g mol BDA} = n_{\text{DE}}
\]

The mol fraction of the DE in the air is

\[
\frac{0.0143}{1+0.0143} = 0.0141
\]

The g mol of an entering (and exit) BDA are (in 1 minute)

\[
19.7n + 100 = 1.412n + 600
\]

\[
n = \frac{32.8 \text{ g mol BDA}}{\text{min}}
\]

20.8

Basis: 1 L saturated solution of nitrobenzene at 20°C

\[
K_{oc} = 10^{3.37} = 186
\]

\[
\text{mass adsorbed (µg)} = \frac{0.11(1000) \text{ g C in soil}}{0.19 \text{ g nitrobenzene}} \cdot \frac{1 \text{ g water}}{100 \text{ g water}} \cdot \frac{10^6 \text{ µg}}{1 \text{ mL water}} \cdot \frac{1 \text{ g}}{1 \text{ g}}
\]

\[
x = 39 \text{ g nitrobenzene}
\]
### Solutions Chapter 21

#### 21.1

**Basis:** 1 lbm

<table>
<thead>
<tr>
<th></th>
<th>252 cal/hr</th>
<th>1 lbm</th>
<th>0.454 kg</th>
<th>Basis: 1 lbm</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>45.0 Btu</td>
<td>1 Btu</td>
<td>0.454 kg</td>
<td>2.5 x 10^4 cal/kg</td>
</tr>
<tr>
<td>b.</td>
<td>45.0 Btu</td>
<td>1 Btu</td>
<td>0.454 kg</td>
<td>1.048 x 10^5 J/kg</td>
</tr>
<tr>
<td>c.</td>
<td>45.0 Btu</td>
<td>1 Btu</td>
<td>0.454 kg</td>
<td>2.91 x 10^7 (kW/hr)/kg</td>
</tr>
<tr>
<td>d.</td>
<td>45.0 Btu</td>
<td>1 Btu</td>
<td>0.454 kg</td>
<td>3.5 x 10^7 (ft^3/lbm)</td>
</tr>
</tbody>
</table>

#### 21.2

<table>
<thead>
<tr>
<th></th>
<th>9.484 x 10^3 Btu/hr</th>
<th>1 g</th>
<th>1°C</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>4.184 J/g (°C)</td>
<td>J</td>
<td>g</td>
<td>°F</td>
</tr>
<tr>
<td>b.</td>
<td>-41.6 J/kg</td>
<td>kg</td>
<td>g</td>
<td>°F</td>
</tr>
<tr>
<td>c.</td>
<td>0.59 (kg/m)</td>
<td>1 N</td>
<td>(J/m^3)</td>
<td>9.484 x 10^3 Btu/hr</td>
</tr>
<tr>
<td></td>
<td>(kg/m) (m/s^2)</td>
<td>1 N</td>
<td>(J/m^3)</td>
<td>3.2808 ft</td>
</tr>
<tr>
<td></td>
<td>0.341 Btu/ft(hr°F)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 21.3

<table>
<thead>
<tr>
<th></th>
<th>6000 Btu/hr</th>
<th>252 cal/hr</th>
<th>1 Btu</th>
<th>3600 s</th>
<th>100 in</th>
<th>1 lbm</th>
<th>144 in.</th>
<th>278 ^oF</th>
<th>453.6 g mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>0.4521 cal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b.</td>
<td>2.3 cal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c.</td>
<td>3.46 cal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d.</td>
<td>0.1055 x 10^7 J</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 21.4

To convert J/(min) (cm^2) (.°C), we set up the dimensional equation as follows:

\[
h = \frac{0.026 G^{°F} \text{ Btu/min} | 1055 J | 1 \text{ hr} | 1 \text{ ft}^2 | 1 \text{ in.} | 2.54 \text{ cm} | 1.8°F | \text{ D}^{°F}(\text{hr}) (°F) | 1 \text{ Btu} | 60 \text{ min} | 12 \text{ in.} | 2.54 \text{ cm} | 1°F \text{ D}^{°F}(\text{min})°(°C) = 8.86 \times 10^4 \text{ G°F}^{°F}}
\]
21.6

Basis: $10^{11}$ watts

\[
\begin{align*}
10^8 W & \times 8.6057 \times 10^4 \text{ cal} \\
1 \text{ hr} & \times 1 \text{ (min)(cm)}^2 \\
10^3 (\text{W})(hr) & \times 60 \text{ min} \times 0.10 \times 32.0 \text{ cal} \\
1 \text{ m}^2 & \times 100 \text{ cm}^2
\end{align*}
\]

\[= 4.5 \times 10^4 \text{ m}^2 \text{ (large)}\]

21.7

a. \[
\frac{975 \text{ W}}{1 \text{ m}^2} \times \frac{320 \text{ days}}{24 \text{ hr}} \times \frac{5 \times 0.21}{1 \text{ day}} \times \frac{3.6 \times 10^6 J}{1 \text{ (kW)(hr)}}
\]

\[= 3 \times 10^{20} \text{ J}\]

\[A = 2.5 \times 10^5 \text{ m}^2 \quad (2.5 \times 10^6 \text{ km}^2)\]

The capital cost is probably too great and the maintenance too high relative to other power sources. Also, the location would have to be in the far western United States to power

---

**Solutions Chapter 21**

b. \[
\begin{array}{ccc}
3 \times 10^{20} & = & 10,000 \text{ Btu} \\
& & 2,000 \text{ lb} \\
& & 1055 \text{ J} \\
& & 1 \text{ Btu}
\end{array}
\]

\[T = 2.0 \times 10^9 \text{ tons}\]

\[2.0 \times 10^9 \text{ tons} = 0.012\]

---

21.8

Yes. Watts are power, and if the energy is transferred for a very short period of time, the power can be quite large. For example, 13 (a very small amount of energy) transferred in $10^{-6}$ is 1 MW!

---

21.9

First substitute for $T_e$

\[T_e = T_e(1.8) + 32\]

Next change units

\[k = \frac{a + bT_e(1.8) + 32}{(\text{br})(0^\circ F)} \times \frac{1055 \text{ J}}{1 \text{ ft} \times 1 \text{ in} \times 1 \text{ hr} \times 1.80 \text{ }^\circ \text{F}}
\]

\[= 1.05[a + b(T_e(1.8) + 32)]^{-1} \left[\frac{J}{(\text{min})(\text{cm})}K\right]
\]

or \[k = 1.05 a + 1.8 bT_e + 33.2\]

---

21.10

\[900,000 \text{ J} \times \frac{1 \text{ (kW)}}{1 \text{ J}} = 10^3 \text{ kW or 100 MW}
\]

(continued)
The answer is yes.

21.11

The trend is to advertise in a way that makes people select a product. And sometimes that just creates confusion.

What the manufacturer is doing is basing the advertisement on the weight of the hot dog. A hot dog weighs about 43 grams and has 8 grams of fat in it. They divided 8 by 43 and get 19 percent fat. They can round it off to 20 and say it’s 80 percent fat free.

But you are concerned with the percentage of fat in the calories. You want 30 percent or less to come from fat.

Your figures are right.

21.12

(a) Some examples are:

How far would you have to run to lose 1 kg of fat?

\[
\frac{32,000 \text{ kJ}}{400 \text{ kJ}} = 80 \text{ km}
\]

about the distance of 2 marathons!

(b) How many days would you have to reduce your diet from 2400 calories to 1400 calories to lose one kg of fat?

\[
\frac{7700 \text{ k cal}}{1 \text{ day}} = 8 \text{ days}
\]

21.13

A main meal is equivalent to about 4000 kJ. A ½ hour is 900 seconds, so that \((700 \text{ J/s}) (900 \text{ s}) / 1000 = 630 \text{ kJ}\), an insufficient amount of time.

21.14

(a) T; (b) T; (c) F; (d) F; (e) T

21.15

(a) T; (b) T; (c) T; (d) T; (e) T; (f) F; (g) F

21.16

<table>
<thead>
<tr>
<th>Partial pressure</th>
<th>Intensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>Extensive</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>Intensive</td>
</tr>
<tr>
<td>Potential energy</td>
<td>Extensive</td>
</tr>
<tr>
<td>Relative saturation</td>
<td>Extensive</td>
</tr>
<tr>
<td>Specific volume</td>
<td>Intensive</td>
</tr>
<tr>
<td>Surface tension</td>
<td>Intensive</td>
</tr>
<tr>
<td>Refractive index</td>
<td>Intensive</td>
</tr>
</tbody>
</table>

21.17

a. Intensive
b. Intensive
c. Intensive
d. Extensive
21.18
A closed system because no mass exchange occurs with the surroundings.

21.19
Basis: 40.0 Newtons × 6.00 m = 240(N)(m)

(a) \[ \frac{240(N)(m)}{1(N)(m)} \times 1 J = 240 J \]

(b) \[ \frac{240(N)(m)}{1(N)(m)} \times 0.738(ft)(lb) = 177.0(ft)(lb) \]

(c) \[ \frac{240(N)(m)}{1(N)(m)} \times 0.239 cal = 57.4 cal \]

(d) \[ \frac{240(N)(m)}{1(N)(m)} \times 9.478 \times 10^4 \text{ Btu} = 0.226 \text{ Btu} \]

21.20
The work done by the cylinder-piston system is \( W = -p(V_2 - V_1) \)

\[ W = \frac{-350 \text{ kPa}}{1 \text{ kPa}/1 \text{ m}^2} \times 0.15 - 0.02 \text{ m}^2 = -45.5 \text{ kJ} \]

21.21
No work is done because the boundary of the system remains fixed.

21.22
Basis: 10 lb water (5 lb vaporized)

The work done by the piston is caused by the water vapor expanding at constant temperature and pressure. Ignore the volume of the liquid water at the initial conditions, and assume the initial amount of vapor is also negligible. From state to state 2

\[ \Delta V_{\text{vapor}} = 4.897 \text{ ft}^3/\text{lb} \text{ from steam tables. For the 5 lb} \]

\[ V_1 = (5 \text{ lb})(4.897 \text{ ft}^3/\text{lb}) = 24.49 \text{ ft}^3 \]

\[ W = \frac{-89.65 \text{ lb}}{1 \text{ ft}^2} \times \frac{144 \text{ in}^2}{1 \text{ ft}^2} \times (24.49 \text{ ft}^3) = -3.16 \times 10^3 \text{ lb f f t}^2 \]

21.23
Basis: 1.2 ft\(^3\) gas at 7.3 atm

\[ p \text{ of } 1 \text{ atm} = 15,450 \text{ lb f t}^2 \]

\[ pV^{1.3} = \text{const.} \]

\[ V_1^{1.3} = (1.2)^{1.3} = 1.27 \]

\[ p_0V_1^{1.3} = 15,450 \times 1.27 = 19,620 \]

\[ W = -\int p dV = -\int \frac{19,620}{V^{1.3}} dV = -19,620 \int \frac{dV}{V^{1.3}} = \frac{19,620}{-0.3V^{0.3}} \]

(continued)
\[ V_1^{1.1} = \frac{(V_1^{1.1})P_0}{P_2} = \frac{(1.27)(7.35)}{(1.0)} = 9.97 \]

\[ V_2 = 5.54 \text{ ft}^2 \]

\[ V_1^{0.1} = (1.2)^{0.1} = 1.06 \]

\[ V_1^{3.1} = (5.54)^{3.1} = 1.67 \]

\[ W = \frac{19,620}{0.3} \left[ \begin{array}{cc} 1 & 1 \\ 1.67 & 1.06 \end{array} \right] = \frac{19,620(0.344)}{0.3} = -22,500(\text{ft})(\text{lb}) \]

21.24

(a) T; (b) F; (c) T; (d) F; (e) F; (f) T; (g) T

21.25

The comment is not a correct use of the term heat, which is a transfer of energy.

21.26

Conservation is confused with balancing. Heat is energy transferred from one system to another, and from the viewpoint of either system (for which an energy balance is made), heat is not conserved. Thus (a) is wrong, heat is part of a balance; (b) same as (a); (c) heat is not conserved – it is transferred and part of the energy balance; (d) the answer should be no with the explanation offered.

21.27

(a) Wrong. Heat is energy, not material.
(b) Wrong. Heat is energy by definition.
(c) Wrong. Heat is energy; cold is related to temperature.
(d) Wrong. See (c).
(e) Wrong. Heat is a transfer of energy.
(f) Heat can be measured, but indirectly via temperature, mass, etc.
(g) Wrong. See (a).
(h) Ok except for “or can be stored” which is wrong.
(i) Burning produces a change in the state of the reactants and products, but the change is not heat. Heat transfer can result from the change in state.
(j) Heat cannot be stored and hence destroyed. Heat transfer can be terminated.

21.28

A better use of words than “absorbing heat” would be “to transfer heat”. Heat is really not “concentrated”. The internal energy of the medium increases.

21.29

(a) F; (b) F; (c) T; (d) F; (e) T; (f) T but debatable; (g) F; (h) F
21.30

Heat transfer rate is \( \dot{Q} = h A \Delta T = \dot{h} = DL \Delta T \)

\[
\dot{Q} = \frac{5 \text{ J}}{(100 \text{ cm})(5 \text{ cm})} \frac{1 \text{ m}}{120 \text{ C}} = \frac{5 \text{ J}}{100 \text{ cm}} = 0.05 \text{ W}
\]

21.31

Basis: 1 minute

\( KE = \frac{1}{2} m v^2 \)

\[
v = \frac{500,000 \text{ g}}{1 \text{ cm}^3} \frac{4 \text{ min}}{1.15 \text{ g/cm}^3} = 22,143 \text{ cm/min}
\]

\[
KE = \frac{1}{2} \left( \frac{500 \text{ kg}}{21 \text{ min}} \frac{22,143 \text{ cm}}{1 \text{ min}} \right) \left( \frac{1 \text{ cm}^3}{1 \text{ kg}} \right) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right)^2 = 6810 \text{ J}
\]

21.32

Basis: 1 lb, H2O

\( KE = \frac{1}{2} m v^2 \)

\[
KE = \frac{1}{2} \left( \frac{1 \text{ lbm}}{2} \right) \left( \frac{10 \text{ ft}^2}{s} \right) \left( \frac{1 \text{ m}^2}{52.2 \text{ ft}^2} \right) \left( \frac{1 \text{ m}}{1 \text{ ft}} \right) = 1.55 \text{ ft} \cdot \text{lb} \cdot \text{s}^2
\]

21.33

The density of air at 27°C and 1 atm is

\[
\rho = \frac{(p)(MW)}{(RT)}
\]

\[
\rho = \frac{101.3 \text{ kPa} \cdot 29 \text{ kg air}}{1 \text{ kg mol air} \cdot 8.314 \text{(kPa)(m)}^3 \cdot 300 \text{ K}} = 1.18 \text{ kg/m}^3
\]

Power = \( \frac{1}{2} m v^2 = \frac{1}{2} (pAv) v^2 = \frac{1}{2} pAv^3 \)

Assume air flow through the windmill is equivalent to the average flow in a pipe of diameter 15m.

\[
v = \frac{20 \text{ mi}}{1 \text{ hr}} \frac{1.61 \times 10^3 \text{ m}}{1 \text{ mi}} \frac{1 \text{ hr}}{3600 \text{ s}} = 8.94 \text{ m/s}
\]

\[
\text{Power} = \frac{1}{2} \left( \frac{1.18 \text{ kg}}{3 \text{ mi}} \right) \left( \frac{15 \text{ m}}{2} \right) \left( \frac{8.94 \text{ m}}{s} \right)^2 \left( \frac{1 \text{ kg} \cdot \text{m}^2}{1 \text{ J}} \right) \left( \frac{1 \text{ W}}{1000 \text{ J}} \right) \left( \frac{74.46 \text{ kW}}{1 \text{ kW}} \right)
\]

Electrical energy = (74.46)(0.30) = 22.3 \text{ kW}

21.34

Basis: 1 lbm of vehicle

\[
a. \quad \dot{F} = \frac{25,000 \text{ mi}}{3600 \text{ s}} \frac{1 \text{ hr}}{1 \text{ mi}} = 36,600 \text{ ft/s}
\]
Solutions Chapter 21

K.E. = \frac{1}{2} \frac{1.34 \times 10^9 \text{ ft}^2}{\text{s}^2} \frac{\text{lb}_m}{\text{lb}_m} = 2.08 \times 10^7 \left( \frac{\text{lb} \cdot \text{ft}}{\text{lb}_m} \right)

K.E. = \frac{2.08 \times 10^7 \left( \frac{\text{lb} \cdot \text{ft}}{\text{lb}_m} \right)}{778 \left( \frac{\text{lb} \cdot \text{ft}}{\text{lb}_m} \right)} \frac{1 \text{ Btu}}{\text{lb}_m} = 2.68 \times 10^6 \frac{\text{Btu}}{\text{lb}_m}

b. Heat capacity of, say, 1 Btu/(lb) (°F) gives

\frac{1 \text{ Btu}}{\text{lb} (°F)} = 20 \text{ Btu/lb}_m.

Essentially all the energy must be transferred to the surroundings.

21.35

Basis: 2 kg mass

\( PE = mgh = \frac{12 \text{ kg} \cdot 9.80 \text{ m} \cdot 25 \text{ m}}{\text{s}^2} \frac{1 \text{ J} \cdot \text{kg} \cdot \text{m}}{1 \text{ kg} \cdot \text{m} \cdot \text{s}^2} = 3240 \text{ J} \)

21.36

Filled reservoir

Assume 7 meters is a constant level difference hence \( h = 7 \text{ m} \)

For one-half of the complete cycle (6 hours):

21.37

Relative to the reference values in the steam tables and the CD:

(a) \( U = 3528 \text{ kJ/kg} \) (from the steam tables)

(b) The quality is 0.13% and \( U = 1219 \text{ kJ/kg} \) from the steam tables

(c) At 100°C and 1000 kPa, \( U \) of the liquid is about \( U \approx 532 \text{ kJ/kg} \) from the steam table

21.38

The heat capacity of a monoatomic ideal gas is \( \frac{5}{2} R \), and the heat capacity at constant volume is \( \frac{5}{2} R - R = \frac{3}{2} R \)

(continued)
You can show that \( C_v = C_p - R \)

\[
C_p = \left( \frac{\partial \hat{H}}{\partial T} \right)_p = \left[ \frac{\partial \hat{U} + \partial (p\hat{V})}{\partial T} \right]_p = \left( \frac{\partial \hat{U}}{\partial T} \right)_p + p \left( \frac{\partial \hat{V}}{\partial T} \right)_p
\]

For the ideal gas \( \hat{U} \) is a function of \( T \) only (not of \( p \) or \( \hat{V} \) ) so that

\[
\left( \frac{\partial \hat{U}}{\partial T} \right)_p = \left( \frac{\partial \hat{U}}{\partial T} \right)_0 = C_v
\]

\[
p \left( \frac{\partial \hat{V}}{\partial T} \right)_p = p \left( \frac{R}{p} \right) = R
\]

\[
\Delta U = \int C_v dT = \frac{3}{2} R T (\text{J}) = 624 \text{ J}
\]

21.39

Basis: 1 kg steam

\[
\begin{array}{c}
1 \\
2
\end{array}
\]

\[
\begin{array}{c}
250.5^\circ C \\
4000 \text{ kPa}
\end{array}
\]

\[
\begin{array}{c}
650^\circ C \\
10,000 \text{ kPa}
\end{array}
\]

\( \Delta U = \Delta H - \Delta pV \) or use \( U \) values directly from SI tables or computer code.

Data here taken from the steam tables.

21.40

Internal energy is the energy contained in the material of a system because of its molecular arrangement. Heat is energy that flows between the system and the surroundings because of a temperature gradient. Therefore they are not the same class of energy.

21.41

\( \Delta H = \Delta U + \Delta (pV) \)

When a liquid vaporizes \( \Delta (pV) \) adds to \( \Delta U \).

21.42

\( \Delta H \) and \( \Delta U \) are zero because \( \Delta H \) and \( \Delta U \) are point (state) functions (variables).

21.43

None. The initial and final states for \( U \) and \( H \) are the same.
21.44

The energy balance is \( \Delta E = \Delta U + \Delta PE + \Delta KE = Q + W \)

\[
\begin{array}{cccc}
(a) & Q & W & \Delta E & \Delta U \\
& >0 & 0 & >0 & >0 \\
(b) & 0 & >0 & >0 & >0 \\
(b) & 0 & >0 & >0 & >0 \\
(c) & 0 & >0 & >0 & >0 \\
\end{array}
\]

21.45

Basis: 10 lb mol ideal gas

(a) Use \( pV = nRT \)

\[ \Delta(pV) = \Delta(\text{RT}) \]

\[(1) \quad 10 \text{ lb mol} \left( \frac{559 \text{ (F)}}{\text{lb mol}} \right) \cdot \frac{500\text{°F}}{1 \text{ atm} \cdot \frac{100 \text{ atm}}{492\text{°F}} } = 36.5 \text{ (ft)} \cdot \frac{100 \text{ atm}}{492\text{°F}} = 100 \text{ atm} \cdot 40\text{°F} \]

\[(2) \quad \frac{500\text{°F}}{180 \text{ atm}} = \frac{500\text{°R}}{500\text{°R}} = \frac{180 \text{ atm}}{500\text{°R}} \]

\[(3) \quad \Delta H = (H_2 - H_1) = 10 \left[ (300 + 8.0 \cdot 440) - (300 + 8.0 \cdot 40) \right] = 32,000 \text{ Btu} \]

(b) The equation for \( H \) is based on the reference conditions where \( \dot{H} = 0 \).

\( \dot{H} = 0 \) when \( 300 = -8T \) or \( T_{ref} = -37.5 \text{ °F} = -38.5 \text{°C} \). \( U \) should have the same reference temperature.

\[ \Delta U = \Delta H - \Delta(pV) = \Delta H - \Delta RT \text{ for an ideal gas} \]

21.46

Use the same reference state, so that

\[ \Delta \dot{H} = \Delta \dot{U} + \Delta (p \dot{V}) \]

For one mole of an ideal gas: \( p \dot{V} = RT \)

\[ \Delta \dot{U} = \Delta \dot{H} - \Delta RT \]

\[ = 6.05 \times 10^5 \frac{J}{\text{kg mol}} \cdot \frac{8.314 J}{\text{mol K}} \cdot \frac{10^3 \text{ g mol}}{1 \text{ kg mol}} \cdot \frac{[(100 + 273) - (273)]K}{1 \text{ kg mol}} \]

\[ = 6.05 \times 10^5 - 8.314 \times 10^5 = -2.26 \times 10^5 \text{ J/kg mol} \]
### Solutions Chapter 21

#### 21.47

<table>
<thead>
<tr>
<th></th>
<th>T</th>
<th>(f)</th>
<th>T</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>F</td>
<td>(g)</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>F</td>
<td>(h)</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>T</td>
<td>(l)</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>F</td>
<td>(j)</td>
<td>T</td>
<td></td>
</tr>
</tbody>
</table>

#### 21.48

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>(f)</th>
<th>T</th>
<th>(k)</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>F</td>
<td>(g)</td>
<td>F</td>
<td>(l)</td>
<td>F</td>
</tr>
<tr>
<td>(b)</td>
<td>F</td>
<td>(h)</td>
<td>T</td>
<td>(m)</td>
<td>T</td>
</tr>
<tr>
<td>(c)</td>
<td>T</td>
<td>(i)</td>
<td>F</td>
<td>(n)</td>
<td>T</td>
</tr>
<tr>
<td>(d)</td>
<td>T</td>
<td>(j)</td>
<td>F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
22.1
All of them.

22.2
(a) pump

\[ \text{system is the pump. Open, steady state.} \]

\[ \begin{array}{cccccc}
\text{Q} & \text{W} & \Delta U & \Delta H & \Delta PE & \Delta KE \\
\text{Very little} & \text{Yes} & \text{No} & \text{Yes (flow)} & \text{No} & \text{No}
\end{array} \]

(b) system is the pump and motor. Open, steady state

\[ \begin{array}{cccccc}
\text{A little} & \text{Yes} & \text{No} & \text{Yes} & \text{No} & \text{No}
\end{array} \]

(c) System is the ice. Closed, unsteady state.

\[ \begin{array}{cccccc}
\text{Yes} & \text{No} & \text{Yes} & \text{Yes} & \text{No} & \text{No}
\end{array} \]

(d) system is the mixer and solution. The process is closed, unsteady state.

Possibly Yes Yes Yes Yes No No

22.3
a. System: can and liquid \( Q = 0, W \neq 0 \)
b. System: motor \( Q = 0, W \neq 0 \) But motor may get hot.
c. System: pipe and water \( Q = 0, W \neq 0 \)

22.4
a. 

[Diagram of a system showing steam in, energy in, water in, energy out, steam out, and a dashed boundary.]

(continued)
b. 

\[ Q = 0 \]

Steam in 

\[ \rightarrow \text{Turbine} \rightarrow \text{Steam out} \]

Energy In 

\[ \rightarrow \text{Work} \rightarrow \text{Energy out} \]

\[ \text{Turbine} \]

\[ \text{Work} \rightarrow \text{Battery} \]

\[ Q = 0 \]

\[ W \neq 0 \]

22.5

No. The energy balance is \[ Q + W = \Delta U \], and for \[ Q = 0 \] and since \[ \Delta U = 0 \] for an isothermal process \[ W = 0 \].

22.6

This is an unsteady state closed process

Data from the CD

**Initial Conditions**

| Basis: 1 lb water |

| \( T = 327.3^\circ \text{F} \) |

**Final conditions**

| \( T = 327.3^\circ \text{F} \) |

22.7

Closed unsteady state system

\[ Q + W = \Delta U \]

\[ 60 + W = 220 \]

\[ W = 160 \text{ Btu} \] (work done on the system)
22.8
Closed unsteady state system

\[ Q + W = \Delta U \]

\[
\ln k_J: (30-5) + 0.5 = U_f - 10 \quad U_f = 35.5 \text{ kJ}
\]

22.9
Closed unsteady state system

\[ Q + W = \Delta U \quad Q = 0 \]

\[ W = \Delta U = C_s \Delta T \]

\[
W = \frac{100 \text{ W}(5 \text{ hr})}{1000 \text{ W}} \cdot \frac{1 \text{ kW}}{1 \text{ kW}} \cdot 3.6 \times 10^3 \text{ kJ} = 1.8 \times 10^3 \text{ kJ}
\]

Mols of air = \( n = \frac{pV}{RT} = \frac{(100 \text{ kPa})(100 \text{ m}^3)}{8314 \text{ kPa} \cdot \text{K} \cdot \text{mol}^{-1}} = 3.97 \text{ kg mol} \)

\[ 1.8 \times 10^3 = 30(3.97)(T - 30) \quad T = 45\degree C \]

22.10
Closed unsteady state process

\[ Q + W = \Delta U + \Delta (PE) \]

22.11
Closed unsteady state system
Use the CD to get data

Initial Conditions

| Basis: 4 kg steam |

| Given: | T = 500K |
| Given: | p = 700 kPa |
| Known: | \( \dot{V} = 0.320 \text{ m}^3/\text{kg} \) |
| Look up: | \( \dot{h} = 2903.94 \text{ kJ/kg} \) |
| Calculate: | \( V = 0.320(4) = 1.280 \text{ m}^3/\text{kg} \) |

Final Conditions

| Given: | T = 400K |
| Known: | \( \dot{V} = 0.320 \text{ m}^3/\text{kg} \) |
| Look up (2 phase system) the quality (trial and error on the CD): | \( x = 0.437 \) |
| Calculate: | \( \dot{h} = 1486.81 \text{ kJ/kg} \) |

\[ \dot{Q} + \dot{W} = \Delta \tilde{U} \quad \dot{W} = 0 \]

\[ Q = (1408.23 - 2680.51)(4) = (-1272.3)(4) = -5,089 \text{ kJ} \]

If you do not use the CD, \( \Delta \tilde{U} = \Delta \tilde{H} - (\Delta p \tilde{V}) \).
Closed, unsteady state process

Initial conditions

\[ V = 1 \text{ ft saturated dry std. steam (the basis)} \]

Final conditions

\[ V = 1 \text{ ft (know) + } V_2 \]

Look up

At \( p = 1 \text{ psia} \) \( T = 200^\circ \text{F} \). The water is vapor

\[ \dot{V} = 33.610 \text{ ft}^3/\text{lb} \]

\[ \dot{H} = 1145.72 \text{ Btu/lb} \]

\[ \dot{U} = 1073.96 \text{ Btu/lb} \]

\[ p = 11.548 \text{ psia} \]

Calculate the lb of steam

\[ m = \frac{1 \text{ lb}}{33.610 \text{ ft}^3/lb} = 0.02975 \text{ lb} \]

\[ Q + W = \Delta U \]

\[ Q = \Delta U \]

\[ \Delta U = U_2 - U_1 = (1077.48 \text{ Btu/lb}) - (1073.96 \text{ Btu/lb}) = 0.105 \text{ Btu/lb} = Q \]

For an ideal gas, \( C_v = 5/2 \text{ R} \) (has to be looked up or calculated) and \( U \) and \( H \) are functions of \( T \) only

Also, \( \Delta(pV) = \Delta (nRT) \)

Calculate some of the missing values

\[ V_A = \frac{(1 \times 10^{-3})(0.7302)(630)}{1} = 0.460 \text{ ft}^3 \]

\[ V_C = \frac{(1 \times 10^{-3})(0.7302)(530)}{10} = 0.0387 \text{ ft}^3 \]

\[ V_B = \frac{(1 \times 10^{-3})(0.7302)(1283)}{10} = 0.0937 \text{ ft}^3 \]

(continued)
Solutions Chapter 22

The work for each stage will be assumed to be $\int pdV$ (ideal process)

$W_{th}$ (constant pressure process)

c. $W = -\int pdV = -p_{st}(V_B - V_A)$

$= -1\text{ atm} \left[(0.387 - 0.460)\text{ ft}^3\right] \left[2.72\text{ Btu/ft}^3\right] = -0.199\text{ Btu}$

$W_{is}$ (isothermal process)

d. $W = \int pdV = \int \frac{nRT}{V} dV = -nRT\int \frac{dV}{V} = -nRT[\ln V]_{st}$

$= -(1\times10^{-3})(1.987)(530)(\ln 0.1) = -2.42\text{ Btu}$

$W_{ac}$ (constant pressure process)

e. $W = -\int pdV = -p_{st}(V_B - V_A) = -(10)(0.0937 - 0.0387) = -0.550\text{ Btu}$

$W_{ad}$ (ideal adiabatic process)

$W = -\int pdV = -\frac{nRT}{V} dV$ However, both T and V vary.

Instead use

$Q + W = \Delta U$

$Q = 0\text{ R} = 1.987\text{ Btu/(lb mol)}\text{ (°R)}$

f. $W = \Delta U = nC_p\Delta T = (10)(\frac{5R}{2})(630 - 1283) = -3.243\text{ Btu}$

R. $W_{enthalpy} = 0.199 + 0.891 - 0.550 - 3.243 = -1.74\text{ Btu}$

Solutions Chapter 22

h. $(\Delta H = 0)$ (a cycle)

i. For the overall process $Q + W = \Delta U$. Because of the cycle, $\Delta U = 0$, and thus $Q \approx -W = 1.74\text{ Btu}$

22.14

A closed, unsteady state system comprised of 2 tanks. Get the steam properties from the CD.

State 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>1 lb</td>
</tr>
<tr>
<td>$p$</td>
<td>600 psia</td>
</tr>
<tr>
<td>$V$</td>
<td>0.795 ft$^3$/lb</td>
</tr>
<tr>
<td>$T$</td>
<td>500°F (960°F)</td>
</tr>
<tr>
<td>$U$</td>
<td>1128.19 Btu/lb</td>
</tr>
<tr>
<td>$H$</td>
<td>1215.97 Btu/lb</td>
</tr>
<tr>
<td>$V_1$</td>
<td>0.795 ft$^3$</td>
</tr>
</tbody>
</table>

State 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>1 lb*</td>
</tr>
<tr>
<td>$p$</td>
<td>330.45 psia</td>
</tr>
<tr>
<td>$V$</td>
<td>1.590 ft$^3$/lb</td>
</tr>
<tr>
<td>$T$</td>
<td>500°F (960°F)*</td>
</tr>
<tr>
<td>$U$</td>
<td>1157.03 Btu/lb</td>
</tr>
<tr>
<td>$H$</td>
<td>1253.98 Btu/lb</td>
</tr>
<tr>
<td>$V_2$</td>
<td>2$V_1$ = 1590 ft$^3$*</td>
</tr>
</tbody>
</table>

* used to get state 2 properties

The closed system is $Q + W = \Delta U$

$\Delta U = 1157.03 - 1128.19 = 28.84\text{ Btu/lb}$

$W = 0$ (fixed boundary)

$Q = \Delta U = 28.84\text{ Btu/lb}$

$\Delta H = 1253.98 - 1215.97 = 38.01\text{ Btu/lb}$
Solutions Chapter 22

22.15

No. For each path \( Q + W = \Delta U \), and for the cycle 1 to 2 and back \( \Delta U = 0 \). Addition gives
\[
(Q_1 + W_1) + (Q_2 + W_2) = \Delta U_{1-2} + \Delta U_{2-1} = 0
\]
\[
(Q_1 + Q_2) = -(W_1 + W_2)
\]

Note: The equations in the problem used a different sign for \( W \). A similar analysis applies to the second equation in the problem.

22.16

A closed steady-state system.

The cooling at the maximum efficiency is
\[
0.695 \text{ kW} \left( \frac{0.948 \text{ Btu}}{1 \text{ kW})} \right) \left( \frac{3600 \text{ s}}{1 \text{ hr}} \right) = 2372 \text{ Btu/hr}
\]

not 5500 Btu/hr.

The main question with the advertisement is: where does the energy go that is removed from the room if the unit does not require outside venting?

22.17

A closed steady-state system

\( \dot{Q} + W = \Delta U = 0 \)

\( \dot{Q} = -W \) Q is negative (heat loss)
22.20

**Basis:** 1 lb H₂O at 212°F, 1 atm

Data from the CD

<table>
<thead>
<tr>
<th>Initial (liquid)</th>
<th>Final (vapor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ü</td>
<td>180.182 Btu/lb</td>
</tr>
<tr>
<td>¹H</td>
<td>180.226 Btu/lb</td>
</tr>
<tr>
<td>¹V</td>
<td>0.017 ft³/lb</td>
</tr>
</tbody>
</table>

p = 1.00 atm

**Non-flow process (unsteady-state)**

\[Q + W = \Delta U\]

\[\Delta U = (1 \text{ lb})(1077.40 - 180.182) \text{ Btu/lb} = 897.22 \text{ Btu}\]

\[W = -\int pdV = -(1 \text{ atm})(26.773 - 0.017) \text{ ft³/lb} (2.72) \text{ Btu/ atm ft³} = -72.78 \text{ Btu}\]

\[Q = 897.22 - (-72.78) = 970.0 \text{ Btu}\]

\[\Delta H = 1150.29 - 180.226 = 970.0 \text{ Btu}\]

**Flow process (unsteady-state)**

\[\Delta U = Q + W - \Delta H\]

Assume the volume of the system is fixed at \(V = 0.017 \text{ ft³}\) and that \(W = 0\). Also assume that nothing is left in the system after the water evaporates.

\[\Delta U = \hat{U}_\text{in}(0) - \hat{U}_\text{out}(1) = -180.182 \text{ Btu}\]

---

22.21

Treat the system (the cylinder) as an unsteady state flow system.

\[\Delta U = Q + W - \Delta H\]

\[W = 0 \quad Q = 0\]

\[U_\text{in} - U_\text{out} = -(H_\text{in} - H_\text{out})\]

\[\hat{U}_\text{in} = \hat{U}_\text{in, ref} \quad n_r = \text{final moles in cylinder}\]

\[\hat{U}_\text{in} = \hat{U}_\text{in, ref} \quad n_i = \text{initial moles in cylinder}\]

\[\hat{H}_\text{in} = 0\]

\[\hat{H}_\text{out} = \hat{H}_\text{out, ref}\]

Let the reference temperature be \(T_r\) that makes \(\hat{H}_\text{in} = 0\). Ignore the effect of pressure on the values of \(\hat{U}\) and \(\hat{H}\).

\[\hat{H}_\text{in} = \hat{H}_\text{out} = C_v(T_\text{in} - T_r) \quad \hat{H}_\text{in} = 0\]

\[\Delta U = 0\]

\[U_\text{in} - U_\text{out} = n_i \hat{U}_\text{in} - n_r \hat{U}_\text{out} = (n_i - n_r)\hat{H}_\text{in} - 0\]

(continued)
\[ n_i\left[C, (T - T_e) - R T_e \right] - n_i\left[C, (T_e - T) - R T_e \right] = (n_i - n_i)\left[C, (T_e - T) \right] \]

\[ = (n_i - n_i)\left[C, + R (T_e - T) \right] \]

Multiply all of the terms out to get (note terms with \( T_e \) cancel):

\[ n_i C, T = n_i C, T_e + n_i R T_e - n_i R T \]

\[ C_V = C_p - R \]

Insert \( pV = nRT \) to get \( n_i \) and \( n_f \)

\[ \frac{R}{C_V} = \frac{2}{5} \] for diatomic gas

The equations reduce to

\[ n_i C, T = n_i C, T_e + n_i R T_e - n_i R T \]

\[ \frac{T}{T_e} = \left[1 + \frac{R}{C_v} \frac{p_e}{p_i} \frac{T}{T_e} \right] \]

\[ T = 298 \left[1 + \frac{2}{5} \left( \frac{1}{140} \frac{T}{298} \frac{2}{5} \right) \right] \]

\[ T = 417 \text{ K} \]

---

**22.22**

The tank is an open unsteady state system. \( f \) stands for final, \( i \) for initial, \( m \) for mass in lb.

**Data:**

<table>
<thead>
<tr>
<th>( \text{at 291°F and 50 psia} )</th>
<th>( \text{at 14.7 psia saturated (212°F)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1179.39 )</td>
<td>( H ) Btu/lb</td>
</tr>
<tr>
<td>( 1099.60 )</td>
<td>( U ) Btu/lb</td>
</tr>
<tr>
<td>( 8.653 )</td>
<td>( V ) ft(^3)/lb</td>
</tr>
</tbody>
</table>

\[ \Delta U = Q + W - \Delta H \]

\[ W = 0 \]

\[ Q = 0 \]

\[ H_{in} = 0 \]

\[ \Delta U = -\Delta H \]

\[ n_i \dot{U}_i - m_i \dot{U}_i = (m_i - m_i)\dot{H}_{in} = 0 \]

\[ V = 50 \text{ ft}^3 \] so

\[ m_i = \frac{50}{8.653} = 5.78 \text{ lb} \]

\[ m_i = \frac{50}{26.818} = 1.86 \text{ lb} \]

\[ 5.78(\dot{U}_i) - 1.86(1077.37) = (5.78 - 1.86)1179.39 \]

\[ \dot{U}_i = 1146.56 \text{ Btu/lb at 50 psia} \]

\[ T_i = 411°F \] (superheated)
22.23

Basis: interval of 1 hr (1800 gal) or (1800)(8.33) = 15,000 lb water

Open, unsteady state system. System is storage tank plus the water lines.

\[ \Delta U = Q + W - (\Delta H + \Delta PE) \]

Data: 25°C saturated water

\[ \dot{U} \text{ Btu/lb} = 3.025 \]

\[ H \text{ Btu/lb} = 3.025 \]

\[ V \text{ ft}^3/\text{lb} = 0.016 \]

Ignore the water in the lines initially and finally assume no change. Also ignore the increased depth of the water in the storage tank.

\[ \Delta PE = \frac{100 \text{ ft}}{15,000 \text{ lb}} \cdot \frac{1 \text{ Btu}}{5.7816 \times 10^4 \text{ ft}^3/\text{lb}^3} = 1928 \text{ Btu} \]

\[ Q = \frac{1000 \text{ Btu}}{60 \text{ min}} \cdot \frac{60 \text{ min}}{\text{ hr}} \cdot 5000 = 5.5 \times 10^4 \text{ Btu} \]

\[ H_{\text{water}} = \frac{15,000 \text{ lb}}{3.025 \text{ Btu/lb}} = 45,380 \text{ Btu} \]

\[ H_{\text{water}} = 0 \text{ (no flow out)} \]

\[ U_{i_1} = 15,000 \dot{U}_{i} \]

\[ U_{i} = 0 \text{ (no water in the tank)} \]

22.24

The general energy balance is

\[ \Delta E = Q + W - \Delta[H + KE + PE] \]

\[ \begin{align*}
(1) & \quad \Delta E = 0 \\
(2) & \quad \text{steady state flow process, one overall system (You can also pick two systems, one the H}_2\text{O and one the benzene).}
\end{align*} \]

\[ \begin{array}{c}
\text{H}_2\text{O} \\
\text{Bz} \leftarrow \text{Q} \rightarrow \text{Bz} \\
\text{H}_2\text{O}
\end{array} \]

\[ (\text{continued}) \]
(2) $Q$ is the net overall heat transfer to and from the heat exchanger with the surroundings.

It is essentially 0 if the exchanger is well insulated. If you pick 2 systems, $Q$ is the heat transfer between the benzene and the $H_2O$, and is not 0.

(3) $W = 0$ no mechanical work in the process

(4) $\Delta H \neq 0$ for all streams

(5) $\Delta KE = 0$ negligible KE change

(6) $\Delta PE = 0$ level exchanger assumed. $Q = \Delta H$

(b)

(1) $\Delta E = 0$ steady state process

(2) $Q$ not zero as isothermal

---

Solutions Chapter 22

22.25

Unknowns

Relationships (R)

(1) $F = P + V$

(2) $0.05F = \chi x p$

(3) $\dot{F} V + S \Delta H_a = \dot{V} H_v + P \dot{V} p$

(4) $S \Delta H_a = Q$

(5) $Q = UA(T_e - T_v)$

$T_v$

$X_p$

Yes, two measurements must be made to balance the unknowns and the relationships. If $x_p$ and $T_v$ are measured, solve (R5) for $Q$, (R4) for $S$, substitute (R2) and (R1) in (R3) and solve for $F$. Use (R2) to calculate $P$ and (R1) to calculate $V$. Note that measuring $T_v$ and $S$ is not satisfactory because this combination eliminates either (R4) or (R5) as an independent relationship. Also note that if you neglect the vapor pressure of the organic, you can set $T_v = 212^\circ F$.

---

22.26

(continued)
Solutions Chapter 22

Steps 1, 2, 3, and 4:

Figure P22.27 shows the known quantities. No reaction occurs. The process is clearly a flow process (open system). Assume that the entering velocity of the air is zero.

Step 5:

Basis: 100 kg of air = 1 hr

Steps 6 and 7:

Simplify the energy balance (only one component exists):

\[
\Delta E = Q + W - \Delta(\dot{H} + \dot{KE} + \dot{PE}m)
\]

(1) The process is in the steady state, hence \( \Delta E = 0 \).

(2) \( m = m_1 = m \).

(3) \( \Delta(\dot{PE})(m) = 0 \).

(4) \( Q = 0 \) by assumption (\( Q \) would be small even if the system were not insulated).

(5) \( v_1 = 0 \) (value is not known but would be small).

The result is

\[
W = \Delta(\dot{H} + \dot{KE}m) = \Delta H + \Delta KE
\]

We have one equation and one unknown, \( W \). \( \Delta KE \) and \( \Delta H \) can be calculated, hence the problem has a unique solution.

Solutions Chapter 22

Steps 7, 8, and 9:

\[
\Delta H = \frac{5009 - 489}{100} \text{kJ} = 2000 \text{kJ}
\]

\[
\Delta KE = \frac{1}{2} m(v_1^2 - v_2^2)
\]

\[
= \frac{1}{2} \left( \frac{100 \text{ kg}}{s} \right) \left( \frac{60 \text{ m}^2}{s^2} \right) \left( \frac{1 \text{ kJ}}{1000 \text{ kg} \cdot \text{m}^3} \right) = 180 \text{kJ}
\]

\[
W = (2000 + 180) = 2180 \text{kJ}
\]

(Note: The positive sign indicates work is done on the air.)

To convert power (work/time).

\[
kW = \frac{2180 \text{kJ}}{1 \text{hr}} \times \frac{1 \text{kW}}{3600 \text{s}} = 0.61 \text{kW}
\]

22.27

(a) Steady state process assumed.

\[
\Delta E = -\Delta \left( \dot{H} + \dot{KE} + \dot{PE}m \right) + Q + W
\]

1. Ignore \( \dot{PE} \); \( \Delta \dot{PE} = 0 \)
2. \( \Delta \dot{KE} \) is small so \( \Delta \dot{KE} = 0 \) (continued)
3. No reaction
4. \( W = 0 \)
5. \( (E_i - E_f) = 0 \), steady state
   \[
   \Delta H = Q
   \]
(b) \( \Delta E = -[(\hat{H} + \hat{KE} + \hat{PE})m] + Q + W \)
   1. Ignore \( \hat{PE} \); \( \Delta \hat{PE} = 0 \)
   2. No reaction
   3. \( (E_i - E_f) = 0 \); steady state
   4. \( Q = 0 \) – assumed
   5. \( W = 0 \)
   6. \( \Delta \hat{KE} = 0 \)
   \[
   \Delta H = 0
   \]

22.28

System: gas

\( E_i - E_f = -\Delta (\hat{H} + \hat{KE} + \hat{PE})m + Q + W \)

a. no reaction

\[-\Delta (\hat{H} + \hat{KE} + \hat{PE})m = 0, \ no \ flow\]

\( \Delta KE \) and \( \Delta PE \) of gas = 0

\[
U_i - U_f = Q + W
\]

b. Here \( W = 0 \)

\[
U_i - U_f = Q
\]

c. Here \( Q = 0 \),

\[
U_i - U_f = W
\]

d. \( U_i - U_f = Q + W \)

e. Here, the system is the gas \( Q = 0 \), \( W = 0 \)

\[
U_i - U_f = 0
\]

22.29

Basis: 1 hour

Input conditions:

\[
500^\circ F \quad h_i = 1264.7 \text{ Btu/lb} \]
\[
250 \text{ psi} \quad h_i = 1264.7 \text{ Btu/lb}
\]

Exit conditions:

\[
14.7 \text{ psi} \quad h_{out} = 1150.4 \text{ Btu/lb} \]
\[
15\% \ \text{liquid} \quad h_{out} = 180.07 \text{ Btu/lb}
\]

\[
H_i = 0.15(180.07) + 0.85(1150.4)
\]

(continued)
= 1004 Btu/lb

The simplified energy balance is:

\[ m\Delta H = Q + W \]

\[ \Delta \dot{H} = 1004 - 1265 = -261 \text{ Btu/lb} \]

\[ m\Delta \dot{H} = -261,000 \text{ Btu} \]

\[ W = \frac{36.5 \text{ hp} \cdot \text{hr}}{2.93 \times 10^5 \text{ (hp)(hr)}} \times 1 \text{ Btu} = -2.20 \times 10^3 \text{ Btu} \]

Thus, \( Q = m\Delta \dot{H} - W = -2.61 \times 10^3 + 2.2 \times 10^3 = -4.1 \times 10^3 \text{ Btu} \)

hence, not adiabatic.

(a) \( \Delta T = 0 \) or \( T_1 = 250 \text{ K} \)

Since \( \Delta H = 0 \) (the kinetic energy term was negligible), the steady-state constraint requires that the mass flow rate be constant:

\[ \dot{m} = pvS = \text{Constant} \]

where: \( p = \text{density} \)
\( v = \text{velocity of the gas} \)
\( S = \text{cross-sectional area of pipe} \)

Since the diameter of the pipe does not change and density is a function of temperature and pressure, the gas velocity is also a function temperature and pressure.

\[ v_{\text{in}} = \frac{100 \text{ lb Air}}{1 \text{ hr}} \times \frac{1 \text{ lb mol}}{29 \text{ lb Air}} \times \frac{1 \text{ hr}}{359 \text{ ft}^3} \times \frac{1}{1560 \text{ s} \times (1.5/12 \text{ ft}^2)} = 7.0 \text{ ft/s} \]

Therefore, the velocity downstream of the valve is:

\[ v_{\text{out}} = \frac{7.0 \text{ ft}}{250 \text{ K}} \times \frac{1 \text{ atm}}{273 \text{ K}} = 3.2 \text{ ft/s} \]

22.31

Basis: 1 second

Steady-state process. Basis: 1 second

(continued)
\[ \dot{m} (\dot{H}_m - \dot{H}_a) = \dot{Q} + \dot{W} \]

To get \( \dot{H}_a \), use the steam tables or a \( C_p \) equation. Using constant \( C_p \) is not the most accurate method, but for liquids for small temperature changes, it is a good approximation.

\[ \dot{m} (C_p) (T_{out} - T_a) = \dot{Q} + \dot{W} \]

Because the tank is well-mixed, the outlet water temperature is the same as the temperature inside the tank \( T \).

\[ T = T_{out} \]

\[ \dot{m} (C_p) (T - T_a) = 100 (20 - T) + 300 \]

\[ \dot{m} = \frac{1 \text{ kg} \text{ min}}{60 \text{ s}} = \frac{1 \text{ kg}}{60 \text{ s}} \]

\[ C_p = 4180 \text{ J/(kg)(K)} \]

\[ \frac{4180}{60} \text{ (T - 40)} = 100 (20 - T) + 300 \]

\[ T = 30.0^\circ \text{C} \]

---

22.32

\[ \dot{Q}_{in} = 200 \text{ W} \]

\[ T_j = ? \]

\[ T_1 = 17^\circ \text{C} \]

\[ h_{v, n} = 15 \text{ kW} \]

\[ \lambda_i = 100 \text{ kPa} \]

\[ V_1 = 150 \text{ m}^3/\text{min} \]

**Assumptions**

1. This is a steady-flow process since there is no change with time at any point, hence \( \Delta E = 0 \).
2. Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point.
3. The kinetic and potential energy changes are negligible \( \Delta KE = \Delta PE = 0 \).
4. Constant specific heats at room temperature can be used for air.

The simplified energy balance is

\[ \dot{Q} + \dot{W} = \Delta H = m(\dot{H}_m - \dot{H}_a) \]

\[ \dot{Q} = -200 \text{ W} \]

\[ \dot{W} = 15 \text{ kW} \]

Assume that with little error (continued)
\[ \Delta H = C_p \Delta T \quad \text{with} \quad C_p = 1.00 \quad \text{kJ/(kg)(K)} \]

Otherwise you will need tables or a database for the properties of air.

The ideal gas law gives the specific volume of air at the inlet of the duct

\[ \frac{V_i}{P_a} = \left( \frac{0.287 \text{ kPa m}^3/(\text{kg})(\text{K})}{100 \text{ kPa}} \right) = 0.832 \text{ m}^3/\text{kg} \]

The mass flow rate of the air through the duct is determined from

\[ \dot{m}_i = \frac{V_i}{\rho_i} = \frac{150 \text{ m}^3/\text{min}}{0.832 \text{ m}^3/\text{kg}} \times \frac{1 \text{ min}}{60 \text{ s}} = 3.0 \text{ kg/s} \]

Substituting the known quantities, the exit temperature of the air is determined to be

\[ (15 \text{ kJ/s}) - (0.2 \text{ kJ/s}) = (3 \text{ kg/s}) [1.00 \text{ kJ/(kg)(K)}] (T_{\text{exit}} - 17) \]

\[ T_{\text{exit}} = 21.9^\circ \text{C} \]

22.33

The procedure is correct only for an open, steady state system.

(a) If the evaporation occurs from an open, unsteady-state system of fixed volume:

\[ \Delta U = Q + W - \Delta H \]

\[ W = 0 \]

\[ \Delta U = Q - \Delta H \]

Data:

\[ U_{\text{max}} = 419.5 \text{ kJ/kg} \]
\[ \dot{U}_{\text{spec}} = 2506.0 \text{ kJ/kg} \]
\[ H_{\text{spec}} = 419.5 \text{ kJ/kg} \]
\[ \dot{H}_{\text{spec}} = 2675.6 \text{ kJ/kg} \]

Assume only 1 kg of water is in the system at \( t = \text{initial} \). At \( t = \text{final} \), 0 kg of water are in the system.

\[ \dot{U}_{\text{in}} = 0 \]
\[ U_{\text{spec}} = (1 \text{ kg})(419.5 \text{ kJ/kg}) = 419.5 \text{ kJ} \]
\[ H_{\text{in}} = (1 \text{ kg})(2675.6 \text{ kJ/kg}) = 2675.6 \text{ kJ} \]

\[ H_{\text{in}} = 0 \]

\[ -419.5 = Q - (2675.6-0) \]

\[ Q = 2256.1 \text{ kJ} \]

(b) If the evaporation occurs in a steady-state open system, \( m_{\text{in}} \) is in kg and \( m_{\text{in}} - 1 = m_{\text{out}} \).

The process is isothermal.

\[ W = 0 \quad \Delta U = 0 \]

\[ Q = \Delta H = \left[ (m_{\text{in}} - 1)\dot{H}_{\text{spec}} + (1)\dot{H}_{\text{spec}} \right] - m_{\text{in}} H_{\text{in}} \]

\[ \dot{H}_{\text{in}} = \dot{H}_{\text{spec}} \]

\[ Q = (1)(2675.6 - 419.5) = 2256.1 \text{ kJ} \]

The answer in the solution is ok, but note that the equation \( \Delta U = Q - p \Delta V \) refers to a closed system, not an open one, in which the vessel expands against the atmosphere. This viewpoint is ok, but an unlikely procedure.
22.34

\[ 2.5 \text{ kg/s} \quad T_i = 600 \text{ OC} \quad P_i = 100 \text{ kPa} \quad T_o = 1000 \text{ OC} \quad P_o = 100 \text{ kPa} \quad 2.5 \text{ kg/s} \]

Open, unsteady state system – the adiabatic turbine

\[ \Delta U = 0 \quad \dot{Q} = 0 \quad \Delta \dot{P}E = 0 \]

\[ \dot{W} = \Delta \dot{H} + \Delta \dot{K}E \]

Data from interpolating in the SI steam tables

<table>
<thead>
<tr>
<th>At 600°C and 100 kPa</th>
<th>At 400°C and 100 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 3697.9 ) (kJ/kg)</td>
<td>( 3278.2 ) (kJ/kg)</td>
</tr>
<tr>
<td>( 0.4011 ) (m³/kg)</td>
<td>( 3.103 ) (m³/kg)</td>
</tr>
</tbody>
</table>

The velocities at the inlet and outlet to the turbine are calculated from the volumetric flow rate \( \dot{m} \dot{V} = \frac{\pi d^2}{4} \cdot v \) where \( d \) is the pipe diameter. Therefore,

\[ v_i = \frac{4 \pi d \dot{V}}{\pi d^2} = \frac{(4) (2.5 \text{ kg/s}) (0.4011 \text{ m}^3/\text{kg})}{(3.14159)(0.1 \text{ m})^2} = 127.7 \text{ m/s} \]

and

\[ v_o = \frac{4 \pi d \dot{V}}{\pi d^2} = 158.0 \text{ m/s} \]

\[ \Delta \dot{K}E = \left( \frac{1}{2} \right)(2.5) \left[ 158.0^2 - 127.7^2 \right] \left( \frac{1}{100} \right) \text{kJ/s} = 10.82 \text{ kJ/s} \]

\[ \Delta \dot{H} = (2.5)(3278.2 - 3697.9) \text{kJ/s} = -1049.25 \text{ kJ/s} \]

\[ \dot{W} = -1049.25 + 10.82 = \frac{1038.4 \text{ kJ/s}}{(1038.4 \text{ kW})} \]
23.1

Any correct examples will be satisfactory for (2), (3), and (4). But for (1), liquid to solid, there are probably no examples. If any, they would be pathological cases.

23.2

Sensible heat refers to the enthalpy change when a compound goes from one temperature to another without a phase change. Latent heat is the enthalpy change that occurs during a phase transition. Generally latent heat is much greater than sensible heat.

23.3

Yes.

23.4

(1) Solid melting.

23.5

(a) 1; (b) 3; (c) 5; (d) 2; (e) 4

The boiling temperature is at 4 reading to the left scale (100°C)
The freezing temperature is at 1 reading to the left scale (0°C)

23.6

\[ \Delta U_{\text{melt}} = \Delta H_{\text{melt}} - \Delta (p \hat{V})_{\text{melt}} \]

\[ \Delta (p \hat{V}) = p(\hat{V}_{\text{solid}} - \hat{V}_{\text{liquid}}) \approx 0 \] because there is essentially no change on melting for most substances, and whatever change there is, relative to \( \Delta H_{\text{melt}} \), the \( \Delta (p \hat{V})_{\text{melt}} \) is very small.

23.7

Vapor pressure equation:

\[ \log p = \frac{-6160}{T} + 8.10, \quad (T \text{ in K}) \]

Clausius-Clapeyron equation:

\[ \frac{d (\log p)}{dT} = -\frac{\Delta H_{m}}{2.303 RT^2} \]

Differentiate the first equation:

\[ \frac{d (\log p)}{dT} = \frac{d}{dT} \left[ -\frac{6160}{T} + 8.10 \right] = \frac{6160}{T^2} \]

Equate the two equations:

\[ \frac{\Delta H_{m}}{2.303 RT^2} = \frac{6160}{T^2} \]

\[ \Delta H_m = (6160)(2.303) \quad (R) \]

\[ = \frac{1.987}{28,190 \text{ cal/g mol}} \]

\[ = \frac{8.314}{28,190 \text{ Btu/ib mol}} \]

\[ = \frac{117,950 \text{ J/g mol}}{R} \]

23.8

Equate the derivative of the Antoine equation \( (d \ln(p^*)/dT) \) to the equivalent in the Clausius - Clapeyron equation:

\[ 200^\circ F = 660^\circ R = 366.7 \text{ K} \]

\[ \frac{d p^*}{dT} = \frac{\Delta H_m}{T(\hat{V} - \hat{V}_{\text{y}})} \]

ignore \( \hat{V} \),
insert \( p \hat{V} = RT \)

\[ \frac{28,190 \text{ cal/g mol}}{R} \]
\[
\frac{dp^*}{dT} = \frac{\Delta H_s}{RT^2}
\]

\[
\frac{dp^*}{p^*} = \frac{d \ln p^*}{dT} = \frac{\Delta H_s}{RT^2}
\]

\[
\frac{d \ln p^*}{dT} = \frac{\Delta H_s}{2.3 RT^2}
\]

\[
T_k = T_c + 273
\]

Antoine eqn: \[\log_{10} p^* = 7.9046 - \frac{2366.4}{T + 230}\]

Differentiate the Antoine equation:
\[
\frac{d \log_{10} p^*}{dT} = 0 - \frac{2366.4}{(T_k - 43)^2} (-1) = \frac{\Delta H_s}{2.3(1.987)T_k^2}
\]

\[
\Delta H_s = \frac{(2.3)(8.314)(366.7)^3}{(366.7 - 43)^2} = \frac{58,070}{2.49 \times 10^4 \text{ Btu/lb mol}}
\]

23.9

\[C_6H_6 \quad \text{MW} = 78\]

Assume: \(\Delta H_s\) is constant, ideal gas

\[
\frac{dp^*}{dT} = \frac{\Delta H_s}{T(\dot{V}_s - \dot{V}_f)}
\]

\[V_s >> \dot{V}_f, \quad 35^\circ C = 308 \text{ K}\]

\[p \dot{V} = RT \quad \text{for 1 mol (basis)}\]

\[\Delta H = 841.5 - 423.8 = 417.7 \text{ J/g}\]

\[\frac{dp^*}{p^*} = \frac{\Delta H_s}{RT^2} \quad \text{or} \quad \frac{dp^*}{dT} = \frac{\Delta H_s}{p^*} \frac{dT}{T^2}\]

Integrate between 308 K and 320 K

\[
\ln \left( \frac{0.2111}{p_{350}} \right) = \frac{\Delta H_s}{R} \left[ \frac{1}{T_3 - T_1} \right] = \frac{\Delta H_s}{R} \left[ \frac{1}{308 - 320} \right]
\]

\[-1.555 - \ln p_{350} = \frac{417.7 J}{78 g} \quad \frac{0.1218 \times 10^3}{8.314 J} \quad 0.4771\]

\[p_{350} = 0.131 \text{ atm}\]

23.10

\[T_r = 540.2 \text{ K} \quad p_r = 27 \text{ atm}\]

\[\Delta H_s = \frac{0.0331 \left( \frac{T_s}{T_r} \right) - 0.0327 + 0.0297 \log (p_s)}{1.07 \left( \frac{T_s}{T_r} \right)} \quad \text{kJ} \quad \left( \text{g mol} \right) \left( \text{K} \right)\]

\[\Delta H_s = 31.679 \quad \text{kJ} \quad \text{g mol}\]

The percent error is negligible in view of the precision of the data.

23.11

From Appendix D1 the normal boiling point of benzene is at 353.26 K, \(T_s = 562.6 \text{ K}\), and \(p_r = 48.6 \text{ atm}\).

Riedel's equation is

\[
\Delta H_s = 1.093 RT_s \frac{T_s \times (\ln p_r - 1)}{0.930 - (T_s / T_r)}
\]

\[= \frac{1.093 \times 8.314 \text{ J}}{562.6 \text{ K} \times 553.26 \text{ K}} \quad \frac{[\ln (48.6) - 1]}{(\text{g mol}) (\text{K})} \]

\[= \frac{562.6 \text{ K}}{0.930 - (553.26 \text{ K} / 562.6 \text{ K})}\]

(continued)
\[ \Delta H = 30641 \text{J/g mol or } 30.64 \text{kJ/g mol} \]

The experimental value from the Appendix is 30.76 kJ/g mol.

23.12

\[ \Delta H_v = 312.13 \text{kJ/kg at } T_1 = 152.4^\circ \text{C} \; ; \; T_T = 360^\circ \text{C} \]

Molecular weight = 120

Watson Equation: \[ \Delta H_v \text{ at } 100^\circ \text{C} = 312.13 \left( \frac{360 - 100}{360 - 152.4} \right)^{2.28} = 340.3 \text{kJ/kg} \]

23.13

The following vapor pressure data are needed:

<table>
<thead>
<tr>
<th>Material</th>
<th>( T ) (°C)</th>
<th>( p ) (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>-4</td>
<td>3.280</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>3.880</td>
</tr>
<tr>
<td>Water</td>
<td>+2</td>
<td>5.294</td>
</tr>
<tr>
<td></td>
<td>+4</td>
<td>6.101</td>
</tr>
</tbody>
</table>

In the Clausius-Clapeyron equation the heat of vaporization is a function of temperature; however, if it is assumed to be independent of temperature the equation can be integrated to give

\[ \ln \left( \frac{p_{vap}(T_2)}{p_{vap}(T_1)} \right) = \frac{\Delta H_{vap}}{R \left( \frac{1}{T_2} - \frac{1}{T_1} \right)} \]

a result that is also valid over small temperature ranges when \( \Delta H_{vap} \) is temperature dependent. The integrated equation has been found to be fairly accurate for correlating the temperature dependence of the vapor pressure of liquids over limited temperature ranges.

(a) For the ice sublimating

\[ \Delta H_{vap} = \frac{\ln \left( \frac{p_{vap}(T_1)}{p_{vap}(T_T)} \right)}{R \left( \frac{1}{T_1} - \frac{1}{T_T} \right)} = \frac{\ln \left( \frac{3.880}{3.280} \right)}{R \left( \frac{1}{271.15} - \frac{1}{269.15} \right)} = 6130 \text{ K} \]

so that

\[ \Delta H_{vap} = (6130 \text{ K}) \left( 8.314 \frac{J}{(\text{g mol}) (\text{K})} \right) = 50.97 \text{ kJ/g mol} \]

(b) For the water vaporizing

\[ \Delta H_{vap} = \frac{\ln \left( \frac{p_{vap}(T_1)}{p_{vap}(T_2)} \right)}{R \left( \frac{1}{T_2} - \frac{1}{T_1} \right)} = \frac{\ln \left( \frac{6.101}{5.294} \right)}{R \left( \frac{1}{277.15} - \frac{1}{275.15} \right)} = 5410 \text{ K} \]

\[ \Delta H_{vap} = (5410 \text{ K}) \left( 8.314 \frac{J}{(\text{g mol}) (\text{K})} \right) = 44.98 \text{ kJ/g mol} \]

(c) For fusion of ice

Since

\[ \Delta H_{fus} = H(\text{vapor}) - H(\text{solid}) \]

and

\[ \Delta H_{vap} = H(\text{vapor}) - H(\text{liquid}) \]

it then follows that

\[ \Delta H_{fus} = H(\text{liquid}) - H(\text{solid}) = \Delta H_{vap} = 50.97 - 44.98 = 5.99 \text{ kJ/g mol} \]

(d) At the triple point temperature \( T_T \), the sublimation pressure of the solid and the vapor pressure of the liquid are equal; we denote this triple point pressure as \( p_T \). Use the integrated equation for both the solid and liquid phases to get

\[ \Delta H_{vap} = \frac{\ln \left( \frac{p_T}{p_{vap}(T_T)} \right)}{R \left( \frac{1}{T_T} - \frac{1}{T_T} \right)} \]

\[ \Delta H_{vap} = \frac{\ln \left( \frac{3.880}{3.280} \right)}{R \left( \frac{1}{271.15} - \frac{1}{269.15} \right)} = 6130 \text{ K} \]

so that

\[ \Delta H_{vap} = (6130 \text{ K}) \left( 8.314 \frac{J}{(\text{g mol}) (\text{K})} \right) = 50.97 \text{ kJ/g mol} \]
Solutions Chapter 23

\[ \frac{\Delta H_{\text{m}}}{R} = 6130 = -\frac{\ln \left( \frac{P_T}{P_{3,880}} \right)}{\frac{T_T}{T}} = -\frac{\ln \left( \frac{P_T}{5.294} \right)}{\frac{T_T}{275.15}} \]

and

\[ \frac{\Delta H_{\text{m}}}{R} = 5410 = -\frac{\ln \left( \frac{P_T}{P_{3,880}} \right)}{\frac{T_T}{T}} = -\frac{\ln \left( \frac{P_T}{3.880} \right)}{\frac{T_T}{275.15}} \]

The solution to this pair of equations is \( T_T = 273.3 \) K, and \( P_T = 4.63 \) mm Hg. The reported triple point is 273.16 K and 4.579 mm Hg, so the estimate is quite good.

23.14

Basis: 1.0 g of \( n-C_4H_{10} \)

Given:

\( (\text{sp.gr})_{\text{solid}} = 0.564 \text{ g/cm}^3 \)

\( \dot{V}_{\text{solid}} = \frac{1}{(0.564)(1)} = 1.77 \text{ cm}^3/\text{g} \)

\( (\text{sp.gr})_{\text{vapor}} = 6.50 \)

\( \dot{V}_{\text{vapor}} = \frac{1}{(6.50)(1.293)} = 119 \text{ cm}^3/\text{g} \)

\( \Delta H_{\text{m}} = 356.5 \text{ J/g} \)

\( \log_{10}(p) = 1.767 - \frac{1.337}{T} + 1.75 \log_{10} T - 0.004T \)

Apply the Clapeyron equation for the vapor liquid transition at 30°C

\[ \frac{dp}{dT} = \frac{\Delta H_{\text{m}}}{T \Delta V} \]

If the data is consistent it must satisfy the Clapeyron equation.

In this case

\[ \frac{\Delta H_{\text{m}}}{T \Delta V} = \frac{356.5}{(303) \Delta V} \]

\[ = \left( \frac{356.5}{g} \right) \left[ \frac{4.13 \times 10^{-4} (L)(atm)}{(303K)0.119 - 0.00177} \right] \]

\[ = \left( \frac{356.5}{(303)(0.117)} \right)^{\text{atm}} \]

\[ = 0.0995 \text{ atm/K} \]

Conclusion: The given data are not consistent.

It shows

\[ \frac{dp}{dT} > \frac{\Delta H_{\text{m}}}{T \Delta V} \]

23.15

Due to the density difference, the water had settled out at the base of the vessel below the heating oils and had remained cold while the oil was heated up to a temperature in excess of 100°C. When the agitator was started the water was brought into contact with the oil and immediately vaporized under the surface of the oil to form an enormous volume of steam.
**23.16**

Below log is \( \log_b \). The critical temperature = 408.1 K

\[ C_p = A + B \log T_c \]

Basis: 1 g mol

\[ B = \frac{C_p - C_s}{\log T_s - \log T_c} \]

\[ A = C_s - B \log T_s \]

\[ C_s = 97.3 \quad T_s = \frac{300}{408.1} = 0.735 \quad \log T_s = -0.134 \]

\[ C_s = 149.0 \quad T_s = \frac{500}{408.1} = 1.225 \quad \log T_s = 0.088 \]

\[ A = 128.5 \quad B = 232.6 \]

at 1000 K: \( T_{1000} = \frac{1000}{408.1} = 2.45 \) \( \log T_{1000} = 0.389 \)

\[ C_p = 128.5 + 232.6(0.389) = \frac{2190 J/(g \text{ mol})(K)}{227.6 - 219.0} = 3.8\% \]

**23.17**

Solution via Polymath:

\[ C_p = 34.5864 + 0.0356677 T - 7.9955 \times 10^{-4} T^2 \]

\[ C_p = 34.8264 + 0.0326495 T - 1.45 \times 10^{-6} T^2 + 3.6363 \times 10^{-9} T^3 \]

The heat capacity equation for NH3 gas from Appendix E is

**23.18**

A second order fit is only good above 300°C. As a guide for an answer:

\[ C_p = 8.3510 + 7.9981 \times 10^{-3} T - 1.5055 \times 10^{-6} T^2 \]

and

\[ C_p = 8.4017 + 7.0601 \times 10^{-3} T + 1.0567 \times 10^{-6} T^2 - 1.5981 \times 10^{-9} T^3 \]

with average deviations of 0.55% and 0.36% and maximum deviations of 1.48% and 0.91%.

**23.19**

Equation is

\[ C_p = 36.7 + 0.0403T - 0.0000221 T^2 \]

**23.20**

To convert \( J/(g \text{ mol})(°C) \) to Btu/(lb mol)(°F)

\[ \frac{J}{(g \text{ mol})(°C)} \times \frac{1 \text{ cal}}{1 \text{ Btu}} \times \frac{454 \text{ g}}{1 \text{ lb}} \times \frac{1 \text{ (°C)}}{1 \text{ (°F)}} \times \frac{4.184 \text{ J}}{1 \text{ cal}} \times \frac{252 \text{ cal}}{1 \text{ Btu}} \times \frac{1 \text{ (°F)}}{1 \text{ (°C)}} \]

Hence the right hand side of the heat capacity equation has to be multiplied by 1/4.184.

To convert the temperatures in °C to °F, substitute

\[ T_{°C} = \frac{T_{°F} - 32}{1.8} \]

\[ C_p \left( \frac{\text{Btu}}{(\text{lb mol})(°F)} \right) = 17.20 + 4.80 \times 10^{-2} \left( \frac{T_{°F} - 32}{1.8} \right) \]

\[-3.054 \times 10^{-5} \left( \frac{T_{°F} - 32}{1.8} \right)^2 + 8.303 \times 10^{-9} \left( \frac{T_{°F} - 32}{1.8} \right)^3 \]
23.21

a. \( T_K = T_C + 273.2 \) so that
\[
C_p = 6.39 + 1.76 \times 10^{-3} (T_C + 273.2) - 0.26 \times 10^{-6} (T_C + 273.2)^2
\]
\[
C_p = 6.852 + 1.62 \times 10^{-3} T_C - 0.26 \times 10^{-4} T_C^2
\]

b. \( T_C = (T_F - 32)/1.8 \)

Multiply the whole equation above by 1/29 to get Btu/(lb)(°F) and insert \( T_C = \frac{T_F - 32}{1.8} \)

\[
C_p = \frac{6.892 \text{ cal}}{(\text{g mol}) (\text{°C})} \left[ \frac{1 \text{ Btu}}{1 \text{ lb mol}} \right] \left[ \frac{1 \Delta \text{ °C}}{29 \text{ lb}} \right]
\]
\[
\Delta H = \Delta \tilde{U} - \Delta (\tilde{V}) = (16.660 - \Delta H_{ref}) \left( \rho_{600 \text{ kPa}} \tilde{V}_{600 \text{ kPa}, 283.5K} - \rho_{ref} \tilde{V}_{ref} \right)
\]

If the reference for CO2 is saturated liquid at 233K, \( \Delta H_{ref} = 0 \text{ kJ/g mol} \). If the reference is at the triple point of CO2, the enthalpy calculated is in error.

23.23

No. The enthalpy and internal energy must be **changes**, and each has a reference point. The calculation should be

\[
\Delta \tilde{U} = \Delta \tilde{H} - \Delta (\tilde{V}) = \left( 16.660 - \Delta \tilde{H}_{ref} \right) \left( \rho_{600 \text{ kPa}} \tilde{V}_{600 \text{ kPa}, 283.5K} - \rho_{ref} \tilde{V}_{ref} \right)
\]

23.24

Differentiate the enthalpy equation

\[
\frac{d(H)}{dT} = C_p = 92.38 + 3.754 \times 10^{-3} T - \frac{2.186 \times 10^6}{T^2}
\]

23.25

Not valid, because introduction of \( T = 298 \) into the equation does not yield \( H(298) - H(298) = 0 \).

23.26

Basis: 1 kg mol \( \text{O}_2 \)

\[
\text{O}_2(\ell) \quad \Delta H_{vap} \quad \text{O}_2(g) \\
\text{stand.} \\ 93.19K \\
1.5 \text{ atm}
\]

\[
\Delta H_{vap} = 6.820 \text{ kJ/g mol}
\]

\[
\Delta H = 6.820 \text{ kJ} + \left[ 7.104(80.6 - (-297.7)) \right] + \frac{0.0785 \times 10^{-7}}{2}
\]

\[
99.5 \text{ cal} + 0.0553 \times 10^{-3} \text{ cal} = 0.0553 \text{ cal} \times 298 \text{ kcal/mole} = \text{Btu}
\]
23.27
\[
\Delta H = 2 \int_{298}^{273} (27.32 + 0.6226 \times 10^{-2} T - 0.0950 \times 10^{-3} T^2) dT
\]
\[
\Delta H = 11,980 \text{ J} \quad (\text{The CD gives 11,784 J})
\]

23.28
Integrate the heat capacity equation, or interpolate in Table D6 in the Appendix. From the latter (easier)
\[
\Delta H = -5 \times 10^6 (29,154 - 9,665) = -97,445 \text{ kJ}
\]

23.29
Integrate the heat capacity equation, use Table D5 in the Appendix, or use CD
From the CD \(\Delta H = 5789 \text{ J/g mol}\)

23.30
Integrate the heat capacity equation, use Table D3 in the Appendix, or use CD
From the CD \(\Delta H = 2580 \text{ J/g mol}\)

23.31
The volume of the wire is \(\frac{\pi d^2}{4}\) \(5.5 = \pi \frac{(0.25)^2}{4} = 0.27 \text{ cm}^3\). The density of Al is 19.35 g/cm³, so 19.35(0.27) = 5.22g or 0.194 g mol Al. From Perry, \(C_p = 20.0 + 0.0135T\) (T in K, \(C_p\) in J/g mol)°C) and \(\Delta H_{fus} = 10,670 \text{ J/g mol at 660}^\circ\text{C}\).

\[
\Delta H = 0.194 \left[ \frac{560 \times 273}{25+273} \right] = \left(20.0 + 0.0135 \times T\right) \times 10,670 = 5560 \text{ J}
\]

\[
5560 \times 2.773 \times 10^{-7} = 1.54 \times 10^{-3} \text{ kWh}
\]

23.32
Basis: 1 g mol
Integrate the respective \(C_p\) equations in the appendix or use the CD. Multiply the resulting J/g mol by 0.80 and 0.20 for \(CH_4\) and \(C_2H_6\), respectively.
Result using the CD: \(2.88 \times 10^2 \text{ J/kg mol}\)

23.33
Basis: 100 mol gas

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>68</td>
</tr>
<tr>
<td>H₂</td>
<td>30</td>
</tr>
<tr>
<td>CO₂</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

\(\Delta H\) (J/g mol) relative to 0°C and 1 atm

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>H₂</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>298 K</td>
<td>728</td>
<td>718</td>
</tr>
<tr>
<td>1500 K</td>
<td>39,576</td>
<td>36,994</td>
<td>62,676</td>
</tr>
<tr>
<td>1400°C</td>
<td>45,723</td>
<td>42,724</td>
<td>72,896</td>
</tr>
<tr>
<td>1750 K</td>
<td>48,459</td>
<td>45,275</td>
<td>77,445</td>
</tr>
</tbody>
</table>
Solutions Chapter 23

\[ \frac{1000 \text{ m}^3}{1673 \text{ K}} \cdot \frac{273 \text{ K}}{22.4 \text{ m}^3} = 7.28 \text{ kg mol} \]

**Calculation of \( \Delta H \):**

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \text{kg mol} )</th>
<th>( \Delta H ) (kJ/kg mol)</th>
<th>( \Delta H ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>7.28 (68)</td>
<td>-44.995</td>
<td>-222,743</td>
</tr>
<tr>
<td>H(_2)</td>
<td>7.28 (30)</td>
<td>-42.010</td>
<td>-91,750</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>7.28 (02)</td>
<td>-71.984</td>
<td>-10,481</td>
</tr>
</tbody>
</table>

\[ \Delta H = \sum \Delta H \text{ (kJ/kg mol)} \cdot \text{kg mol} \]  

\[ \Delta H = 7.28 \times \sum \Delta H \text{ (kJ/kg mol)} \]  

\[ \Delta H = 7.28 \times (7.28 \times 30 + 7.28 \times -355.5 + 7.28 \times -755) \]  

\[ \Delta H = 7.28 \times (222.743 + 91.750 - 10,481) \]  

\[ \Delta H = 7.28 \times -9,290 \]  

\[ \Delta H = -67,290 \text{ kJ} \]

\[ \text{From Table D.1 in the Appendix.} \]

**Benzene Properties:**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mol. wt.</td>
<td>78.11</td>
</tr>
<tr>
<td>Boiling point</td>
<td>353.26 K</td>
</tr>
<tr>
<td>Melting point</td>
<td>278.69 K</td>
</tr>
<tr>
<td>( \Delta H )_fusion</td>
<td>984 kJ/g mol</td>
</tr>
</tbody>
</table>

\[ \Delta H \text{ (fusion)} = 984 \text{ kJ/g mol} \]

\[ \text{K} \quad ^\circ \text{C} \]

<table>
<thead>
<tr>
<th>K</th>
<th>^\circ C</th>
</tr>
</thead>
<tbody>
<tr>
<td>423</td>
<td>150</td>
</tr>
<tr>
<td>353.3</td>
<td>80.1</td>
</tr>
<tr>
<td>278.7</td>
<td>5.5</td>
</tr>
</tbody>
</table>

**Heat Capacity Equation Coefficients:**

\[ \Delta H = \int (74.06 + 32.95 \times 10^{-2} T - 25.20 \times 10^{-5} T^2 + 77.57 \times 10^{-9} T^3) dT = -11,790 \text{ J/g mol} \]

**Condensation:**

\[ \Delta H = -3.076 \times 10^7 \text{ J/g mol} \]

**Liquid:**

\[ \Delta H = \int (62.55 + 23.36 \times 10^{-2} T) dT = -10,180 \text{ J/g mol} \]

**Fusion:**

\[ \Delta H = -9.84 \times 10^7 \text{ J/g mol} \]
Solid

From Perry, 5th edition:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Solid C_p (J/(g°C))</th>
<th>Solid C_p (J/(g mol°C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>0.375</td>
<td>12.3</td>
</tr>
<tr>
<td>-50°C</td>
<td>0.299</td>
<td>97.7</td>
</tr>
</tbody>
</table>

If a linear relationship exists between C_p and T,

\[ C_p = 119 \text{ J/(g mol°C)} \]

\[ \Delta H = \int_{T_1}^{T_2} (119) dT = -30.76 \text{ kJ/mol} \]

\[ \Delta H = \sum_{i=1}^{n} \Delta H_i = -65.604 \text{ kJ/mol} \]

\[ \frac{-65.604 \text{ kJ/mol}}{1000 \text{ g mol/78.11 kg}} = \frac{-8.40 \times 10^7 \text{ J/kg}}{ \text{kg} } \]

23.37

Basis: 1 lb mol

6.00 lb mol gaseous H_2O, 4.00 lb mol CO_2

Heated from 60°F (15.6°C) to 600°F (315.6°C)

From appendix E for H_2O:

\[ \Delta H = \int_{15}^{315} (33.46 + 0.6880 \times 10^{-2} T + 0.7604 \times 10^{-3} T^2 - 3.593 \times 10^{-9} T^3) dT \]

\[ \Delta H = 33.46 (315.6 - 15.6) + \frac{0.6880 \times 10^{-2}}{2} (315.6^2 - 15.6^2) \]

\[ + \frac{0.7604 \times 10^{-3}}{3} (315.6^3 - 15.6^3) - \frac{3.593 \times 10^{-9}}{4} (315.6^4 - 15.6^4) \]

\[ \Delta H = 1.045 \times 10^4 \text{ J/g mol} \]

\[ \text{Put } \frac{1.045 \times 10^4 \text{ J}}{454 \text{ g mol}} \times \frac{9.484 \times 10^4 \text{ Btu}}{1 \text{ lb mol}} = 4.499 \times 10^3 \text{ Btu/lb mol} \]

For CO_2 in Btu/(lb mol)(°F):

\[ \Delta H = \int_{60}^{2125} (8.448 + 0.5757 \times 10^{-2} T - 0.2159 \times 10^{-5} T^2 + 0.3059 \times 10^{-9} T^3) dT \]

(continued)
23.38

Basis: liquid water at 32°F and 1 atm

a. \[ \Delta H = 3 (\Delta H_{300°F,1 \text{ atm}} - \Delta H_{32°F,1 \text{ atm}}) = 3 (1192 - 0) = 3576 \text{ Btu} \]

b. Basis: liquid water at 40°F and 60 psia

\[ \Delta H_{32°F,60 \text{ psia}} = 0 \quad \Delta H = 3 \times 1192 = 3576 \text{ Btu} \]

c. Basis: liquid water 40°F and 60 psia

\[ \Delta H = \left( \Delta H_{300°F,60 \text{ psia}} - \Delta H_{40°F,60 \text{ psia}} \right) = (1181.4 - 8.05) = 1173.4 \text{ Btu} \]

d. Basis: water-steam mixture of 60% quality

<table>
<thead>
<tr>
<th>State</th>
<th>( \Delta H ), Btu/lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60% steam - 40% water at 300°F; sat’d steam</td>
</tr>
<tr>
<td>2</td>
<td>80% steam - 20% water at 300°F; water</td>
</tr>
</tbody>
</table>

\[ \Delta H = \Delta H_2 - \Delta H_1 \]

\[ \Delta H_2 = (0.80) (1179.7) + (0.20) (269.6) = 998 \text{ Btu/lb} \]

\[ \Delta H_1 = (0.60) (1179.7) + (0.40) (269.6) = 816 \text{ Btu/lb} \]
(i) A 2.5 ft³ tank of water at 160 psia and 363.5°F at 160 psia and 636.5°F total volume is occupied by steam.

\[ V_{\text{steam}} = 2.834 \text{ ft}^3 / \text{lb} = m_{\text{steam}} = \frac{2.5}{2.834} = 0.88 \text{ lb} \]

\[ V_{\text{Liq/water}} = 0.0182 \text{ ft}^3 / \text{lb} = m_{\text{water}} = (1-m_{\text{steam}}) \]

\[ V_{\text{water}} = \frac{2.5}{2.834} \times 0.0182 = 0.016 \text{ ft}^3 \]

\[ V_{\text{steam}} = 2.5 - 0.016 = 2.49 \text{ ft}^3 \]

Of 5 lb H₂O assume x lb is sat steam (5-x)lb is sat. water

\[ x(2.834) + (5-x)(0.0182) = 2.5 \]

\[ x(2.834 - 0.0182) = 2.5 - 5(0.0182) \]

\[ x = \frac{2.5 - 0.0910}{2.816} = 0.86 \text{ lb} \]

(Yes, it is possible)

(k) Enthalpy of 10 lb steam @ 100 psia = 9000 Btu

Enthalpy/lb steam @ 100 psia = 900 Btu

\[ \Delta H_{\text{steam}} @ 100 \text{ psia} = 1187.3 \text{ Btu} \]

\[ \Delta H_{\text{water}} @ 100 \text{ psia} = 298.43 \text{ Btu} \]

Let x be fraction of steam

\[ (1-x) \text{ is fraction of water} \]

\[ (1187.3)x + (1-x)298.43 = 900 \]

\[ x(1187.3 - 298.43) = 900 - 298.43 \]

\[ x = \frac{601.57}{888.87} = 0.68 \text{ or } 68\% \]

Solutions Chapter 23

23.39

State 1

\[ T = 400 \text{ K} \]

\[ p = 100 \text{ kPa} \]

State 2

\[ T = 900 \text{ K} \]

\[ p = 100 \text{ kPa} \]

a. From the steam tables in SI units (interpolation required):

\[ (1) \quad \Delta H_1 = 2729.8 \text{ kJ/kg} \quad (2) \quad \Delta H_2 = 3763.6 \text{ kJ/kg} \]

\[ \Delta H = 3763.6 - 2729.8 = 1033.8 \text{ kJ/kg} \]

\[ \frac{1033.8 \text{ kJ}}{18 \text{ kg mol}} \cdot \frac{2 \text{ kg mol}}{2 \text{ kg mol}} = 5.7217 \times 10^4 \text{ kJ/kg mol} \]

b. Using the table for the enthalpies of combustion gases:

\[ (1) \quad \Delta H = 4284 \text{ J/g mol} \quad (2) \quad \Delta H = 22,760 \text{ J/g mol} \]

\[ \Delta H = 22,760 - 4284 = 18.48 \times 10^4 \text{ J/g mol} = 18.48 \times 10^4 \text{ J/kg mol} \]

\[ \frac{1.1848 \text{ kJ}}{2 \text{ kg mol}} \cdot \frac{3.695 \times 10^4 \text{ J/kg mol}}{2 \text{ kg mol}} = 5.695 \times 10^4 \text{ J/kg mol} \]

c. Using the heat capacity equation for steam:

\[ \Delta H = \int_{1173}^{273} C_p \text{ d}T = \int_{0}^{x} (33.46 + 0.6880 \times 10^{-2} \cdot T + 0.7604 \times 10^{-5} \cdot T^2) \text{ d}T 

- 3.593 \times 10^{-9} \cdot T^3 \text{ d}T \]

\[ = 33.46(900 - 400) + \frac{0.6880 \times 10^{-2}}{2} (900^2 - 400^2) 

+ \frac{0.7604 \times 10^{-5}}{3} (900^3 - 400^3) - \frac{3.593 \times 10^{-9}}{4} (900^4 - 400^4) \]

\[ = 20,085 \text{ J/g mol} = 20,085 \text{ kJ/kg mol} \]

(continued)
23.40

Basis: 5 ft$^3$ vessel  
Vapor = 4 ft$^3$, Liquid = 1 ft$^3$

Steam tables: Sat'd steam at 1000 psia

\[
\begin{align*}
V_v &= 0.44596 \text{ ft}^3/\text{lb} \\
V_l &= 0.02159 \text{ ft}^3/\text{lb}
\end{align*}
\]

\[
\begin{align*}
m_v &= \frac{4 \text{ ft}^3}{0.44596 \text{ ft}^3/\text{lb}} = 8.97 \\
m_l &= \frac{1 \text{ ft}^3}{0.02159 \text{ ft}^3/\text{lb}} = 46.32 \\
m_t &= m_v + m_l = 55.29
\end{align*}
\]

Quality = 0.162

23.41

We will use the steam tables for this problem.

Basis: 1 lb of H$_2$O at 60°F

From steam tables (ref. temp. = 32°F):

\[
\begin{align*}
\hat{H}_v &= 28.07 \text{ Btu/lb at 60°F} \\
\hat{H}_l &= 1604.5 \text{ Btu/lb at 1150°F and 240 psig (254.7 psia)} \\
\Delta \hat{H} &= (1604.5 - 28.07) = 1576.4 \text{ Btu/lb} \\
\Delta \hat{H} &= 1576(8.345) = 13150 \text{ Btu/gal}
\end{align*}
\]

Note: The enthalpy value which has been used for liquid was taken from the steam tables for the saturated liquid under its own vapor pressure. Since the enthalpy of liquid water changes negligibly with pressure, no loss of accuracy is encountered for engineering purposes if the initial pressure on the water is not stated.

23.42

Basis: 3 kg H$_2$O

The initial conditions are obtained from the SI steam tables for saturated liquid. Enthalpy is a function of the temperature and pressure, but the effect of pressure on liquid water under these conditions is negligible. Therefore the enthalpy of water at 300K and 101.3 kPa can be approximated by the enthalpy of saturated water at the same temperature but at the vapor pressure of 3.536 kPa.

The final conditions are presumably a state in which water is all vapor. A check of the steam tables show this assumption to be true.

At

<table>
<thead>
<tr>
<th>T(K)</th>
<th>p(kPa)</th>
<th>$\Delta \hat{H}(\text{kJ/kg})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>3.536</td>
<td>111.7</td>
</tr>
<tr>
<td>800</td>
<td>1500</td>
<td>3384.3</td>
</tr>
</tbody>
</table>

The enthalpy change is

\[\Delta \hat{H} = \frac{3 \text{ kg} \times (3384.3 - 111.7) \text{ kJ}}{\text{kg}} = 9817.8 \text{ kJ}\]

23.43

Steady state flow process, no reaction

\[
\begin{align*}
700 \text{ kPa} & \quad \rightarrow \quad \text{Dry steam, 100 kPa and 125°C} \\
\text{wet steam} & \quad \rightarrow \\
\Delta \hat{H} &= ? \quad \Delta \hat{H} = 2725.5 \text{ kJ/kg}
\end{align*}
\]

The energy balances reduces to $\Delta \hat{H} = 0$ for this process. At 700 kPa saturated (438.1K)

\[\Delta \hat{H}_v = 696.7 \text{ kJ/kg} \quad \Delta \hat{H}_l = 2763.1 \text{ kJ/kg}\]

Let $x =$ vapor fraction

\[0.97(696.7) + 0.03(2763.1) = 725.4\]

$x = 0.98$
23.44

Basis: 30 m³ at 101.3 kPa and 1100K

Use \( pV = nRT \) to calculate the number of moles

\[
n = \frac{pV}{RT} = \frac{101.3 \text{ kPa} \times 30 \text{ m}^3}{1100 \text{ K} \times 8.314 \text{ kPa} \text{ m}^3 / \text{kg mol K}} \times 1000 \text{ g mol}^{-1}
\]

\[
n = 332.3 \text{ g mol}
\]

<table>
<thead>
<tr>
<th>Compound</th>
<th>( % )</th>
<th>( g \text{ mol} )</th>
<th>( \Delta H(\text{J/mol}) )</th>
<th>( \text{Final} 1100K )</th>
<th>( \text{Initial} )</th>
<th>( \Delta H(J) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( O_2 )</td>
<td>6.2</td>
<td>20.6</td>
<td>790</td>
<td>26,940</td>
<td>16,274</td>
<td>554,964</td>
</tr>
<tr>
<td>( H_2O )</td>
<td>1.0</td>
<td>3.3</td>
<td>905</td>
<td>31,011</td>
<td>2987</td>
<td>102,336</td>
</tr>
<tr>
<td>( CO_2 )</td>
<td>12.3</td>
<td>40.9</td>
<td>986</td>
<td>39,802</td>
<td>40,327</td>
<td>1627902</td>
</tr>
<tr>
<td>( N_2 )</td>
<td>80.5</td>
<td>267.5</td>
<td>786</td>
<td>25,472</td>
<td>210,255</td>
<td>6813760</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>332.3</td>
<td></td>
<td>269,843</td>
<td>9,098,963</td>
<td></td>
</tr>
</tbody>
</table>

\( \Delta H = \Delta H_{\text{final}} - \Delta H_{\text{initial}} = -8829 \text{ kJ} \)

23.45

The amount of energy that the water gives up in cooling to 0°C is not enough to melt all the ice, since each gram of water will give up 209 J in cooling, while heating 1 g of ice to 0°C and melting it requires that 2 \( \times \) 40 \( \times \) 355 = 415 J be expended (the heat capacity of ice is \( 2.1J/(g°C) \)).

23.46

[Yes] 40°F and saturated liquid is an arbitrary reference state for enthalpy that can be assigned a value of zero. Only enthalpy changes can be computed using the chart; the enthalpy itself cannot be determined.

23.47

23.48

Basis: 1 lb CO₂

Ref. is -40°F satd. liquid

\[
\Delta U = \Delta H - \Delta (pV) = (\Delta H_{\text{final}} - \Delta H_{\text{initial}}) - [(pV)_{\text{final}} - (pV)_{\text{initial}}]
\]

\[
\Delta (pV) = \frac{40 \text{ lb}}{\text{in}^2} \cdot \frac{3.2 \text{ ft}^3}{\text{in}^3} \cdot \frac{144 \text{ in}^3}{1 \text{ ft}^3} \cdot \frac{Btu}{(778 \text{ ft})(1lb)} = 100 \text{ lb} \cdot \frac{0.0148 \text{ ft}^3}{\text{lb}} \cdot \frac{144 \text{ in}^3}{\text{ft}^3} \cdot \frac{Btu}{(778 \text{ ft})(1lb)}
\]

\[
= 23.69 \cdot 0.44 = 23.25 \text{ Btu/lb}_w
\]

\[
\Delta U = (161) - 23.25 = 138 \text{ Btu}
\]
23.49

Basis: 1 g mol CO₂

\[ \Delta H = m \left[ \frac{100c}{75c} (a + bT + cT^2 + dT^3) \right] \]

\[ \Delta H = m \left[ a(100 - 50) + \frac{b}{2}(100^2 - 50^2) + \frac{c}{3}(100^3 - 50^3) + \frac{d}{4}(100^4 - 50^4) \right] \]

\[ \Delta H = 1 \text{ g mol} \left[ \frac{36.11(100 - 50) + 4.233 \times 10^{-2} (100^2 - 50^2) - 2.887 \times 10^{-1} (100^3 - 50^3) + 7.464 \times 10^{-4} (100^4 - 50^4)}{2} \right] \]

\[ \Delta H = 1956 \text{ J} \]

From the CO₂ chart \( \Delta H \approx 198-178 = 20 \text{ Btu/lb or 2040 J/g mol.} \) From the enthalpy tables (interpolating) \( \Delta H = 1957 \text{ J/g mol.} \) The CD gives 2038 J/g mol.

23.50

\[ \Delta H = 10(\Delta H_1 - \Delta H_2) = 10(86 - 288) = -2020 \text{ Btu}. \] The CD gives -1962 J.

23.51

Assume the temperature is 80°F, and the propane is saturated liquid and vapor. The corresponding pressure is the saturation pressure, namely about 2.3 atm. Another temperature would correspond to another pressure. After 80% of the propane is used, the conditions are still saturated liquid-vapor mixture at 80°F and 2.3 atm.
24.1

(1) System is the tank

(2) Closed, unsteady state process

(3) The 8 lb H₂O occupy 0.129 ft³ hence the rest of space is vapor.

We will ignore the initial vapor (see note at end of solution)

Basis: 8 lb H₂O

Initial data for H₂O are (saturated liquid)

\[ T = 100^\circ F \]
\[ \dot{V} = 0.01613 \text{ ft}^3/\text{lb} \]
\[ p = 0.9487 \text{ psia} \]
\[ \Delta H = 67.97 \text{ Btu/lb if neglect vapor} \]

Basis: 1 hr

The energy balance is

\[ \Delta E = \Delta U + \Delta PE + \Delta KE \]
\[ \Delta U = W = \Delta H - \Delta(pV) \]
\[ \Delta E = Q - W - \Delta H - \Delta PE - \Delta KE \]

(4) \[ W = 0.25 \text{ hp} \times 0.7068 \text{ Btu} \times 3600 \text{ s} \times \frac{1 \text{ hr}}{1 \text{ (hp)} (6) \text{ hr}} = 636 \text{ Btu} \]

This proves to be negligible quantity

(5a) \[ 636 = \Delta H_{\text{sat}} \text{ (8) - 2 ft}^3 \left[ \left( p_{\text{sat}} - 0.9487 \right) \frac{\text{lb}}{\text{in}^2} \right] \times 44 \text{ in}^2 \times \frac{1 \text{ Btu}}{748 \text{ ft}^3(\text{lb})(\text{in})} \]

(6) Since \( p_{\text{sat}}, \dot{V}_{\text{sat}}, \text{ and } \Delta H_{\text{sat}} \text{ are in the tables, you have to get a } \Delta H_{\text{sat}} \text{ and } \dot{V}_{\text{sat}} \text{ vapor given an assumed } p_{\text{sat}} \text{ that satisfy the equation. } \Delta H_{\text{sat}} \text{ will be composed of saturated liquid and vapor. } \Delta H_{L} (8-\text{m}) + \Delta H_{v}(\text{m}) = \Delta H_{\text{sat}} \text{ m = lb vapor. } \]

(7b) \[ 2 \text{ ft}^3 = \dot{V}_{L}(8-\text{m}) + \dot{V}_{v}(\text{m}) \]

\[ \dot{V}_{L}, \dot{V}_{v}, \Delta H_{L}, \Delta H_{v}, \text{ and } p \text{ final are all related in the steam tables. } \]

* \( \dot{V} \) of saturated vapor = 350.8 ft³/ lb so that 1.87 ft³ represents 0.0053 lb, a negligible amount relative to 2 lb.

24.2

(1) The system is the mixing point of the 1000°F "air" and water at 70°F

(2) Open system

(3) and (4)

The enthalpies of water come from the steam tables. The properties of air come from the tables in Appendix D7 (with interpolation). The reference temperature for the enthalpy is 32°F.

(5) \[ \Delta E = \Delta U + \Delta PE + \Delta KE \text{ in the tables} = Q + W - \Delta H - \Delta PE - \Delta KE \]

* 0 because steady state (continued)
24.3
You can write one material balance for each unit and one energy balance for each unit, or a total of 6. You can write numerous equations but only 6 are independent.

24.4
The equation is

\[ \Delta E = \Delta(U + PE + KE)_{\text{total}} = Q + W - \Delta(H + PE + KE)_{\text{flow}} \]

(a) \( W = 0 \)
(b) \( Q = 0 \)
(c) \( \Delta(KE)_{\text{flow}} = 0 \)
(d) \( \Delta PE = 0 \)

24.5
The exit enthalpies are all the same since the states of \( p \) and \( T \) are the same. The turbine is the only process that yields work.

24.6
a. \( (E_2 - E_1) = -\Delta[H + KE + PE]_m \) + \( Q + W \) for all parts of this problem

1. Ignore \( \hat{PE} \); \( \Delta \hat{PE} = 0 \)
2. \( \Delta \hat{KE} \) is small so \( \Delta \hat{KE} = 0 \) (or it can be included)
3. No reaction
4. \( W = 0 \)
5. \( (E_2 - E_1) = 0 \); steady state

\[ \Delta H = Q \]

b. 1. Ignore \( \hat{PE} \); \( \Delta \hat{PE} = 0 \)
2. No reaction
3. \( W = 0 \)
4. \( (E_2 - E_1) = 0 \); steady state
5. \( Q = 0 \)

\[ -\Delta[H + KE]_m = 0 \]

(c). 1. Ignore \( \hat{PE} \); \( \Delta \hat{PE} = 0 \)
2. $\Delta \dot{KE} = 0$

3. No reaction

4. $(E_2 - E_1) = 0$; steady state

5. $Q = 0$ (assume)

$$\Delta H = W$$

d. 1. Ignore $\dot{PE}$; $\Delta \dot{PE} = 0$

2. No reaction

3. $(E_2 - E_1) = 0$; steady state (may be not the $\dot{KE}$)

4. $Q = 0$ (assumed)

$$\Delta [\dot{H} + \dot{KE}] = W$$

24.7

General balance is

$$\Delta E = [\Delta U + \Delta KE + \Delta PE]_{\text{Ideal}} + \Delta [\dot{H} + \dot{KE} + \dot{PE}] = -Q + W$$

(1) (2) (3) (4) (5) (6) (7) (8)

Assume all reactants are in bomb at start of reaction.

---

**Diagram a.**

- $Q$
- $W$

**Diagram b.**

- Fuel
- $Q$
- $W$

Result: $\Delta H = Q + W$
### Solutions Chapter 24

24.8

Closed, unsteady state process

- **Basis:** 10 lb steam @ 300 psia and 480°F
- **Q + W = ΔU** for the closed system. **W = 0**

$$\Delta H = 1246.6 \text{ Btu/lb}$$

\[ \dot{V} = 1.7164 \text{ ft}^3/\text{lb} \]

\[ \dot{U} = 1150.38 \text{ Btu/lb} \]

After cooling to 30 psia, the steam is saturated and liquid forms. Thereafter the steam proceeds at constant total and specific volume.

Ignore the volume of the liquid. Final conditions are 30 psia and 17.164 ft\(^2\) for the residual vapor

\[ \Delta H_1 = 218.33 \text{ Btu/lb} \]

\[ \dot{V}_L = 0.0170 \text{ ft}^3/\text{lb} \]

\[ \dot{U}_L = 218.81 \text{ Btu/lb} \]

\[ \Delta H_v = 1164.0 \text{ Btu/lb} \]

\[ \dot{V}_v = 13.763 \text{ ft}^3/\text{lb} \]

\[ \dot{U}_v = 1087.3 \text{ Btu/lb} \]

---

24.9

Unsteady state, closed, isothermal process at 25°C

- **Basis:** 1 kg CO\(_2\)

\[ p_1 = 550 \text{ kPa} \]

\[ T_1 = 25^\circ \text{C} \]

\[ p_2 = 3500 \text{ kPa} \]

\[ T_2 = 25^\circ \text{C} \]

From CO\(_2\) chart

\[ \Delta H = 205 \text{ kJ/kg} \]

\[ \Delta H_1 = 170 \text{ kJ/kg} \]

(continued)
Energy balance

\[ \Delta E = \Delta(U + PE + KE)_{\text{total}} = Q + W - \Delta(H + PE + KE) \]

\[ \Delta U = Q + W = \Delta H = -z \Delta(pV) - W \]

\[ \Delta H = (170 - 205)(l) = -35kJ \]

\[ W = 4.106 \text{ kJ} \]

\[ \Delta(pV) = \left[ \frac{3500 \text{ kPa}}{0.0125 \text{ m}^3/\text{kg}} - \frac{550 \text{ kPa}}{0.10 \text{ m}^3/\text{kg}} \right] \left[ 10^7 \frac{\text{N}}{\text{m}^2} \frac{\text{m}^3}{\text{kg}} \frac{\text{m}}{1 \text{ kPa}} (N)(N/m) \right] = -11.25 \text{ kJ} \]

\[ Q = (-35) - (-11.25) - 4.106 = 27.86 \text{ kJ/kg CO}_2 \]

\[ \text{removed} \]

24.10

This is an unsteady-state closed process. The energy balance reduces to

\[ \Delta E = \Delta U + \Delta PE + \Delta KE = Q + W \quad \Delta PE = \Delta KE = 0 \]

\[ Q = \Delta U = U_{f2} - U_i = \Delta H = -z \Delta(pV) = \Delta H - (p_2V_2 - p_iV_i) \]

where 2 (327.8°F) is the final state and 1 (406°F) is the initial state

Get the data from the CD in the back of the book. The final state is saturated conditions. \( \dot{U} \) and \( \dot{H} \) are in Btu/lb and \( \dot{V} \) is ft³/lb.
For the system of the air

\[ Q + W = \Delta E = \Delta U + \Delta P + \Delta K = \Delta H - \Delta (pV) \]

For the water:

\[ Q = \Delta H = \Delta (pV) \] but \( \Delta (pV) \) is negligible for liquid water so that

\[ Q = \Delta H = \int_c^H \frac{C_p dT}{T} = C_p(T + 2.3 - T) \] for constant \( C_p \).

(or use the steam tables)

\[ C_p = 8.0 \text{ Btu/(lb mol)(}^\circ \text{F)} \]

\[ Q = 8.0 \frac{\text{Btu}}{\text{lb mol}} \times \frac{2.3 \times 1 \text{ lb mol H}_2\text{O}}{18 \text{ lb H}_2\text{O}} \times 5 \text{ lb H}_2\text{O} = 5.11 \text{ Btu} \]

Q is removed from the air, so for the system comprised of the air, \( Q = -5.11 \text{ Btu} \).

For the system of the air

\[ W = \frac{12,500(\text{ft})(\text{lb} \text{y})}{0.0012854 \frac{\text{Btu}}{\text{ft} \text{y}}} = 16.07 \text{ Btu} \]

\( W \) is positive when the surroundings do work on the system of the air.

---

Basis: 3 ft\(^3\) air (not essential)

\[ \Delta U = -5.11 \text{ Btu} + 16.07 \text{ Btu} = 10.96 \text{ Btu} \]

---

24.12

Closed system

The system initially is like the figure, but since \( p_A > p_B \), the plug moves to the right. The energy balance here is \( Q + W = \Delta E = \Delta U \). Since \( Q = 0 \) and \( W = 0 \), \( \Delta U = 0 \). \( \Delta P E \) and \( \Delta KE \) = 0.

---

24.13

Closed system

The energy balance reduces to \( Q + W = \Delta E = \Delta U + \Delta P E + \Delta KE \)

\( Q = 0, W = 0, \Delta P E = 0, \Delta KE = 0 \), hence \( \Delta U = 0 \).

---

24.14

Steps 1, 2, 3 and 4

Get the needed properties from the CO\(_2\) chart or tables (Be sure to use the same reference value). Let \( m_{CO_2} \) be the mass of CO\(_2\) in the cylinder at the final state, \( V \) is the specific volume, \( \dot{U}_{int} \) is the specific internal energy of the CO\(_2\) at the end of the filling, and \( \dot{H}_m \) is the specific enthalpy of the CO\(_2\) in the pipeline.

(continued)
At 200 psia, 40°F, $\dot{H} = 153$ Btu/lb and $V = 0.57$ ft$^3$/lb

**Step 5**

**Basis:** 3 ft$^3$ of CO$_2$ @ 200 psia (final conditions)

**System:** The cylinder (open system, unsteady state)

**Steps 6 and 7:**

**Unknowns:** $\dot{V}_{CO_2}, m_{CO_2}, T_{CO_2}$

**Equations:** energy balance, enthalpy chart

We need two points on the $p-\dot{H}$ chart to fix the conditions in the cylinder. The energy balance reduces to $(W = 0, Q$ assumed to be 0)$

\[ \Delta U = -\Delta H \]

which gives one point:

\[ m_{CO_2} (\dot{H}_{ini}) - m_{ref} (\dot{H}_{ref}) = m_a (\dot{H}_{a}) - m_{ref} (\dot{H}_{ref}) \]

\[ m_{ref} = 0 \quad m_a = 0 \quad m_{CO_2} = m_a \]

\[ \dot{H}_{ini} = \dot{H}_{a} = 153 \text{ Btu/lb} \]

The other point is the pressure $p = 200$ psia. Unfortunately the CO$_2$ chart is $p-\dot{H}$ and not $p-\dot{V}$, thus requiring a trial and error solution. Assume a $T$, lookup $\dot{V}$, and calculate $\dot{U} = \dot{H} - p\dot{V}$ (ignore $p\dot{V}$ at the reference state of 40°F).

When $\dot{U} = 153$ Btu/lb, then you have determined $T$. If you used tables of $p$ vs $\dot{U}$ in a handbook, the calculations would be easier.

---

**Solutions Chapter 24**

**Assume $T = 160^\circ F$.** Then $\dot{H} - p\dot{V} = 182\times(200)(0.68)(0.185) = 157$

**$T = 140^\circ F$.** Then $\dot{H} - p\dot{V} = 178\times(200)(0.70)(0.185) = 153$

The calculations are quite approximate but

\[ m_{CO_2} = \frac{3}{0.70} \frac{\text{ft}^3}{\text{lb}} = 4.3 \text{ lb} \]

---

**24.15**

**Basis:** 1 lb steam

Closed system; hence $Q + W = \Delta E = \Delta U$

\[ \begin{align*}
A & \quad 130 \text{ psia, } 600^\circ F \\
& \quad \text{expand} \quad 75 \text{ psia, } 600^\circ F \\
& \quad \text{const. } T \\
B & \quad \text{adiabatic compression} \\
& \quad \text{cool, const. } V \\
& \quad Q = 0 \\
& \quad 60 \text{ psia}
\end{align*} \]

Basis: 1 lb steam

Note: The CD will result in slightly different values for $\Delta \dot{H}$.

\[ \Delta \dot{H} = 1329.6 - 1326.1 = 3.5 \text{ Btu/lb} \]

Use the steam tables or the CD directly for $U$, or calculate

$\Delta \dot{U} = \Delta \dot{H} - \Delta (p\dot{V})$ (continued)
Solutions Chapter 24

> 3.5 \times \begin{bmatrix} 75 \text{ lb} & 8.319 \text{ ft}^3 & 130 \text{ lb} & 4.760 \text{ ft}^3 \\ \text{in}^2 & \text{lb} & \text{in}^2 & \text{lb} \\ \end{bmatrix} \begin{bmatrix} 144 \text{ in}^2 & 1 \text{ Btu} \\ \text{ft}^2 & 778 \text{ (ft) (lb)} \end{bmatrix} 

= 3.5 \times 95 = 2.5 \text{ Btu/lb} 

\dot{W} = \int p dV \text{ but } pV \text{ relation is not known.}

\dot{W} = \int p dV \text{ but } pV \text{ relation is not known.}

\Delta \dot{H} = 1323.7 - 1329.6 = -69.9 \text{ Btu/lb}

\Delta \dot{U} = 96.9 \times \begin{bmatrix} 60.319 & 27 \times 3.19 \\ \text{ft}^2 & \text{ft} \end{bmatrix} \begin{bmatrix} 144 \text{ in}^2 & 1 \text{ Btu} \\ \text{ft}^2 & 778 \text{ (ft) (lb)} \end{bmatrix} = -73.8 \text{ Btu/lb}

\dot{Q} = \Delta \dot{U} = -73.8 \text{ Btu/lb}

\Delta H = 1326.1 - 1323.7 = 93.4 \text{ Btu/lb}

\Delta p \dot{V} = \begin{bmatrix} 1304.36 & -60.319 \\ \text{ft}^2 & \text{ft} \end{bmatrix} \begin{bmatrix} 144 \text{ in}^2 & 1 \text{ Btu} \\ \text{ft}^2 & 778 \text{ (ft) (lb)} \end{bmatrix} = 22.15 \text{ Btu/lb}

\dot{W} = 93.4 - 22.15 = 71.3 \text{ Btu/lb} \quad \Delta U = 93.4 - 22.15 = 71.3 \text{ Btu/lb}

24.16

Closed system, unsteady state; system is both tanks together

Basis: 1 m³ dry steam, 350 K, 40 kPa, \( \bar{V} = 4.005 \text{ m}^3/\text{kg} \), equivalent to \( \frac{1 \text{ kg}}{4008} \approx 0.25 \text{ kg} \)

Basis: 0.1 kg steam

Final pressure = 700 kPa

Batch process, unsteady state. The system is the gas plus the piston.

(continued)
(a) The work can be calculated from \(\int pdV\) if some assumptions are made about the process. No information is given about the process other than "slowly". Assume the work done (against the atmosphere) is carried out at constant atmospheric pressure. Then \[ W = -p\Delta V \]

Initial conditions:

\[ V = 0 \text{ at the start of the expansion} \]

\[ \dot{V} = 0.2995 \text{ m}^3/\text{kg} \]

\(\Delta V\) is what counts so that letting \(V = 0\) initially is ok.

(d) Change in volume of the system:

\[ \text{added } V = \left( \frac{60 \text{ cm} \times 118 \text{ cm}^2}{100 \text{ cm}^2} \right) \times 1 \text{ m}^3 = 0.00944 \text{ m}^3 \]

\[ W = -101.3 \text{ kPa} \times 0.00944 \text{ m}^3 = -0.96 J \]

(work done by system; does not include raising of the piston)

To get \(Q\) apply the energy balance to the gas:

\[ Q + W = \Delta U + \Delta PE_{\text{gas}} \]

To get \(\Delta U\), have to determine \(\dot{U}_{\text{final}}\) and \(\dot{U}_{\text{initial}}\).

At 650 K and 1000 kPa:

\[ \dot{U}_{\text{initial}} = 0.2955 \text{ m}^3/\text{kg} \]

\[ \dot{U}_{\text{final}} = 2918.8 \text{ kJ/kg} \]

At 700 kPa and \(\dot{V}_{\text{final}}\):

Initial volume = (0.2995)(0.1) = 0.02995 m³

Added volume = 0.00944 m³

Final volume = 0.03939 m³

\[ \dot{V}_{\text{final}} = \frac{0.03939}{0.1} = 0.394 \text{ m}^3/\text{kg} \]

At these conditions:

(b) \[ \dot{U}_{\text{final}} = 2841.9 \text{ kJ/kg} \]

\[ \Delta PE = PE_f - PE_i = mgh_f - mgh_i \]

\[ = 0.46 \text{ kg} \times 9.8 \text{ m/s}^2 \times \left[ \frac{0.80 \text{ m}}{\text{kg}} \right] = 3.61 \text{ J} \]

(c) \[ Q = (2841.9 - 2918.8)(0.1) + 3.61 - (0.56) = 5.48 \text{ J} \]

24.18

Pick the room as the system. The simplified form of the energy balance is (for no mass flow):

\[ \Delta E = \Delta U = Q + W = \Delta U \]

where \(Q = 0\) (room is insulated)

\(W\) is the electrical energy provided through the system boundary and is positive. (No volume change occurs). Hence \(\Delta U = C_v\Delta T\) is positive and \(\Delta T\) is positive; i.e. the temperature increases.

24.19

Basis: 1 hour

Assume:

(1) Thermal properties are constant

(2) No work is done

(continued)
Closed unsteady-state system

The energy balance is

\[ \Delta U = Q \]
\[ \Delta U \text{ includes "heat of respiration" and change in temperature} \]

The mass of potatoes is: \((52)(24)(20) = 24,960 \text{ kg}\)

The mass of the boxes is: \((52)(24)(2.1) = 2,621 \text{ kg}\)

Respiration = \((24,960 \text{ kg})(0.035 \text{ W/kg}) = 873.6 \text{ W}\)

\[ \Delta U_{\text{potato}} = \frac{mC_p\Delta T}{\Delta t} = \frac{24,960 \text{ kg}}{(\text{kg})(\text{C})} \left(3.05 \text{ kJ/}\text{C}\right) = -22,838 \text{ kJ/hr} \]
\[ (-6344\text{W}) \]

\[ \Delta U_{\text{box}} = \frac{mC_p\Delta T}{\Delta t} = \frac{2,621 \text{ kg}}{(\text{kg})(\text{C})} \left(1.7 \text{ kJ/}\text{C}\right) = -1,337 \text{ kJ/hr} \]
\[ (-371\text{W}) \]

\[ Q = 873.6 - [6344 + 371] = -5842 \text{ W} \]
\[ 5.84 \text{ kW energy is removed} \]

24.20

(a) Assume steady state flow process. The system includes the orifice.

\[ \Delta U = Q + W - \Delta H - \Delta PE - \Delta KE \]

\[ \Delta U = 0 \] (steady state) \(\Delta PE = 0\)

\[ Q = 0 \] (adiabatic essentially) \(\Delta KE = 0\)

\[ W = 0 \] (no work done)

Final simplified equation: \(\Delta H = 0\)

(b) \(\Delta KE \neq 0, Q = 0, \Delta PE = 0, \Delta U = 0\)

\[ \Delta H = W \]

(c) \(\Delta E = 0 \quad \Delta PE = \Delta KE = 0 \quad [\Delta H = 0] \quad W = 0, Q = 0\)

24.21

Steady state, open system

\[ Q = -3 \text{ Btu/lb steam condensed} \]

\[ \Delta H = 1146.6 \text{ Btu/lb} \]

\[ \Delta H = 170 \text{ Btu/lb} \]

Basis: 1000 \(\text{ft}^3\) at 1 atm and 66\(^\circ\text{F}\)

\[ -\Delta H + Q + W = 0 \]

Steady state, no PE, no KE, no W

\[ Q = \Delta H \]

\[ Q = -3 \text{ Btu/lb steam} \]

\[ m \text{ lb steam} = -3m \]

\[ -3m = (170 - 1146.6) \frac{\text{Btu}}{\text{lb steam}} \cdot \frac{\text{lbf}}{\text{lb} \cdot \text{sec}} + \int_{6900}^{6.900} 0.02884 \times 10^{-7} \text{T} \]

(continued)
Solutions Chapter 24

\[ +0.02429 \times 10^{-5} T^2 - 0.0852 \times 10^{-3} T + 2 \frac{0.02884 \times 10^{-2}}{2} (T^2 - 66^2) + \frac{0.02429 \times 10^{-5}}{3} (76^3 - 66^3) \]
\[ - \frac{0.08052 \times 10^{-9}}{4} (76^4 - 66^4) = 69.03 \text{ Btu/lb mol} \]

\[ \frac{n}{RT} = \frac{1 \text{ atm}}{1000 \text{ ft}^3} \times \frac{0.7302 \text{ ft}^3 \text{ atm}}{\text{lb mol} \text{ K}} \times 531^\circ \text{K} \]
\[ = 2.58 \text{ lb mol} \]

\[ 973.6^\circ \text{m} = 69.03 (2.58) \]
\[ m = 0.18 \text{ lb steam} \]

24.22
Assume steady state, open system, no change in height or velocity, and \( Q = 0 \).

Basis: 1 hr

\[ 10 \text{ atm} = 1013 \text{ kPa} \]

\[ \Delta E = -(\Delta H + \Delta K + \Delta P)m + Q + W \]

\[ W = \Delta H_m = (\Delta H_2 - \Delta H_1)m \]

IC
\[ p: 1013 \text{ kPa} - 1000 \text{ kPa} \]
\[ T: 500K - 373.1 \text{ K} \]
\[ \Delta H_1: 2890.2 \text{ kJ/kg} \]
\[ \Delta H_2: 2675.6 \text{ kJ/kg} \]

Solutions Chapter 24

\[ W = (2675.6 - 2890.2) (700) = -150,200 \text{ kJ/hr} \]
(work done by the system per hour)

\[ \frac{-150,200}{\text{hr}} \cdot \frac{8 \times 10^5}{\text{kJ}} \cdot \frac{1 \text{ hr}}{3600 \text{s}} = -41.7 \text{ kW} \]

24.23

Assume: Steady-state, open system with no change in elevation (no potential energy), and constant velocity (no \( \Delta KE \)). No work is done on or by the system.

Basis: 1 hour

\[ Q = \Delta H_m = (\Delta H_2 - \Delta H_1)m \]

From the steam tables for the liquid water

\[ \Delta H_1 = 148.00 \text{ Btu/lb} \]
\[ \hat{v}_{sat,l,ice} = 0.01651 \text{ ft}^3/\text{lb} \]
\[ \Delta H_2 = 67,999 \text{ Btu/lb} \]

Amount of water is (continued)
\[ m = \frac{1 \text{ lb}_m}{0.01651 \text{ ft}^3/\text{hr}} = 6057 \frac{\text{lb}_m}{\text{hr}} \text{ enter and leave} \]

\[ Q = (67.999 - 148.00) \frac{\text{Btu}}{\text{lb}_m} \cdot \frac{6057 \text{ lb}_m}{\text{hr}} = -4.85 \times 10^9 \frac{\text{Btu}}{\text{hr}} \]

(heat removed)

24.24

Steady state, open system

\[ \text{CO}_2 \text{ in @ 250°F and 1800 psia} \rightarrow \text{CO}_2 \text{ @ 60 psia} \]

\[ Q + W = -\Delta H \text{ and } Q = W = 0 \text{ so } \Delta H = 0 \]

Point A is given. See chart. Point B is determined as follows:

For adiabatic throttling: \( \Delta H_{\text{in}} = \Delta H_{\text{out}} \), hence you can read on chart:

(a) \( T = 130^\circ F \)
(b) Superheated conditions mean the quality = 100% vapor
(c) Specific volume from chart = 2.5 ft\(^3\)/lb

24.25

Part a

Assume the process is a steady-state open process. The system is the turbine.

The energy balance is (continued)
\[ \Delta E = Q + W - \Delta H - \Delta PE - \Delta KE \]

\[ \Delta E = 0 \text{ (steady state)} \]

\[ \Delta PE = 0 \]

\[ \Delta KE \approx 0 \text{ (quite small effect)} \]

so that the energy balance reduces to \( Q + W = \Delta H \)

\[ \Delta H_{\text{in}} = 177 \text{ Btu/lb} \quad \Delta H_{\text{out}} = 135 \text{ Btu/lb} \quad Q = -25 \text{ Btu/lb} \]

Basis: 1 lb steam

\[ W = -(-25) + (135 - 177) = -17 \text{ Btu/lb} \text{ (Work done by turbine)} \]

Part b

The system is the valve. The energy balance is not needed because the CO2 is saturated at 140 psia, hence this corresponds to 28°F.

Part c

The energy balance reduces to

\[ Q = \Delta H = \Delta H_{\text{out}} - \Delta H_{\text{in}} = 95 - 135 = \frac{-40}{\text{Btu/lb}} \]

(heat removed)

24.26

Assume a steady-state open process. The system is the heater.

76°F, 1 atm

Basis: 1 lb water

Data:

<table>
<thead>
<tr>
<th>p (psia)</th>
<th>( V/(\text{ft}^3/\text{lb}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>76°F</td>
<td>0.444</td>
</tr>
<tr>
<td>220°F</td>
<td>14.696</td>
</tr>
</tbody>
</table>

Ignore the vapor that exists at the initial state. The water is superheated at the final condition.

The energy balance reduces to: \( Q = \Delta H = 1154.4 - 44.03 = 1110.4 \text{ Btu/lb} \)

Alternate solution

Assume an unsteady state process with no mass exchanger between the system and surroundings.

The energy balance reduces to

\[ \Delta E = \Delta U = Q \]

Calculate

\[ \Delta U = \Delta H - (pV) = 1110.4 \text{ in}^2 \text{ft}^{-1} \]

\[ = 1110.4 \times 73.9 = 80365 \text{ Btu/lb} \]
or use the \( U \) values from the steam tables to avoid calculating \( \Delta(pV) \).

24.27

\[
\begin{align*}
\Delta H_1 & = \Delta H_1 \text{ can be calculated} \\
\Delta H_2 & = 1235.2 \text{ Btu/lb} \\
\Delta H_3 & = 168 \text{ Btu/lb} \\
\text{SO psia} & = 400^\circ F \\
\text{6 psia} & = 200^\circ F \\
\end{align*}
\]

To make the process a steady state open process from (1) to (3) assume the system is the coil plus the compressor. Then

\[
\dot{Q} = -\Delta\dot{H} = \dot{m}C_{p} + Q + W \quad \text{or} \quad W = \Delta H - Q
\]

Basis: 1 lb water evaporated

Calculate \( \Delta H @ (1): (0.98)(1143.3) + (0.02)(161.17) = 1123.6 \text{ Btu/lb} \)

From (1) to (2): Balance on the compressor

\[
\Delta H_2 - \Delta H_1 = 1235.2 - 1126.6 = 111.6 \text{ Btu/lb} \quad \dot{Q} = -6 \text{ Btu/lb}
\]

Solutions Chapter 24

W = 111.6 \text{ Btu/lb}

From (2) to (3): Balance on the coil

\[\Delta H_3 - \Delta H_2 = 168 - 1235.2 = -1067.2 \text{ Btu/lb} \quad \dot{W} = 0 \quad \dot{Q} = -1067.2 \text{ Btu/lb}\]

a. \[
\frac{\dot{W}}{117.6} = 0.1 \quad \text{(Note: the problem asks for the heat transfer out as a positive value)}
\]

\[
V_{S} = \left[ \frac{38.46 \text{ ft}^3}{\text{lb}} \cdot 0.98 \right] + \left[ \frac{(0.016) \text{ ft}^3}{\text{lb}} \cdot 0.02 \right] \cdot \frac{1067.2 \text{ Btu}}{1067.2 \text{ Btu}} = 37.69 \text{ ft}^3/\text{lb}
\]

Basis: 1,000,000 Btu/hr

b. \[
\text{10}^{6} \text{ Btu/hr} \quad \text{hr} \quad \text{1 lb steam} \quad \text{37.69 ft}^3/\text{min}
\]

\[
\text{hr} \quad \text{60 min} \quad \text{1067.2 Btu} \quad \text{lb steam} = \frac{589 \text{ ft}^3}{\text{min}}
\]

24.28

Basis: 55 gallon oil, °API = 15

\[
C_p = 0.41 \frac{\text{Btu}}{(\text{lb} \cdot ^\circ F)} \quad @ \text{70°F} \quad C_p = 0.467 \frac{\text{Btu}}{(\text{lb} \cdot ^\circ F)} \quad @ \text{180°F}
\]

\[
C_{p,\text{sp}} = 0.5(0.41 + 0.467) = 0.44 \text{ Btu/(lb °F)}
\]

sp. gr. = \[\frac{141.5}{\text{°API} + 131.5} = 0.966\]

\[
\Delta H_{oil} = (0.44)(180 - 70)(55)(0.966)(8.33) = 21,500 \text{ Btu}
\]

(continued)
Assume water leaves @ 212°F, saturated liquid:

\[ \Delta H_{\text{H}_2O} @ 212°F = 180.07 \text{ Btu/lb} \]

\[ \Delta H_{\text{H}_2O} @ 220°F = 1153.3 \text{ Btu/lb} \]

Then \[ \Delta H_{\text{H}_2O} = 1153.3 - 180 = 973 \text{ Btu/lb} \]

\[ m_{\text{steam}} = \frac{21500 \text{ Btu}}{1973 \text{ Btu}} = 22.1 \text{ lb steam} \]

24.29

Process: Flow, steady-state

System: the pipeline

a. \[ Q + W = (\Delta H + \Delta KE + \Delta PE) \]

Assume \( \Delta KE \)

\[ W = 0 \]

Basis: 1 lbm of oil

\[ \dot{Q} = \frac{1 \times 10^5 \text{ Btu}}{1 \text{ hr}} \times \frac{1 \text{ hr}}{160 \text{ min}} < 2000 \text{ lb} = 0.834 \text{ Btu/lbm} \]

\[ \Delta PE = \frac{1000 \text{ ft}}{1 \text{ ft}} \times \frac{\text{Btu}}{1 \text{ Btu}} \times \frac{160 \text{ min}}{1 \text{ hr}} = -1.285 \text{ Btu/lb} \]

Without the pump \( \Delta H = Q - \Delta PE \):

\[ \Delta H = 0.834 - (-1.285) = 2.120 \text{ Btu/lb} \]

b. \[ W = \frac{1 \text{ hp} \times 550(\text{ft}) (\text{lb})}{60 \text{ sec} \times 1 \text{ Btu} \times \frac{1 \text{ min}}{778(\text{ft}) (\text{lb})}} \times \frac{2000 \text{ lb}}{1 \text{ hp}} = 0.0106 \text{ Btu/lb} \]

\[ \Delta H = Q + W - \Delta PE \]

With the pump: \[ \Delta H = 0.834 - (-1.285) + (0.0106) = 2.131 \text{ Btu/lb} \]

24.30

\[ \dot{H} (\text{Btu/lb}) \]

Assume a steady state flow system \( (\Delta E = 0) \) \( \Delta PE = \Delta KE = 0 \).

Then

\[ \Delta H = Q + W \]

\[ \Delta H = m(\Delta H_2 - \Delta H_1) = 1000 (1005 - 1264.7) = -259,700 \text{ Btu} \]

\[ W = \frac{33,500 \text{ (ft})(\text{lb})}{1 \text{ Btu} \times \frac{60 \text{ min}}{778 \text{ (ft)} (\text{lb})}} \times \frac{1 \text{ Btu}}{1 \text{ hr}} = 223,500 \text{ Btu/hour} \]

\[ Q = \Delta H - W = -258,600 - (-223,500) = 36,400 \text{ Btu/hr} \]

(heat loss)

The turbine does not operate adiabatically. The ratio \[ \frac{Q}{\Delta H} = 36,400 \text{ Btu/hr} \times \frac{259,700}{9.13} \]
24.31

Basis: 25 kg exit fluid

\[ Q = \Delta H = \Delta H_{\text{vap}} - \Delta H_{\text{liq}} = 2784.4 \text{ kJ/kg} - (2784.4)(15) - (82.2)(10) \]

\[ Q = \frac{-50 \text{ ft}^3 \text{min}}{g \text{exit}} \times 25 \times 10^3 \text{g} = -1250 \text{ kJ} \]

\[ \text{For the exit fluid} \]

\[ \Delta H_{\text{vap}} = 798.5 \text{ kJ/kg} \]

\[ \Delta H_{\text{liq}} = 2784.4 \text{ kJ/kg} \]

Let \( x = \text{kg vapor,} 25 - x = \text{kg liquid} \)

\[ -1250 = \frac{25-x}{15} \times 2784.4 \times 10 \text{ kg} \]

\[ x = 10.76 \text{ fraction vapor} = \frac{10.76}{25.0} = 0.43 \]

24.32

Open, unsteady state system (the tubing)

Basis: 1 hour

The energy balance reduces to \( Q = \Delta H = mc_p \Delta T \).

\[ Q = \frac{300 \text{ Btu/hr}}{(hr)(\text{ft})} = \frac{1 \text{ gal H}_2 \text{O}}{60 \text{ min}} \times \frac{1 \text{ hr}}{1 \text{ gal}} \times \frac{0.1337 \text{ ft}^3}{1 \text{ lb H}_2 \text{O}} \times \frac{1 \text{ lb H}_2 \text{O}}{1 \text{ Btu}} \times (200-50) \text{°F} \]

\[ L = 248 \text{ ft} \]

24.33

The energy balance reduces to

\[ \Delta H = 0 \]

\[ \Delta H_{\text{air}} + \Delta H_{\text{eng}} = 0 \]

(continued)
For aqueous solutions, the heat capacity is dominated by the water, and the solute mass may be neglected with minimal error.

\[
m\left(\Delta H_{\text{air}}^{400} - \Delta H_{\text{air}}^{200}\right) + m\left(\Delta H_{\text{H}_2\text{O}}^{25^\circ C} - \Delta H_{\text{H}_2\text{O}}^{100}\right) = 0
\]

\[
1 \text{ hr} \times 300 \text{ kg} \times \frac{3696 - 6660 \text{ J}}{1 \text{ g mol} \times 1000 \text{ g}} = 0
\]

\[
\frac{+ 1 \text{ hr} \times 230 \text{ kg soln} \times 97.5 \text{ g H}_2\text{O} \times (\Delta H_{\text{H}_2\text{O}}^{25^\circ C} = \Delta H_{\text{H}_2\text{O}}^{100}) \times 111.7 \text{ J}}{100 \text{ kg soln}} = 0
\]

\[
\Delta H_{\text{H}_2\text{O}}^{25^\circ C} = \frac{30.622 + 25.049}{224.25 \text{ kg}} = \frac{248 \text{ kJ}}{248 \text{ kg}}
\]

Interpolating from SI steam tables

\[
330 \text{ K} + \frac{(335 - 330) \text{ K}}{(259.4 - 238.4) \text{ kJ/kg}} \times (248.25 - 238.4) \text{ kJ/kg} = \frac{248 \text{ kJ}}{248 \text{ kg}}
\]

\[
= 332 \text{K} \text{ or} \ 59^\circ \text{C}
\]

**Open system, steady state**

\[
DH = Q + W
\]

\[
Q = DH_{\text{air}} + DH_{\text{vap}} \text{ at 6 bp.}
\]

\[
W = 0
\]

\[
= m \int_{25^\circ C}^{130^\circ C} C_p dT + \Delta H_{\text{vap}} \text{ at } 250^\circ C
\]

Since the data are incomplete the following assumptions are made:

1. \( C_p \) is linear in \( T \) and the average value may be used.
2. The vapor behaves ideally.
3. \( V_L \) is negligible with respect to \( V_V \).

(continued)
4. $\Delta H_{\text{vap}}$ is constant within the temperature range of concern.

By 1, $C_{pL} = \frac{(2.09 + 2.13)\ J/(g\ ^\circ C)}{2} = 2.11\ J/(g\ ^\circ C)$

By 2, 3, 4 the Clausius Clapeyron equation reduces to

$$\log_{10} \frac{p_1^{*}}{p_2^{*}} = \frac{\Delta H_{\text{vap}}}{2.303\ R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right)$$

Substituting values:

$$\log_{10} \left( \frac{55.0\ \text{kPa}}{101.3\ \text{kPa}} \right) = \frac{\Delta H_{\text{vap}}}{2.303\ \text{J}/(g\ \text{mol})} \left( \frac{1}{523\ \text{K}} - \frac{1}{503\ \text{K}} \right)$$

$$-0.2654 = -3.9706 \times 10^{-6} \Delta H_{\text{vap}}$$

$$\Delta H_{\text{vap}} = -\frac{0.2654}{-3.9706} \times 10^{-6} \text{ g mol}^{-1} \text{ g mol}^{-1} = 547.88\ \text{kJ/kg}$$

$$Q = \frac{1\ \text{hr}}{1\ \text{hr}} \left( \frac{10,000\ \text{kg}}{(211\ \text{kJ}/(g\ ^\circ C))} \right) = 547.88\ \text{kJ/kg}$$

$$= 8,911,000\ \text{kJ}$$

---

24.35

Energy balance at condenser:

The energy balance reduces to $\Delta H = 0$

$\Delta H_C + \Delta H_F = 0$

(continued)
Solutions Chapter 24

\[ m_{\text{C}_2\text{H}_6} \int_{0}^{60} C_p \, dT + m_{\text{H}_2\text{O}} \int_{150}^{60} C_p \, dT - \Delta H_{\text{vap at } 100^\circ C} + \int_{100}^{60} C_p \, dT \]

\[ + m_{\text{tot}} \left[ \int_{111}^{111} C_p \, dT - \Delta H_{\text{vap at } 111^\circ C} + \int_{111}^{60} C_p \, dT \right] = 0 \]

\[ 50,000 \text{ kg} \left[ \frac{2.1 \text{ kJ}}{\text{kg} \cdot \text{C}^\circ} \right] T_2 - 20^\circ C \]

\[ + 1,251.25 \text{ kg H}_2\text{O} \left[ \frac{2.1 \text{ kJ}}{\text{kg} \cdot \text{C}^\circ} \right] \left(100 - 150 \right) ^\circ C + \frac{2260 \text{ kJ}}{\text{kg}} + \frac{4.2 \text{ kJ}}{\text{kg} \cdot \text{C}^\circ} (90 - 100) ^\circ C \]

\[ + 12,498.75 \text{ kg tot} \left[ \frac{1.3 \text{ kJ}}{\text{kg} \cdot \text{C}^\circ} \right] \left(111 - 150 \right) ^\circ C + \frac{230 \text{ kJ}}{\text{kg}} + \frac{1.7 \text{ kJ}}{\text{kg} \cdot \text{C}^\circ} (90 - 111) ^\circ C = 0 \]

\[ 105,000 T_2 - 2,100,000 - 3,011,758.75 - 3,954,604.5 = 0 \]

(a) \[ T_2 = \frac{9,066,363.25}{105,000} = 86.3^\circ C \]

Enthalpy balance at cooler:

\[ \Delta H = 0 \]

\[ (\Delta H_w^{\text{m}} - \Delta H_{\text{vap}}) - (\Delta H_C - \Delta H_{\text{vap}}) = 0 \]

\[ m_{\text{w}} \int_{0}^{60} C_p \, dT - m_{\text{H}_2\text{O}} \int_{60.34}^{60} C_p \, dT - m_{\text{w}} \int_{60.34}^{60} C_p \, dT = 0 \]

\[ m_{\text{w}} \frac{4.2 \text{ kJ}}{(60 - 20) ^\circ C} \left(60 - 20 \right) ^\circ C = \frac{2260 \text{ kJ}}{\text{kg} \cdot \text{C}^\circ} 4.2 \text{ kJ} \left(40 - 90 \right) ^\circ C \]

Solutions Chapter 24

\[ 12498.75 \text{ kg tot} \frac{1.7 \text{ kJ}}{(\text{kg} \cdot \text{C}^\circ) (40 - 90) ^\circ C} \]

\[ m_{\text{w}} \frac{168 \text{ kJ}}{\text{kg}} - 262,762 \text{ kJ} - 1,062,394 \text{ kJ} \]

\[ m_{\text{w}} = 1,325,156 \text{ kJ} \frac{\text{kg H}_2\text{O}}{168 \text{ kJ/kg}} = \frac{7,887 \text{ kg H}_2\text{O}}{} \]

24.36

Basis: 1 lb water/steam

Steady-state, open system for each unit

The data:

Tabulation of p, T, \( \dot{V} \), \( \dot{H} \) and quality or superheats at the numbered points:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>p (psia)</td>
<td>14.7</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>40</td>
</tr>
<tr>
<td>T (°F)</td>
<td>65</td>
<td>65</td>
<td>401</td>
<td>550</td>
<td>268</td>
</tr>
<tr>
<td>( \dot{V} ) (ft³/lb)</td>
<td>0.026</td>
<td>0.016</td>
<td>1.844</td>
<td>2.202</td>
<td>10.14</td>
</tr>
<tr>
<td>qual./sup.heat</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>149°</td>
<td>96.5%</td>
</tr>
<tr>
<td>( \dot{H} ) (Btu/lb)</td>
<td>33.09</td>
<td>33.79</td>
<td>1201.1</td>
<td>1291</td>
<td>1137</td>
</tr>
</tbody>
</table>

Calculate the specific volume at point 5:

\[ \dot{V} = 0.965(0.506) + 0.035(0.01715) = 10.14 \]

(a) Heat to boiler:

\[ Q = \Delta H = H_1 - H_0 = 1201.1 - 33.8 = 1167.3 \text{ Btu/lb} \]

(b) Heat to superheater: (continued)
Solutions Chapter 24

Q = ΔH = H₂ - H₁ = 1291 - 1201.1 = 90 Btu/lb

(c) Heat removed in condenser = H₄ - H₃ = 33 - 1137 = -1104 Btu/lb

(d) Work delivered by turbine: Q + W = ΔH
   Q = 0
   W = ΔH = H₄ - H₃ = 1137 - 1291 = -154 Btu/lb

(e) Work required by the pump between 1 and 2:
   Q + W = ΔH
   Q = 0
   hence W = ΔH
   Because we do not have values of ΔH for compressed water at 65°F, we will use
   W = ΔU + Δ(pV)
   ΔU = \int_{V₁}^{V₂} C_v dT = 0

   Δ(pV) = p₂V₂ - p₁V₁ = (p₂ - p₁)V = (250 - 14.7) \times 0.016 \times 144 = 0.070 Btu/lb

   Efficiency = \frac{Net \ work \ delivered}{Total \ heat \ Supplied} = \frac{154 - 0.70}{1167.3 + 90} = 0.121

   For a water rate of 2000 lb/hr:
   hp = \frac{154 \ Btu}{2000 \ lb} \times \frac{1 \ hr}{1.415 \ hp} = \frac{3600 \ Btu}{hr} \times \frac{1 \ Btu/s}{1 \ Btu/s} = 121

   You can improve the efficiency by:
   (a) Exhausting the turbine at a lower pressure.
   (b) Use higher boiler pressure.
   (c) Use higher superheat.

Solutions Chapter 24

24.37

Basis: 100 lb/day liquid C₁₂ feed at 8°F

Assume
(1) Adiabatic operation of all units
(2) Flow process, steady-state

First find the enthalpy lost or gained by the C₁₂ in the heat exchanger from which we can get the work done by compressor A on the Freon.

Overall C₁₂ balance through the heat exchanger

F + R = P  
100 + 2.5 = 102.5

Energy balance for C₁₂ through the heat exchanger

For a flow process:  Q + W = ΔH
   W = 0
   Q = ΔH

Choose as the reference state liquid C₁₂ at -30°F (continued)
\[ \Delta H = H_{in} - H_{out} \]

\[ \Delta H = \frac{8.1 \text{ Btu}}{(\text{lb mol})(^\circ F)} \cdot \left( \frac{71 \text{ lb}}{100 \text{ lb F}} \right) \cdot \left( \frac{8 - (-30)^\circ F}{100 \text{ lb F}} \right) \]

\[ \Delta H = \frac{8.1 \text{ Btu}}{(\text{lb mol})(^\circ F)} \cdot \left( \frac{71 \text{ lb}}{100 \text{ lb F}} \right) \cdot \left( \frac{8 - (-30)^\circ F}{100 \text{ lb F}} \right) \]

\[ \Delta H = \frac{8.1 \text{ Btu}}{(\text{lb mol})(^\circ F)} \cdot \left( \frac{71 \text{ lb}}{100 \text{ lb F}} \right) \cdot \left( \frac{8 - (-30)^\circ F}{100 \text{ lb F}} \right) \]

Consequently

\[ Q = -442.1 \text{ Btu}/100 \text{ lb F} \]

This means heat is lost by the C\textsubscript{12} and gained by the Freon

Energy balance for the Freon flowing through compressor A:

\[ Q + W = \Delta H \]

But since the flow of Freon is cyclical

\[ \Delta H = 0 \]

\[ Q_{\text{trans}} = -Q_{ch} = -(-442.1) = 442.1 \text{ Btu}/100 \text{ lb F} \]

\[ W_{\text{a}} = Q_{\text{trans}} = 442.1 \text{ Btu}/100 \text{ lb F} \]

Energy balance for the C\textsubscript{12} flowing through the compressor B:

2.5 lb/day @ -30\degree F \rightarrow 2.5 lb/day at 0\degree F

\[ Q + W = \Delta H \quad Q = 0 \]

\[ \Delta H = \text{Enthalpy change across compressor} = H_{A} - H_{A} \]

Other units

\[ W = 539 \text{ Btu/mole} \]

\[ H_{A} = C_{pA} \Delta T + \Delta H_{\text{up}} \]

\[ \Delta H = \frac{2.5 \text{ lb}}{100 \text{ lb F}} \cdot \frac{8.1}{71} \cdot [0 - (-30)] \]

\[ \Delta H = \frac{2.5 \text{ lb}}{100 \text{ lb F}} \cdot \frac{8.1}{71} \cdot [0 - (-30)] \]

\[ \frac{4878 \text{ cal}}{1.8 \text{ Btu/lb}} \cdot \frac{1 \text{ lb mol}}{2.5 \text{ lb}} \cdot \frac{1 \text{ g mol}}{71 \text{ lb}} = 8.55 + 309 = 317.5 \text{ Btu}/100 \text{ lb F} \]

Total work input needed to make the process operational:

\[ \text{hp} = \frac{317.5 + 442.1 \text{ Btu}}{2000 \text{ lb}} \cdot \frac{1 \text{ ton}}{100 \text{ lb F}} \cdot \frac{778 \text{ ft}}{1 \text{ Btu}} \]

\[ \delta = \frac{1 \text{ day}}{(24 \times 60) \text{ min}} \cdot \frac{33,000 \text{ ft}}{1 \text{ lb} \cdot \text{min}} \cdot 0.30 \]

\[ = 82.9 \text{ horsepower} \text{ (actual power input)} \]

24.38

Basis: 1 day; Reference temp = 80\degree F

a. Material and Energy Balances:

**Overall Material:**
### Solutions Chapter 24

**In = 1,000,000 lb**  
**Out: residue = 500,000 lb**  
**naphtha = 200,000 lb**  
**gasoline = 300,000 lb**  
**Total out = 1,000,000 lb**

#### Tower I:

<table>
<thead>
<tr>
<th>Material</th>
<th>In</th>
<th>vapor</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>feed</td>
<td>1,000,000</td>
<td></td>
<td>2,000,000</td>
</tr>
<tr>
<td>reflux</td>
<td>1,500,000</td>
<td>residue</td>
<td>500,000</td>
</tr>
<tr>
<td>total</td>
<td>2,500,000</td>
<td>total</td>
<td>2,500,000</td>
</tr>
</tbody>
</table>

#### Energy:

- **In: feed = (1×10^4)(0.53)(480-90)+10^4(100)**
  
- **reflux = (1.5×10^4)(0.59)(180-90)**
  
- **steam = (by difference)**
  
- **total = 509,700,000 Btu**

- **Out: residue = (5×10^3)(0.51)(480-90)**
  
- **vapor = (2×10^3)(111)**
  
- **liquid = (2×10^3)(0.59)(250-90)**
  
- **total (Btu) = 509,700,000**

#### Furnace:

<table>
<thead>
<tr>
<th>Material</th>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td></td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

#### Energy:

- **In: feed = (10^4)(0.53)(200-90) = 58,300,000 Btu**
  
- **furnace hr = 257,200,000**
  
- **total = 315,500,000**

#### Condenser I:

<table>
<thead>
<tr>
<th>Material</th>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000,000</td>
<td></td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

#### Energy:

- **In: feed = 105,150,000 Btu**
  
- **reflux = 6×10^5(0.63)(120-90)**
  
- **steam = (by difference)**
  
- **total = 159,150,000**

---

**H_2O = 304,500,000/(1)(120-70)**

**Energy**

- **H_2O = 6.1×10^6 lb**
  
- **In: vapor = 222×10^6 + 188.5×10^6 = 410.5×10^6 Btu**
  
- **Out: liquid = (2×10^4)(0.59)(180-90) = 106×10^6 Btu**
  
- **Removed by water = 304.5×10^6 Btu**
  
- **Total out = 410.5×10^6 Btu**

#### Preheater I:

<table>
<thead>
<tr>
<th>Material</th>
<th>In = 500×10^4 lb</th>
<th>Out = vapor = 500×10^4 lb</th>
</tr>
</thead>
</table>

#### Energy:

- **In: liquid = 5×10^3 (0.59)(180-90)**
  
- **steam = 78.65×10^6 Btu**
  
- **Total = 105.15×10^6 Btu**

- **Out: vapor = 5×10^3 (0.59)(250-90)**
  
- **+(5×10^3)(11)**
  
- **Total = 105.15×10^6 Btu**

#### Tower II:

<table>
<thead>
<tr>
<th>Material</th>
<th>In = 500,000 lb</th>
<th>Out = vapor = 900,000 lb</th>
</tr>
</thead>
</table>

#### Energy:

- **In: feed = 600,000 lb**
  
- **reflux = 200,000 lb**
  
- **Total = 1,100,000 lb**

- **Energy = 105,150,000 Btu**

- **In: feed = (6×10^5)(0.63)(120-90)**
  
- **steam = (by difference)**
  
- **Total = 42,200,000**

- **Total (Btu) = 159,150,000**

(continued)
Out: vapor: \((9 \times 10^3)(0.63)(150 - 90) + 9 \times 10^1(118) = 140.05 \times 10^0\)
residue: \((2 \times 10^3)(0.58)(255 - 90) = 19.1 \times 10^3\)
Total (Btu): = 159.15 \times 10^6

Condenser II

Material
In: vapor: = 0.9 \times 10^6 lb
\(\text{H}_2\text{O}: \frac{123.0.5 \times 10^6}{(1)(110 - 70)} = 3.08 \times 10^6 \text{ lb}\)
Out: liquid: = 0.9 \times 10^6 lb
\(\text{H}_2\text{O}: = 3.08 \times 10^6 \text{ lb}\)

Energy
In: (Btu) = 140.05 \times 10^6
Out: liquid: \((9 \times 10^3)(0.63)(120 - 90) = 17 \times 10^6\)
removed by \(\text{H}_2\text{O}: = 123.05 \times 10^6\)
Total (Btu): = 140.05 \times 10^6

Heat Exchanger II (Assume \(T_{\text{ref}} = 90^\circ\text{F}\))

Material
In: liquid: 300,000 lb
\(\text{H}_2\text{O}: 5,670,000/(1)(80 - 70) = 567,000 \text{ lb}\)
Out: liquid: 300,000 lb
\(\text{H}_2\text{O}: 567,000\)

Energy
In: \((300,000)(0.63)(120-90) = 5.67 \times 10^6 \text{ Btu}\)
Out: liquid: = 0.00
removed by \(\text{H}_2\text{O}: = 5.67 \times 10^6 \text{ Btu}\)

Heat Exchanger III

Material

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid: 300,000 lb</td>
<td>liquid: 300,000 lb</td>
</tr>
<tr>
<td>(\text{H}_2\text{O}: 5,670,000/(1)(80-70) = 567,000 \text{ lb})</td>
<td>(\text{H}_2\text{O}: 567,000)</td>
</tr>
</tbody>
</table>

Energy
In: \((5 \times 10^6)(0.51)(480-90) = 99.3 \times 10^4\)
\((1 \times 10^6)(0.53)(140-90) = 26.5 \times 10^6\)
Total (Btu): = 125.8 \times 10^6
Out: \((5 \times 10^6)(0.51)(257-90) = 67.5 \times 10^6\)
\((1 \times 10^6)(0.53)(200-90) = 58.3 \times 10^6\)
Total (Btu): = 125.8 \times 10^6

Heat load of furnace = \(315.5 \times 10^6 - 58.3 \times 10^6 = 257.2 \times 10^6 \text{ Btu}\)

b. Additional heat if charge to furnace is at 90°F
Total heat load = \(315.5 \times 10^6 \text{ Btu}\)
Additional heat = \(315.5 \times 10^6 - 257.2 \times 10^6 = 58.3 \times 10^6 \text{ Btu}\)
Solutions Chapter 24

24.39

Basis: 1 hour  Open steady-state process

De DA lter Balance

\[
\begin{align*}
F_1 & = 1164.1 \text{ lb/h} \\
F_2 & = 428 \text{ lb/h} \\
F_3 & = 2127 \text{ lb/h}
\end{align*}
\]

Material Balance: \( F_1 + F_2 = 50,000 = 105,000 \)

Energy Balance: \( F_1 \cdot 164.1 + F_2 \cdot 48.0 + 50,000 \cdot 218.9 = 105,000 \cdot 218.9 \)

a. \( F_1 = 8,422 \text{ lb/hr} \) steam

b. \( F_3 = 46,578 \text{ lb/hr} \) make-up feedwater

Boiler Feedwater Pump

\[
\text{mVap} = \left( \frac{105,000 \text{ lb}}{0.01 \text{ hr}} \right) \left( \frac{800 \text{ lb}}{30 \text{ ft}^2} \right) \left( \frac{144 \text{ in}^2}{33 \text{ in}^2} \right) \left( \frac{1 \text{ (hp)(s)}}{550 \text{ (ft)(lb)}} \right) \left( \frac{3600 \text{ s}}{\text{ hr}} \right)
\]

= 100 hp

c. For 55% efficiency: \( 181.7 \text{ hp} \)

d. \( (181.7 \text{ hp}) \left( \frac{0.7457 \text{ kW}}{\text{ hp}} \right) = 135.5 \text{ kW} \)

e. \( (135.5 \text{ kW}) \left( \frac{8760 \text{ hr}}{\text{ yr}} \right) \left( \frac{\$0.05}{\text{kWhr}} \right) = \$59,360/\text{year} \)

f. Savings = \( (105,000 \cdot 0.017) \cdot 200 \cdot 144 \cdot \frac{1}{550} \cdot \frac{1}{3600} \cdot \frac{0.7457}{0.55} \cdot (8760) \cdot (0.05) \)

= \$15,420/\text{year}

Steam Drum

\[
\begin{align*}
\text{Heat Input} & = 102.4 \times 10^6 \text{ Btu/hr} \\
\text{Super heater} & = (100,000 \cdot (1351.8-1230.7) = 12.1 \times 10^6 \text{ Btu/hr}
\end{align*}
\]

(continued)
\[ x = \text{vapor flowrate} \]
\[ (100,000 - x)(218.93) + x(1164.1) = 100,000(330.65) \]
\[ x = 11,820 \text{ lb/hr} \]
\[ \text{vapor flowrate} \]
\[ 88,180 \text{ lb/hr} = \text{liquid flowrate} \]
\[ \text{i. Steam Lost} = 11,820 - 8,422 = 3,398 \text{ lb/hr} \]
\[ \text{j. Condensate Lost} = 88,180 - 50,000 = 38,180 \text{ lb/hr} \]

Basis: one hour operation open, steady-state process.

A material balance initially is necessary to determine amounts and compositions of streams.

A. Feed

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt.%</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\text{H}_6</td>
<td>65</td>
<td>650</td>
</tr>
<tr>
<td>C\text{H}_4</td>
<td>35</td>
<td>350</td>
</tr>
</tbody>
</table>

B. Product

Have 97% recovery of ethylene

\[ \text{lb C}_2\text{H}_4 = (0.97)(350) = 340 \]
Now, since the product is 98% \( \text{C}_2\text{H}_6 \)

\[
\frac{340 \text{ lb} \ \text{C}_2\text{H}_6}{98 \text{ lb} \ \text{C}_2\text{H}_6} = 0.695 \text{ lb} \ \text{C}_2\text{H}_6
\]

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt. %</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{C}_2\text{H}_6</td>
<td>98</td>
<td>340</td>
</tr>
<tr>
<td>\text{C}_2\text{H}_4</td>
<td>2</td>
<td>6.95</td>
</tr>
</tbody>
</table>

C. **Bottoms**

\[
\begin{align*}
\text{lb} \ \text{C}_2\text{H}_6 &= 350 - 340 = 10 \\
\text{lb} \ \text{C}_2\text{H}_4 &= 650 - 6.95 = 643.05
\end{align*}
\]

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt. %</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{C}_2\text{H}_6</td>
<td>98.47</td>
<td>643.05</td>
</tr>
<tr>
<td>\text{C}_2\text{H}_4</td>
<td>1.53</td>
<td>10</td>
</tr>
</tbody>
</table>

We are now ready to determine, by a series of energy balances, the quantities desired.

**Energy Balance on System "A" (see Fig.)**

Energy in with Feed + Energy in with Steam = Energy out with Product + Energy out with bottoms + Energy out with refrigerant

We will assign an arbitrary enthalpy of zero to the liquid feed as it enters the Pre-heater at -100°F. Actually, any reference condition could be chosen since we are only concerned with enthalpy changes in the balances.

The feed undergoes at 20°F rise before it enters the still.

\[ T = -80°F \text{ and} \]

\[
C_p \ \text{feed} = (0.65 \times 0.65) + (0.35 \times 0.55) = 0.62 \text{ Btu/(lb) (°F)}
\]

Enthalpy in with feed = (lb feed) \( (C_p \Delta T) = (1000) (0.62) (-80-(-100)) \)

\[ = 12,400 \text{ Btu/hr} \]

Enthalpy in with steam = (lb steam) \( (\Delta H_v) \) at 30 psig,

\[ \Delta H_v = 945 \text{ Btu/lb} \]

Enthalpy in with steam = (S) (945) btu/hr

From the data given, the temperature of the saturated liquid product is +30°F since it is essentially pure ethylene.

\[ C_p = 0.55 \text{ Btu/(lb) (°F)} \]

Enthalpy out with product = (346.95) (0.55) [-30-(-100)] = 13,360 Btu/hr

The bottoms are practically pure ethane so, \( T = 10°F \),

\[ C_p = 0.65 \text{ Btu/(lb) (°F)} \]

Enthalpy out with bottoms = (653.05) (0.65) [-10-(-100)] = 46,700 Btu/hr

The refrigerant experiences a temperature rise of 25°F as it passes through the condenser. The heat capacity may be assumed to be 1.0 Btu/(lb) (°F)

Enthalpy out with refrigerant = (lb refriger.) (1.0) (25) m Btu/hr

Now, rewriting the energy balance "A" with a substitution of known terms:

\[ 12,400 + 945S = 13,360 + 46,700 + 2S + \text{(1) (continued)} \]
It is evident from this first balance that a second balance will be necessary to determine the unknown quantities.

Energy Balance "B"

Energy in with Overhead = Energy out with refrigerant + Energy out with Product + Energy out with Reflux

Since we are using a reflux ratio of 6.1

lb reflux = (6.1)(346.95) = 2,120 lb/hr.

Now, the specific enthalpy of the reflux = the specific enthalpy of the product, since they are from the same stream, and the differences in enthalpy between the overhead and the product, or overhead and reflux, is merely the heat of vaporization of ethylene (neglecting the small amount of C2H4 present), therefore, we can rewrite Energy Balance "B" as:

(lb Overhead) (ΔHv) = 25 m

(2,120 + 346.95) (135) = 25 m

or m = 13,320 lb/hr.

Now substituting this value into equation (1) we have

12,400 + 945 S = 13,360 + 46,700 + (25) (13,320)

so that [9.46 lb/hr

a. 403 lb steam/hr = 0.403 lb steam/lb feed

b. 13,320 lb refrigerant/hr = 1,993 gallons of refrigerant/hr

Solutions Chapter 24

The bottoms leave the still and enter the Pre-heater at approximately 10°F, the saturation temperature of pure C2H4. The final temperature of the bottoms as it leaves the Pre-heater can be calculated from a simple energy balance around the Pre-heater.

c. Enthalpy Balance "C"

(lb bottoms) [0.65 Btu/(lb °F)] (10 – Tf) = (lb feed)

x[0.62 Btu/(lb °F)][-80 – (-100)]

(653.05)(54)(10- Tf) = (1000)(0.62)(20)

\[T_f = 19.2°F\]
25.1
(2), (4), (6)

25.2
(1)

25.3
(3)

25.4

\[ \begin{align*}
C_2H_4(g) & \rightarrow C_2H_2(g) + H_2(g) \quad \Delta H^\circ = +123.8 \\
3CO_2(g) + 4H_2O(l) & \rightarrow C_3H_6(g) + 5O_2(g) \quad \Delta H^\circ = +2220.0 \\
4[H_2(g) + 1/2O_2(g) & \rightarrow H_2O(l)] \quad \Delta H^\circ = 4 \times (-285.8) \\
3(C(s) + O_2(g) & \rightarrow CO_3(g)) \quad \Delta H^\circ = 3 \times (-393.4) \\
3C(s) + 3H_2(g) & \rightarrow C_3H_6(g) \quad \Delta H^\circ = +20.1 \text{ kJ/g mol}
\end{align*} \]

\[ \Delta H^\circ \text{ of } C_2H_2 = \frac{20.1 \text{ kJ/g mol}}{3} \]

25.5
The \( \Delta H^\circ \) is 0 by definition.

25.6

[Chemical reactions and \( \Delta H \) values are listed.]

25.7

(a) \( \text{NH}_4^+ \): \(-67.20 \text{ kJ/g mol}\) from Appendix F
(b) \( \text{Formaldehyde gas (H}_2\text{CO)} \): \(-115.89 \text{ kJ/g mol}\) from Appendix F
(c) \( \text{Acetaldehyde liquid (CH}_3\text{CHO)} \):
   For gas \( \Delta H^\circ = -166.44 \text{ kJ/g mol} \) from Appendix F
   The heat of vaporization at 293.2 K is 25.732 kJ/g mol from the CD. The value is close enough to \( \Delta H^\circ_{\text{vap}} \) (298 K) to use.
   \[ \Delta H^\circ_{\text{vap}} = -166.44 + 25.732 = -140.7 \text{ kJ/g mol} \]

25.8

You want to get \( \Delta H \) for

\[ \begin{align*}
C_2H_4(g) + \frac{1}{2} \text{ Br}_2(g) & \rightarrow C_2H_2\text{Br}(g) + \frac{1}{2} \text{ H}_2(g) \quad \Delta H \ (J) \\
(-b) \quad C_3H_6(g) & \rightarrow C_3H_4(g) + \text{ H}_2(g) \quad +126,000
\end{align*} \]
Solutions Chapter 25

(+a) \[ \text{HBr}(g) + \text{C}_3\text{H}_6(g) \rightarrow \text{C}_3\text{H}_7\text{Br} \] \[-84.441\]
(+c) \[ \text{H}_2(g) + \text{Br}_2(g) \rightarrow 2\text{HBr}(g) \] \[-36.233\]
(-d) \[ \text{Br}_2(g) \rightarrow \text{Br}(l) \] \[-15.355\]

Total \[ -10.029 \text{ J/g mol C}_3\text{H}_3 \]

25.9

a. Basis: 1 g mol NH\textsubscript{3}(g)

\[ \text{NH}_3(g) + \text{HCl}(g) \rightarrow \text{NH}_4\text{Cl}(s) \]
\[ \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = -46.191 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = -92.311 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = -315.4 \]

\[ \Delta \tilde{H}^\circ_{\text{rxn}} = \sum n_i \Delta \tilde{H}^\circ_f \text{products} - \sum n_i \Delta \tilde{H}^\circ_f \text{reactants} \]
\[ = (0)(-315.4) - [(0)(-46.191) + (0)(-92.311)] \]
\[ = -176.9 \text{ kJ/g mol NH}_3(g) \]

b. Basis: 1 g mol CH\textsubscript{4}(g)

\[ \text{CH}_4(g) + 2 \text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(l) \]
\[ \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = -74.84 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = 0 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = -393.51 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = -285.840 \]

\[ \Delta \tilde{H}^\circ_{\text{rxn}} = \sum n_i \Delta \tilde{H}^\circ_f \text{products} - \sum n_i \Delta \tilde{H}^\circ_f \text{reactants} \]

Solutions Chapter 25

\[ = \left[ (2)(-285.840) + (1)(-393.51) \right] - \left[ (1)(-74.84) + 0 \right] \]

\[ = -890.4 \text{ kJ/g mol CH}_4(g) \]

c. Basis: 1 g mol \text{C}_6\text{H}_2(g)

\[ \text{C}_6\text{H}_2(g) \rightarrow \text{C}_6\text{H}_6(l) + 3\text{H}_2(g) \]

\[ \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = 123.1 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = 48.66 \quad \Delta \tilde{H}^\circ_f (\text{kJ/g mol}) = 0 \]

\[ \Delta \tilde{H}^\circ_{\text{rxn}} = [0 + (1)(48.66)] - [(1)(123.1)] \]

\[ = 171.76 \text{ kJ/g mol C}_6\text{H}_2(g) \]

25.10

a. Basis: 1 g mol \text{CO}_2(g)

\[ \text{CO}_2(g) + \text{H}_2(g) \rightarrow \text{CO}(g) + \text{H}_2\text{O}(1) \]

\[ \Delta \tilde{H}^\circ_{\text{rxn}} = (110.52 - 285.84) - (-393.51) = -2849 \text{ kJ} \]

b. Basis: 1 g mol \text{CaO}(s)

\[ \Delta \tilde{H}^\circ_{\text{rxn}} = (-986.59 - 924.66) = (-635.55 - 601.83) - 2(285.84) \]

\[ = \boxed{102.19 \text{ kJ per mol CaO}(s)} \]

Multiply by 2 for the reaction listed \boxed{-204.38 kJ}

c. Basis: 1 g mol \text{Na}_2\text{SO}_4(s)

\[ \Delta \tilde{H}^\circ_{\text{rxn}} = (-1090.35 - 110.54) - (-1384.49) = 183.59 \text{ kJ} \]

(continued)
d. Basis: 1 g mol NaCl (s)
\[ \Delta H_{\text{rxn}}^\circ = (-92.31 - 1126.33) - (-811.32 - 411.01) = 367 \text{ kJ} \]

e. Basis: 1 g mol O₂
\[ \Delta H_{\text{rxn}}^\circ = [2 (-1384.5) + 4 (-92.31)] - [(811.00) + 2 (-296.90)] + 2 (-285.84)] = -1561.76 \text{ kJ} \]

f. Basis: 1 g mol SO₂ (g)
\[ \Delta H_{\text{rxn}}^\circ = (-811.32) - (-285.84 - 296.90) = -228.58 \text{ kJ} \]

g. Basis: 1 g mol N₂
\[ \Delta H_{\text{rxn}}^\circ = 2 (90.374) = 180.75 \text{ kJ} \]

h. Basis: 1 g mol Na₂CO₃ (s)
\[ \Delta H_{\text{rxn}}^\circ = [3 (-1117.13) + (-393.51)] - (1130.94 + 2 (-373.21)] + 4 (-296.90)] = -1867.54 \text{ kJ} \]

i. Basis: 1 g mol CS₂ (l)
\[ \Delta H_{\text{rxn}}^\circ = (-1394.69 - 60.25) - (+87.86) = -287.61 \text{ kJ} \]

j. Basis: 1 g mol C₂H₂ (g)
\[ \Delta H_{\text{rxn}}^\circ = (+105.02) - (52.28 - 92.31) = -145.05 \text{ kJ} \]

k. Basis: 1 g mol CH₃OH (g)
\[ \Delta H_{\text{rxn}}^\circ = (-115.90 - 241.82) - (-201.25) = -156.48 \text{ kJ} \]

25.11
Basis: 1 g mol FeS₂
\[ \Delta H_{\text{rxn}}^\circ = -567.4 \text{ kJ} / \text{g mol FeS}_2 \]
\[ (-567.4 \text{ kJ} / \text{g mol FeS}_2) \frac{1 \text{ g mol FeS}_2}{1000 \text{ g}} \frac{1000 \text{ g}}{120 \text{ g FeS}_2} \frac{1 \text{ kg}}{1 \text{ kg FeS}_2} = -4728.3 \text{ kJ} / \text{kg FeS}_2 \]

Note: The information about conversion does not affect the value of the standard heat of reaction. It will affect the values in the energy balance.

25.12
\[ \Delta H_f^\circ \text{ of } \text{FeS}_2 \text{ is calculated as follows.} \]

(1) \[ \Delta H_{\text{Re}} = \frac{\Sigma n_i \Delta H_f^\circ \text{ products} - \Sigma n_i \Delta H_f^\circ \text{ reactants}}{\text{products}} \]

\[ -822.200 \text{ kJ} = \Delta H_f^\circ \text{ reactants} - \Delta H_f^\circ \text{ products} (2) \]

\[ \Delta H_f (\text{FeS}_2) = -822.200 \text{ kJ} \] (continued)
\[ \Delta H_{\text{rxn}}^\circ = -284.100 \text{ kJ} \]

\[ \Delta H_{\text{rxn}}^\circ = \Delta H_{\text{glyc}}^\circ \cdot \Delta H_{\text{CO}_2}^\circ (2) - \Delta H_{\text{aq}}^\circ \left(\frac{1}{2}\right) \]

\[ -284.100 = -822.200 - \Delta H_{\text{aq}}^\circ (2) - 0 \left(\frac{1}{2}\right) \]

\[ \Delta H_{\text{aq}}^\circ = -\frac{538.10}{2} \text{ kJ} = -269.05 \text{ kJ} \]

\[ \text{vs} - 267 \text{ in Appendix F} \]

### 25.13

The problem requires more information to solve. To make the solution easier but approximate, assume the reaction takes place at 25°C and 1 atm. Assume that the energy balance reduces to \( Q = \Delta H \), and that \( Q \) represents the desired kJ. Data:

\[ \Delta H^c_{\text{f, H}_2 \text{O}} = -285.840 \text{ kJ/g mol, } \Delta H^c_{\text{f, CO}_2} = -393.51 \text{ kJ/g mol. Ref. temp. = 25°C. Basis: } 1 \text{ g mol glucose. MW of glucose = 180.} \]

\( \text{C}_6\text{H}_{12}\text{O}_6 \text{glucose} + 6\text{O}_2(g) \rightarrow 6\text{H}_2\text{O}(l) + 6\text{CO}_2(g) \)

\[ \Delta H^\circ = \Delta H_{\text{product}}^\circ - \Delta H_{\text{reactants}}^\circ \]

\[ = [6(-285.840) + 6(-393.51)] - [(1260) + 6(0)] = -2816 \text{ kJ} \]

\[ \frac{0.90(-2816)}{180} = 14.0 \text{ kJ/g glucose} \]

At 37°C (body temperature), assume only the \( \text{O}_2 \) is used in a reaction

\[ \text{6 g mol O}_2 \rightarrow 22.4L \text{ at STP} \mid 310K \mid 1 \text{ g mol suc.} \mid 1 \text{ g mol O}_2 \mid 273K \mid 180g \text{ suc.} = 0.85 \text{ L/g at 37°C and 1 atm} \]

### 25.14

\[ \text{G + E } \xrightarrow{\text{E}} \text{ E + F} \]

\[ \Delta H_{\text{rxn}}^\circ \text{ is at } 25^\circ \text{C, 1 atm} \]

\[ \Delta H_{\text{rxn}}^\circ = \Sigma \Delta H_{\text{prod.}}^\circ - \Sigma \Delta H_{\text{react.}}^\circ = \left(1.040 \times 10^{-9} - 0.990 \times 10^{-9}\right) / \text{g mol G} \]

\[ = 50 \times 10^3 \text{ J/g mol G converted} \]

Since 0.48 reacts, \( \Delta H_{\text{rxn}}^\circ = 0.48(50) \times 10^3 \text{ J/g mol G} \]

\[ = 24 \times 10^3 \text{ J/g mol G fed (not asked for)} \]

### 25.15

The reaction is

\[ \text{C}_3\text{H}_8(\ell) + 5\text{O}_2(g) \rightarrow 3\text{CO}_2(g) + 4\text{H}_2\text{O}(\ell) \]

Need to calculate the heat of formation of \( \text{C}_3\text{H}_8(\ell) \) and \( \text{H}_2\text{O}(\ell) \) first

\[ \text{C}_3\text{H}_8(\ell) \]

\[ \Delta H^\circ_f (\text{C}_3\text{H}_8(\ell)) = \Delta H^\circ_f (\text{glyc}) - \Delta H^\circ_f (\text{water}) \]

\[ = -24.820 - 3.820 = -28.643 \text{ k cal/g mol} \]

\[ \text{H}_2\text{O}(\ell) \]

\[ \Delta H^\circ_f (\text{H}_2\text{O}(\ell)) = \Delta H^\circ_f (\text{glyc}) - \Delta H^\circ_f (\text{water}) \]

\[ = -57.798 - 10.519 = -68.317 \text{ k cal/g mol} \]

(continued)
Basis: 1 g mol \( \text{C}_2\text{H}_8 \) (\( l \))
\[
\Delta H_{\text{fus.} \text{C}_2\text{H}_8} = 4(-68.317) + 3(-94.052) - (-28.643) = -526.781 \text{ kJ/mol}
\]

25.16
a. Presumably \( \text{H}_2, \text{O}, \text{Cl}, \text{HCl}, \) and \( \text{H}_2 \) are gases.

1) 6 g mol \( \text{FeCl}_3 \)\( (403.34 \text{ kJ/g mol FeCl}_3) \) + 9 g mol \( \text{H}_2\text{O} \)\( (-241.826 \text{ kJ/g mol H}_2\text{O}) \)
-3 g mol \( \text{Fe}_2\text{O}_3 \)\( (-822.156 \text{ kJ/g mol Fe}_2\text{O}_3) \) - 18 g mol \( \text{HCl} \)\( (-92.312 \text{ kJ/g mol HCl}) \) = \(-468.39 \text{ kJ} \)

2) 6 g mol \( \text{FeCl}_3 \)\( (-342.67 \text{ kJ/g mol FeCl}_3) \) + 3 g mol \( \text{Cl}_2 \)\( (0 \text{ kJ/g mol Cl}_2) \) - 6 g mol \( \text{FeCl}_3 \)\( (-403.34 \text{ kJ/g mol FeCl}_3) \) = \(364.02 \text{ kJ} \)

3) 2 g mol \( \text{Fe}_2\text{O}_3 \)\( (-1116.7 \text{ kJ/g mol Fe}_2\text{O}_3) \) + 12 g mol \( \text{HCl} \)\( (-92.312 \text{ kJ/g mol HCl}) \) + 2 g mol \( \text{H}_2 \)\( (0 \text{ kJ/g mol H}_2) \) - 6 g mol \( \text{FeCl}_3 \)\( (-342.67 \text{ kJ/g mol FeCl}_3) \) - 8 g mol \( \text{H}_2\text{O} \)\( (-241.826 \text{ kJ/g mol H}_2\text{O}) \) = \(649.48 \text{ kJ} \)

4) 3 g mol \( \text{Fe}_2\text{O}_3 \)\( (-822.156 \text{ kJ/g mol Fe}_2\text{O}_3) \) - 2 g mol \( \text{Fe}_2\text{O}_3 \)\( (-1116.7 \text{ kJ/g mol Fe}_2\text{O}_3 + 1/2 \text{g mol O}_2 \)\( (0 \text{ kJ/g mol O}_2) \) = \(-233.07 \text{ kJ} \)

5) 6 g mol \( \text{HCl} \)\( (-92.312 \text{ kJ/g mol HCl}) \) + 3/2 g mol \( \text{O}_2 \)\( (0 \text{ kJ/g mol O}_2) \) - 3 g mol \( \text{H}_2\text{O} \)\( (-241.826 \text{ kJ/g mol H}_2\text{O}) \) - 3 \( \text{Cl}_2 \)\( (0 \text{ kJ/g mol Cl}_2) \) = \(171.61 \text{ kJ} \)

b. \( 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \)
\[
\sum \Delta H_{fus.} = \text{483.65 kJ}
\]

25.17
Basis: 1 g gasoline
\[
\Delta H = \frac{40 \text{ kJ}}{g} \text{g} \text{cm}^3 = 33.6 \text{ kJ/cm}^3
\]

Methanol:
Assume the reaction is:
\[
\text{CH}_3\text{OH}(l) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(g)
\]

\[
\Delta H^\circ_r \text{(kJ/g mol)} = -238.64 \quad 0 \quad -393.51 \quad -241.826
\]

\[
\Delta H_{\text{fus.}} = -638.52 \text{ kJ/g mol}
\]

\[
\frac{638.52 \text{ kJ}}{1 \text{ g mol}} \left( \frac{0.792 \text{ g}}{32.04 \text{ g}} \right) = \frac{15.79 \text{ kJ/cm}^3}{\text{cm}^3 \text{ methanol}}
\]

\[
\text{33.6 kJ/cm}^3 \text{ methanol} = 2.15 \text{ cm}^3 \text{ methanol/cm}^3 \text{ gas}
\]

\[
\text{a. (2.13} \times 10^3 \text{) 100} = \text{113% larger tan k}
\]

Ethanol:
\[
\text{C}_2\text{H}_5\text{OH}(l) + \text{O}_2(g) \rightarrow 2\text{CO}_2(g) + 3\text{H}_2\text{O}(g)
\]

\[
\Delta H^\circ_r \text{(kJ/g mol)} = -277.63 \quad 0 \quad -393.51 \quad -241.828
\]

\[
\Delta H_{\text{fus.}} = -1235 \text{ kJ/g mol}
\]

\[
\frac{1235 \text{ kJ}}{1 \text{ g mol}} \left( \frac{0.789 \text{ g}}{46.07 \text{ g}} \right) = 21.15 \text{ kJ/cm}^3
\]

(continued)
25.18

No

The value reported is the heat transfer for constant volume, Q. The heating value at constant pressure should be reported for the standard heat of reaction (an enthalpy change). Assume the reaction is at 25°C.

\[
\text{CH}_4(g) + 2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(f)
\]

Basis: 1 g mol CH₄

\[Q = \Delta H = \Delta H - \Delta(pV)\]

If the gases can be treated as ideal \(\Delta(pV) = \Delta(nRT) = \Delta n \cdot (RT)\).

\[\Delta n = 1 - 2 - 1 = -2\]

The correction is

\[\Delta nRT = -2 \cdot (8.314) \cdot (298) = -4958 \text{ J/g mol}\]

In SI units of 273.15 K and 101.3 kPa, the volume is 22.415 m³ g mol.

The correction is (ignoring the pressure change from 1000 kPa to \(p_2\))

\[-4958 = 221.2 J/m³ \text{ or } 0.22 \text{ kJ/m³}\]

Otherwise you have to calculate \(p_2 \cdot V - p_1 \cdot V\) where \(p_1 = 1000 \text{ kPa}\) and \(p_2 = p_{H_2O} + p_{CO_2}\).

The value to be reported should be 39.97 - 0.22 = 39.75 kJ/m³

25.19

Basis: 1 g mol C₂H₆(g)

\[
\text{C}_2\text{H}_6(g) + 2\text{H}_2(g) \rightarrow 2\text{CH}_4(g) \quad 25°C
\]

\[\Delta H°^\circ (\text{kJ/mol}) = 52.283 \quad 0 \quad -74.84\]

\[\Delta H°_{\text{reaction}} = 2(-74.84) - 52.283 = -202.0 \text{ kJ/g mol}\]

The reaction gives \(Q = \Delta U = \Delta H - \Delta(pV)\). Assume ideal gases so that \(\Delta(pV) = \Delta(nRT) = \Delta n \cdot (RT)\).

\[Q = -202.0 - (-1) \cdot (8.31 \times 10^{-3}) \cdot (298) = -199.5 \text{ kJ/g mol}\]

25.20

Basis: 1 g mol Cu and 1 g mol H₂SO₄

Data from Perry

\[
\text{Cu(s) + H₂SO₄(ℓ) → H₂(g) + CuSO₄(s)}
\]

\[\Delta H°_{\text{reaction}} = (0 - 772.78) - (0 - 810.40) = 37.61 \text{ kJ}\]

For a constant volume process:

\[Q = \Delta U = \Delta H - \Delta(pV) = \Delta H - \Delta n \cdot (RT) \quad \Delta n = 1\]

\[Q = 37.61 - (1) \cdot (8.31 \times 10^{-3}) \cdot (298) = 35.13 \text{ kJ/g mol}\] (continued)
Basis: 1 lb mol of each reactant

\[
\frac{(37.13 \times 1000) \text{ J}}{\text{g mol}} \times \frac{454 \text{ g}}{1 \text{ lb}} \times \frac{1 \text{ Btu}}{1055 \text{ J}} = 15,978 \text{ Btu/lb mol}
\]

25.21
Yes. Calculate the sensible heats using the tables and using a common reference temperature.

\[
\Delta H^r_{\text{reac}} = \left( -3 \right) \times (-964.3) + \left( -3 \right) \times (-159.16) - \left( -3820 \right) \times (1) = -449.6 \text{ kJ/g mol}
\]

25.22

\[
\text{C}_{46}\text{H}_{96}\text{O}_{15} \rightarrow 3 \text{ C}_{6}\text{H}_{10}\text{O}_{7} \quad + \quad 3 \text{ C}_{2}\text{H}_{4}\text{O}_{2}
\]

tristearin \hspace{1cm} \text{stearic and} \hspace{1cm} \text{glycerol}

\[
\Delta H^r_{\text{prod}} = -449.6 \text{ kJ/g mol}
\]

25.23
a. If the exit temperature is > 25°C, and the diluent is at the entering temperature of the reactants, then less heat has to be removed from the process.

b. Remains the same as the presumption is in calculating \( \Delta H^r_{\text{reac}} \) that stoichiometric quantities react to completion.

c. At 25°C, \( \Delta H^r_{\text{reac}} \) \( \Delta H^r_\text{H}_2\text{O} \) with \( \text{H}_2\text{O}_\text{(g)} \) = -241.826 kJ/g mol \( \text{H}_2\text{O} \).

At 500 K, the sensible heats have to be considered, and \( \frac{3}{4} \) \( \text{O}_2 \) and \( \text{H}_2 \) together have a larger \( \Delta H \) than does \( \text{H}_2\text{O} \) so that \( \Delta H_{\text{reac}} \) at 500 K is less than \( \Delta H_{\text{reac}} \) at 25°C.

25.24
Yes (just the enthalpy of formation in the standard state is fixed).

25.25
No. \( \Delta H^r_f \) is arbitrarily assigned a value of 0 at the reference temperature.

25.26
\( S (s) + O_2 (g) \rightarrow SO_2 (g) \)

\[
\begin{array}{c}
\Delta H_{\text{prod}} \\
\Delta H_{\text{Reac}} \\
\Delta H^r_{\text{reac}} \\
\end{array}
\]

\[
\begin{array}{c}
600K (327°C) \\
298K (25°C)
\end{array}
\]

Basis: 1 g mol \( S(s) = 1 \text{ g mol SO}_2 (g) \)

\[
\Delta H_{\text{reac}} \text{, } 800 \text{ K} = \Delta H^r_{\text{reac}} + \sum \Delta H_{\text{prod, } 800 \text{ K}} - \sum \Delta H_{\text{reac, } 800 \text{ K}}
\]

\[
\Delta H^r_{\text{reac}} \text{, } 300 \text{ K} = \sum \Delta H^r_{\text{f prod}} - \sum \Delta H^r_{\text{f reac}}
\]

\[
\begin{align*}
\Delta H^r_{\text{reac, } 800 \text{ K}} &= \left( -296.90 \right) - \left[ 0 + 0 \right] = -296.90 \text{ kJ/g mol } S \\
&= -296,900 \text{ J/g mol } S
\end{align*}
\]

\[
\sum \Delta H_{\text{prod, } 800 \text{ K}}
\]

(continued)
\[ \Delta H_{\text{mol}} = \Delta H_{\text{f}} + \sum \Delta H_{\text{mol}} = \sum \Delta H_{\text{m}} \]

\[ \Delta H_{\text{f}25} = 226.75 + (-74.84) + 0 - (-103.85) = 255.76 \text{ kJ/g mol} \]

\[ \Delta H = \int C_p \,dT = aT + b/2 \, T^2 + c/3 \, T^3 + d/4 \, T^4 \]

\[ \Delta H_{\text{C}_2\text{H}_2} = 68.032T + 1.130 \times 10^{-1}T^2 - 4.37 \times 10^{-2}T^3 + 7.928 \times 10^{-4}T^4 \]

\[ = 55.53 \text{ kJ/g mol} \]

\[ \Delta H_{\text{C}_2\text{H}_2 \text{H}_2} = 42.43 \, T + 3.027 \times 10^{-1}T^2 - 1.678 \times 10^{-2}T^3 + 4.55 \times 10^{-4}T^4 \]

\[ = 25.89 \text{ kJ/g mol} \]

\[ \Delta H_{\text{C}_2\text{H}_4} = 34.31 \, T + 2.735 \times 10^{-1}T^2 + 1.220 \times 10^{-2}T^3 + 2.75 \times 10^{-4}T^4 \]

\[ = 23.10 \text{ kJ/g mol} \]

\[ \Delta H_{\text{C}} = 28.84 \, T + 3.825 \times 10^{-1}T^2 + 1.096 \times 10^{-2}T^3 + 2.175 \times 10^{-4}T^4 \]

\[ = 13.83 \text{ kJ/g mol} \]

\[ \Delta H_{\text{C}} = (255.76 + 25.89 + 23.10 + 13.83) - 55.53 = 263.05 \text{ kJ/g mol} \]

25.28

All data is from Tables E.1 and F.1 of the Appendix.

a. \[ \text{CH}_3\text{OH}(g) + 1/2\text{O}_2(g) \rightarrow \text{H}_2\text{CO}(g) + \text{H}_2\text{O}(g) \]

Basis: 1 g mol CH\textsubscript{3}OH
Solutions Chapter 25

<table>
<thead>
<tr>
<th>Comp.</th>
<th>( C_p ) (J/g mol)(K or °C)</th>
<th>( T ) °C</th>
<th>( \Delta H(T) ) (kJ/g mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CH}_3\text{OH}(g) )</td>
<td>42.39 + 8.301 \times 10^{-2} T - 1.87 \times 10^{-3} T^2 - 8.03 \times 10^{-4} T^3</td>
<td>-201.25</td>
<td></td>
</tr>
<tr>
<td>( \text{O}_2(g) )</td>
<td>29.10 + 1.158 \times 10^{-1} T - 0.6076 \times 10^{-3} T^2 + 1.311 \times 10^{-4} T^3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>( \text{H}_2\text{CO}(g) )</td>
<td>34.28 + 4.268 \times 10^{-2} T - 8.694 \times 10^{-3} T^2</td>
<td>-115.89</td>
<td></td>
</tr>
<tr>
<td>( \text{H}_2\text{O}(g) )</td>
<td>33.46 + 0.6860 \times 10^{-2} T + 0.7604 \times 10^{-3} T^2 - 3.593 \times 10^{-4} T^3</td>
<td>-241.826</td>
<td></td>
</tr>
</tbody>
</table>

25°C = 298 K
200°C = 473 K

\( \Delta H_{\text{mol,298}^\circ} \) = \(-115.89 \times -241.826\)\( \) = \(-156.47 \text{ kJ/mol} \) = \(-156.470 \text{ J/g mol} \)

Products

Add the \( C_p \) equations for the two products and integrate (each involves 1 mole).

\[ \Sigma \Delta H_{\text{mol,298}^\circ} = \int_{298}^{298} (67.74 + 4.95 \times 10^{-3} T + 0.7604 \times 10^{-3} T^2 - 1.228 \times 10^{-4} T^3) dT \]

= 12,850 J/g mol

Reactants

\[ \Delta H_{\text{CH}_3\text{OH}} = \int_{298}^{298} (42.39 + 8.301 \times 10^{-2} T - 1.87 \times 10^{-3} T^2 - 8.03 \times 10^{-4} T^3) dT \]

= 9000 J/g mol

\[ \Delta H_{\text{O}_2} = \int_{298}^{298} (29.10 + 1.158 \times 10^{-1} T - 0.6076 \times 10^{-3} T^2 + 1.311 \times 10^{-4} T^3) dT \]

= 2,650

\[ \Delta H_{\text{mol,298}^\circ} = -156,470 + 12,850 - 2,650 = 146,270 \text{ J/g mol} \]

b. \( \text{SO}_2(g) + 1/2 \text{ O}_2(g) \rightarrow \text{SO}_3(g) \)

Basis: 1 g mol \( \text{SO}_2 \)

\[ \Delta H_{\text{so,298}^\circ} = -395.18 + 296.50 = -98.28 \text{ kJ/g mol} = -98,280 \text{ J/g mol} \]

Products

\[ \Sigma \Delta H_{\text{mol,298}^\circ} = \int_{298}^{298} (48.50 + 9.188 \times 10^{-3} T - 8.540 \times 10^{-3} T^2 + 32.40 \times 10^{-4} T^3) dT \]

= 16,740 J/g mol

Reactants

\[ \Delta H_{\text{SO}_2} = \int_{298}^{298} (39.81 + 3.904 \times 10^{-2} T - 3.104 \times 10^{-3} T^2 + 8.606 \times 10^{-4} T^3) dT \]

= 12,180 J/g mol

(continued)
\[
\Delta H_{\text{O}_3} = 8,470 \text{ J/g mol}
\]

\[
\Delta H_{\text{red,300°C}} = -98,280 + 16,740 - 12,180 - (8,470) \frac{1}{2} = -97,960 \text{ J/g mol SO}_3
\]

25.29

**Basis:** 1 g mol SnO

SnO + 1/2O\(_2\) → SnO\(_2\)

\[
\Delta H_{\text{SnO}} = -577.8 - (-283.3 + 0) = -294.5 \text{ kJ/g mol}
\]

\[
\Delta H_{\text{H_2O}} = \Delta H_{\text{H_2O, 31}} + \sum \Delta H_{\text{prod}} - \sum \Delta H_{\text{mol}}
\]

\[
\Delta H = \int_{31^\circ C}^{T} C_p dT
\]

\[
\Delta H_{\text{SnO}} = 39.33T + 7.575 \times 10^{-3}T^3 |_31 = 2.88 \text{ kJ}
\]

\[
\Delta H_{\text{SnO}} = 29.1T + 5.79 \times 10^{-3}T^2 - 2.025 \times 10^{-4}T^3 + 3.278 \times 10^{-10}T^4 |_31 = 1.93 \text{ kJ}
\]

\[
\Delta H_{\text{H_2O}} = -294.5 + 2.89 - (2.88 + 0.5(1.93)) = -295.46 \text{ kJ/g mol}
\]

---

25.30

Assume steady state flow process with reaction.

\[
\begin{align*}
N_2(g) & \quad \rightarrow \quad H_2(g) \\
C_6H_12(g) & \quad \rightarrow \quad C_4H_8(g) + 3H_2(g)
\end{align*}
\]

Ref. temp. = 25°C

\[
C_4H_8(g) \rightarrow C_4H_6(g) + 3H_2(g)
\]

The standard heat of reactions is

\[
\Delta H_{\text{H_2O, 31}} = [1(82,927) + 3(0)] - [1(-123,100)] = 2.06 \times 10^3 \text{ J/g mol C}_4\text{H}_12
\]

Material balance:

**Step 5:** Basis: 1 g mol C\(_4\)H\(_12\) (g) in

**Steps 6 to 9:**

Make balances for each species so that the unknowns H\(_2\) and C\(_4\)H\(_6\) can be calculated.

**Results:**

\[
\begin{align*}
\text{n}_{\text{H}_2} & \quad \text{out} = 0.70(1)(3) = 2.10 \\
\text{n}_{\text{C}_4\text{H}_8} & \quad \text{out} = 0.70(1) = 0.70 \\
\text{n}_{\text{C}_4\text{H}_6} & \quad \text{out} = 0.30(1) = 0.30 \\
\text{n}_{\text{H}_2} & \quad \text{in} = 0.50 \\
\end{align*}
\]

Energy balance

(continued)
**Solutions Chapter 25**

### Table

<table>
<thead>
<tr>
<th>Component</th>
<th>( \Delta H^\circ / (\text{kJ/mol}) )</th>
<th>( n )</th>
<th>( \Delta H^\circ ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out: H(_2)(g)</td>
<td>0</td>
<td>2.10</td>
<td>16.865</td>
</tr>
<tr>
<td>C(_2)H(_6)(g)</td>
<td>+52.927 \times 10^3</td>
<td>0.70</td>
<td>71.226</td>
</tr>
<tr>
<td>CO(_2)(g)</td>
<td>-123.1 \times 10^3</td>
<td>0.30</td>
<td>-47.552</td>
</tr>
<tr>
<td>N(_2)(g)</td>
<td>18,834</td>
<td>0.50</td>
<td>-4.016</td>
</tr>
<tr>
<td>In:</td>
<td>(a) ( Q = 1.44 \times 10^4 \text{J/mol} )</td>
<td>(b) ( Q = 1.68 \times 10^3 \text{J/mol} )</td>
<td></td>
</tr>
<tr>
<td>N(_2)(g)</td>
<td>0</td>
<td>1.00</td>
<td>-123.1</td>
</tr>
<tr>
<td>CO(_2)(g)</td>
<td>0</td>
<td>0</td>
<td>-0</td>
</tr>
</tbody>
</table>

\*at 25°C exit temp. and entrance temp., these terms are 0.

### Equations

25.31

**Basis:** 100 g mol CO

Assume pressure is 1 atm, and an open, steady state process.

\[
\text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2
\]

The energy balance reduces to \( Q = \Delta H \). The reference temperature is 25°C.

![Energy balance diagram](image)

### Data:

100 g mol CO

100 g mol O\(_2\)

100 g mol CO\(_2\)

### Sensible Heats

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol</th>
<th>( T(\degree\text{C}) )</th>
<th>( \Delta H^\circ / (\text{kJ/g mol}) )</th>
<th>from CD: ( \Delta H^\circ / (\text{kJ/g mol}) )</th>
<th>( \Delta H / (\text{kJ}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>In:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(_2)</td>
<td>100</td>
<td>100</td>
<td>-</td>
<td>2.235</td>
<td>223.5</td>
</tr>
<tr>
<td>CO</td>
<td>100</td>
<td>300</td>
<td>-110.541</td>
<td>8.294</td>
<td>-10,225</td>
</tr>
<tr>
<td>Out:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(_2)</td>
<td>50</td>
<td>400</td>
<td>-</td>
<td>11.715</td>
<td>585.8</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>100</td>
<td>400</td>
<td>-393.505</td>
<td>16.245</td>
<td>-37,726</td>
</tr>
</tbody>
</table>

\*You can calculate \( \Delta H_{\text{react}} \) using the tables in the appendix, but the process requires interpolation.

\( Q = \Delta H = (37.726 + 585.8) - (10.225 + 223.5) = -27.139 \text{kJ} \)

### Example Calculation

- **Basis:** 1 gal of benzene
- **MW:** Density (g/cm\(^3\))

<table>
<thead>
<tr>
<th>Compound</th>
<th>MW</th>
<th>Density (g/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>46</td>
<td>0.789</td>
</tr>
<tr>
<td>Benzene</td>
<td>78</td>
<td>0.879</td>
</tr>
<tr>
<td>Isooctane</td>
<td>114</td>
<td>0.692</td>
</tr>
</tbody>
</table>

### Example Calculation (continued)

\[
\begin{align*}
\text{Benzene:} & \quad \begin{array}{l}
\text{1 gal Bz} \quad 0.879 \text{g Bz} \\
\text{3.785 L} \quad 1000\text{cm}^3 \\
\text{1 g mol Bz} \quad 6 \text{g mol CO}_2
\end{array} \\
\text{cm}^3 \text{Bz} & \quad 1 \text{gal} \\
\text{1 L} & \quad 78 \text{g Bz} \\
\text{1 g mol Bz} & \quad 454 \text{g}
\end{align*}
\]

\[\times 44 \text{ g CO}_2 \quad \text{1 lb} \quad 24.8 \text{ lb CO}_2 / \text{gal Bz} \]

(continued)
Other results:
Ethanol: 12.5 lb CO₂/gal EtOH
Isooctane: 17.8 lb CO₂/gal iso

Carry out the standard combustion material balance for stoichiometric air. The ratios are at SC or the same temperature and pressure.

Example of the calculation for benzene (Reaction 2)

Use data from the CD, heat capacity equations, or tables to get the sensible heats. The data below are from the CD. Reference T = 25°C.

<table>
<thead>
<tr>
<th>IN:</th>
<th>T(°C)</th>
<th>mol</th>
<th>ΔH°₁(kJ/g mol)</th>
<th>ΔH°(kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆H₆(l)</td>
<td>25</td>
<td>1</td>
<td>+4.66</td>
<td>46.66</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>100</td>
<td>7.5</td>
<td>-</td>
<td>2.235</td>
</tr>
<tr>
<td>N₂(g)</td>
<td>100</td>
<td>28.21</td>
<td>-</td>
<td>2.183</td>
</tr>
</tbody>
</table>

| OUT: | | | | |
| CO₂(g) | 25 | 6 | -393.505 | -2361.030 |
| H₂O(l) | 25 | 3 | -285.840 | 857.520 |
| N₂(g) | 25 | 28.21 | - | - |

ΔH° = (2361.030 - 857.520) - (46.66 + 16.763 + 61.553) = -3093.6 kJ/g mol Bz

25.33

Steady State, open process. Ref T = 25°C

Basis: 100 g mol feed

The moles out come from the material balance, and the other data from the CD.

\[ Q = \Delta H \]

ΔH data from the CD.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>% or g mol</th>
<th>T(°C)</th>
<th>ΔH°₁(kJ/g mol)</th>
<th>ΔH°(kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>6.4</td>
<td>500</td>
<td>-393.505</td>
<td>20.996</td>
</tr>
<tr>
<td>O₂</td>
<td>0.2</td>
<td>500</td>
<td>-</td>
<td>15.034</td>
</tr>
<tr>
<td>CO</td>
<td>40.0</td>
<td>500</td>
<td>-110.541</td>
<td>14.690</td>
</tr>
<tr>
<td>H₂</td>
<td>50.8</td>
<td>500</td>
<td>-</td>
<td>13.834</td>
</tr>
<tr>
<td>N₂</td>
<td>2.6</td>
<td>500</td>
<td>-</td>
<td>14.242</td>
</tr>
</tbody>
</table>

100.0

= -1.251 x 10⁸ Btu per gal Bz (exothermic)
### Solutions Chapter 25

<table>
<thead>
<tr>
<th></th>
<th>O₃</th>
<th>N₂</th>
<th>Out with fg</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63.28</td>
<td>240.65</td>
<td>303.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>25</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>32.006</td>
<td>-16,773.55</td>
</tr>
<tr>
<td>CO₂</td>
<td>46.4</td>
<td>50.8</td>
<td>-393.505</td>
<td>26.133</td>
</tr>
<tr>
<td></td>
<td>720</td>
<td>720</td>
<td>-241.835</td>
<td>-10,957.66</td>
</tr>
<tr>
<td>H₂O(g)</td>
<td>0.8</td>
<td>4.3</td>
<td>5,111.89</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>240.65</td>
<td>720</td>
<td>21.242</td>
<td>5,111.89</td>
</tr>
<tr>
<td>CO₂</td>
<td>18.1</td>
<td>720</td>
<td>22.555</td>
<td>408.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>356.0</td>
<td>-22,21.08</td>
</tr>
</tbody>
</table>

\[ Q = \Delta H = (-22,211.08) - (-5,475.29) = -16,736 \text{ kJ} \]

(Heat leaving)

### 25.34

Steady state, open process. Ref T = 25°C

Basis: 100 g mol P

**Data come from the material balances and the CD.**

\[ C_p \text{ (J/g mol) (°C)} \]

\[ H \quad 20.8 \]

\[ C \quad 14.3 \]

<table>
<thead>
<tr>
<th>Comp. in F (214.8 g solid)</th>
<th>Percent (g)</th>
<th>g mol</th>
<th>T(°C)</th>
<th>( \Delta H^* ) (kJ/g mol)</th>
<th>( \Delta H_{\text{made}} ) (kJ/gmol)</th>
<th>( \Delta H ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>90.0</td>
<td>16.1</td>
<td>40</td>
<td>-</td>
<td>0.214</td>
<td>3.456</td>
</tr>
<tr>
<td>H</td>
<td>6.0</td>
<td>12.79</td>
<td>40</td>
<td>-</td>
<td>0.312</td>
<td>3.991</td>
</tr>
<tr>
<td>Inert</td>
<td>4.0</td>
<td></td>
<td>40</td>
<td>-</td>
<td>ignore</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>28.90</td>
<td></td>
<td></td>
<td>7.447 (continued)</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
Solutions Chapter 25

In air (99.7 g mol)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>20.94</td>
<td>40</td>
<td>0.442</td>
<td>9.255</td>
</tr>
<tr>
<td>N₂</td>
<td>78.76</td>
<td>40</td>
<td>0.436</td>
<td>34.339</td>
</tr>
<tr>
<td></td>
<td>99.70</td>
<td></td>
<td></td>
<td>43.595</td>
</tr>
</tbody>
</table>

Out in P (g)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>16.1</td>
<td>1100</td>
<td>-393.505</td>
<td>24.744</td>
</tr>
<tr>
<td>CO</td>
<td>0.8</td>
<td>1100</td>
<td>-110.541</td>
<td>25.032</td>
</tr>
<tr>
<td>O₂</td>
<td>4.3</td>
<td>1100</td>
<td>-</td>
<td>26.209</td>
</tr>
<tr>
<td>N₂</td>
<td>78.8</td>
<td>1100</td>
<td>-</td>
<td>38.891</td>
</tr>
<tr>
<td>Water out (g)</td>
<td>100.0</td>
<td></td>
<td>-241.826</td>
<td>30.174</td>
</tr>
<tr>
<td>Refuse</td>
<td>10 g</td>
<td>200</td>
<td>-</td>
<td>1.488 per g</td>
</tr>
</tbody>
</table>

\[ Q = \Delta H = \left( -2828.17 + 205.18 + 14.88 \right) - \left( 7.447 + 43.595 \right) = -2659.2 \text{ kJ} \]

(heat exiting)

25.35

Basis: 1 g mol CaCl₂ · 6H₂O(s)

Unsteady state, open process. Reference T = 25°C.

68°F → 20°C and 86°F → 30°C

\[ \Delta U = \Delta H \text{ inside the system} \]

\[ \Delta U = \frac{\Delta H_{\text{ref}}}{T_{\text{ref}}} \]

Assume \( \Delta U = \Delta H \)

Data

\begin{align*}
\text{Data} & \quad \Delta H_{\text{ref}}^{\circ} (\text{kJ/mol}) \quad C_p (\text{J/g} \cdot \text{°C}) \quad MW \\
\text{CaCl₂} \cdot \text{6H₂O(s)} & \quad -2607.89 \quad 1.34 \quad 219 \\
\text{CaCl₂} \cdot \text{2H₂O(s)} & \quad -1402.90 \quad 0.97 \quad 147 \\
\end{align*}

Calculate \( \Delta U \)

Comp. | g mol | T°C | MW | \( \Delta H_{\text{ref}}^{\circ} (\text{kJ/mol}) \) | \( \Delta H_{\text{enthalpy}} (J) \) | \( \Delta H (\text{kJ}) \)
\hline
Initial | CaCl₂ · 6H₂O(s) | 1 | 20 | 219.1 | -2607.89 | (1)(1.34)(219.1)(25-20) | -2606.422
| Final | CaCl₂ · 2H₂O(s) | 1 | 30 | 129.0 | -1402.90 | (1)(0.97)(129.0)(30-25) | -1402.274
\hline
Out | H₂O(g) | 4 | 30 | 18.0 | -241.826 | (1)(4.18)(18)(30-25) | -965.798
\hline
CaCl₂ · 6H₂O(s) → CaCl₂ · 2H₂O + 4H₂O(g)

Per g mol CaCl₂ · 6H₂O(s):

\[ Q = \Delta U + \Delta H_{\text{enthalpy}} = \left( -1402.274 - (-2606.422) \right) + (-965.798) = 238 \text{ kJ} \]

or 226 Btu/g mol CaCl₂ · 6H₂O(s)

\begin{align*}
\text{200,000 Btu} & \quad 1 \text{ g mol CaCl₂ · 6H₂O(s)} \quad 219 \text{ g} \quad 1 \text{ kg} \quad 194 \text{ kg} \\
\text{226 Btu} & \quad 1 \text{ g mol} \quad 100 \text{ g} \quad (427 \text{ lb})
\end{align*}
25.36
At 25°C and 1 atm H₂O is a liquid.

\[ H_2(g) + \frac{1}{2} O_2(g) \rightarrow H_2O(l) \]

\[ \Delta H_r^\circ (kJ/g \text{ mol}) = -285.84 \]

\[ \Delta H_{\text{prod}} \]

\[ \Delta H_{\text{react}} \]

\[ \Delta H_{\text{prod}} \rightarrow 25^\circ C \]

\[ \Delta H_{\text{react}} \rightarrow 0^\circ C \]

Basis: 1 g mol H₂ (g)

\[ \Delta H^\circ_{\text{mix}} = -\left[ \sum \Delta H^\circ_{\text{prod}} - \sum \Delta H^\circ_{\text{react}} \right] \]

\[ = -(1)(0) - (1)(-285.84) - (\frac{1}{2})(0) = -285.84 \text{ kJ/g mol } H_2 \]

H₂O at 25°C is a liquid

\[ \Delta H_{\text{prod}} = \int C_p \text{ d}T \]

\[ = \frac{4.184 \text{ J}}{(g/0^\circ C) \text{ mol}} \times 18 \text{ g} \times \frac{(25^\circ C)}{(1 \text{ mol})} = -1.883 \text{ kJ} \]

\[ \Delta H_{\text{react}} = (1) \int C_p \text{ d}T + (\frac{1}{2}) \int C_p \text{ d}T = -(718)(1) - (727)(\frac{1}{2}) = -1.081 \text{ kJ} \]

\[ \Delta H_{\text{react}} (0^\circ C) = (-1.883) - (-1.081) + (-285.84) = -286.64 \text{ kJ/g mol } H_2 \]

25.37
(a) HHV = 14,544 (80) + 62,028 \left( \frac{0.0003 - \frac{0.005}{8}}{} \right) + 4050(0.006)

\[ = 11,640 \text{ Btu/lb} \]

LHV = 11,800 - 91.23(0.3) = 11,770 Btu/lb

(b) HHV = 17,887 + 57.5(30) - 102.2 (0.5) = 19,560 Btu/lb

LHV = 19,560 - 91.23 (12.05) = 18,460 Btu/lb

25.38
If the fuel cannot produce H₂O as a product, HHV = LHV, but the concept really refers to cases in which water is produced so that HHV ≠ LHV.

25.39
Both H₂ and O₂ enter at 0°C, and the products leave at 0°C. The reference temperature is 25°C. Stoichiometric quantities react according to the reaction equation.

\[ H_2 (g) + \frac{1}{2} O_2 (g) \rightarrow H_2O (l) \]

\[ \Delta H_f (kJ/g \text{ mol}): \quad 0 \quad 0 \quad -285.83 \]

\[ \Delta H_{\text{prod}} \quad 25^\circ C \]

\[ \Delta H_{\text{react}} \quad 0^\circ C \]

Basis: 1 g mol H₂ (g)

(continued)
\[ \Delta H_{\text{Rx}}(0^\circ \text{C}) = \Sigma \Delta H_{\text{Products}} - \Sigma \Delta H_{\text{Reactants}} \]

\[ \Sigma \text{Products} = (-285.83) + \int_{25^\circ \text{C}}^{10^\circ \text{C}} \left( 4.184 \cdot \frac{18 \text{g H}_2\text{O}}{\text{g mol}} \right) \frac{dT}{(\text{g mol})} = -287.71 \text{ kJ} \]

Alternately you can use the steam tables or the CD to get the value. The reactants are gases, hence \( \Delta H \) can be obtained from tables.

\[ \Sigma \text{Reactants} = \left( 0 + 0 \right) + \left( \int_{25^\circ \text{C}}^{10^\circ \text{C}} \left( 28.84 + 0.00765 \times 10^{-2} T \right) \frac{dT}{\text{g mol}} \right) + (-1.45) \text{ kJ} \]

\[ \Delta H_{\text{Rx}}(0^\circ \text{C}) = -287.71 - (-1.45) = -286.26 \text{ kJ} \]

25.40

Basis: 100 lb mol gas

The reaction for each compound is the stoichiometric amount of \( \text{O}_2 \) going to \( \text{CO}_2 \) gas and \( \text{H}_2\text{O} \) (f)

<table>
<thead>
<tr>
<th>Comp.</th>
<th>lb mol</th>
<th>( \Delta H_{\text{Btu/lb mol}} )</th>
<th>( \Delta H ) (Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CO}_2 )</td>
<td>9.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{C}_2\text{H}_4 )</td>
<td>0.4</td>
<td>598,000</td>
<td>239,000</td>
</tr>
<tr>
<td>( \text{CO} )</td>
<td>20.9</td>
<td>122,000</td>
<td>2,544,000</td>
</tr>
<tr>
<td>( \text{H}_2 )</td>
<td>15.6</td>
<td>123,000</td>
<td>1,918,000</td>
</tr>
<tr>
<td>( \text{CH}_4 )</td>
<td>1.9</td>
<td>383,000</td>
<td>728,000</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>52.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100.0</td>
<td></td>
<td></td>
<td>5,429,000</td>
</tr>
</tbody>
</table>

Note: NGI standard state is 60°F

\[ \text{HHV} = \frac{5,429,000 \text{ Btu}}{100 \text{ lb mol}} = 54,290 \text{ Btu/lb mol} = 520^\circ \text{R} \]

25.41

Basis: 1 m³ gas at 25°C and 1 atm with 40% relative saturation

Calculate the moles of \( \text{C}_4\text{H}_{12} \) gas. Its pressure at 25°C is calculated as follows:

\[ (p_{\text{H}_2\text{O}}) = 3.2 \text{ kPa} \]

\[ (3.2)(0.40) = 1.28 \text{ kPa}, \text{ and thus the pressure of the C}_4\text{H}_{12} \text{ (g)} \text{ is } (101.3-1.28) = 100 \text{ kPa}. \]

\[ n = \frac{pV}{RT} = \frac{100 \text{ kPa}}{1 \text{ atm}} = \frac{1 \text{ m}^3}{298 \text{ K}} = 0.0404 \text{ kg mol} \]

Basis: 1 g mol n-propyl benzene \( (\text{C}_6\text{H}_5 \cdot \text{CH}_2 \cdot \text{C}_2\text{H}_5) \)

The higher heating value is with \( \text{H}_2\text{O} \) as a liquid. Also, at 25°C, \( \text{C}_9\text{H}_{16} \) is a liquid; its normal boiling point is 432 K.

\[ \text{C}_9\text{H}_{12} \text{ (f)} + 12 \text{ O}_2 \text{ (g)} \rightarrow 9 \text{ CO}_2 \text{ (g)} + 6 \text{ H}_2\text{O} \text{ (f)} \]

\[ \Delta \hat{H}_{\text{f}}^\circ \left( \frac{\text{kJ}}{\text{g mol}} \right) = 38.40 \quad 0 \quad -393.51 \quad -285.840 \]

\[ \Delta \hat{H}_{\text{f,n}} = \left[ (6 \times (-285.840) + 9 \times (-393.51)) - [(1) \times (-38.40)] \right] 
\]

\[ = -5218.2 \text{ kJ/g mol C}_4\text{H}_{12} \]

\[ \text{HHV} = \frac{-5218.2 \text{ kJ}}{40.4 \text{ g mol C}_4\text{H}_{12}} = \frac{2.11 \times 10^4 \text{ kJ/m}^3}{1 \text{ m}^3 \text{ gas}} \]
25.42

Basis: 100 mol of gas

\[ \text{Comp.} \quad \text{mol wt.} \quad \text{Vol. %} \quad \text{lb} \quad \text{kJ/g mol} \quad \text{kJ/g mol} \\
\text{CH}_4 \quad 16 \quad 88 \quad 1408 \quad 890.35 \quad 802.32 \\
\text{C}_2\text{H}_6 \quad 30 \quad 6 \quad 180 \quad 1559.88 \quad 1427.84 \\
\text{C}_3\text{H}_8 \quad 44 \quad 4 \quad 176 \quad 2220.05 \quad 2044.00 \\
\text{C}_4\text{H}_{10} \quad 58 \quad 2 \quad 116 \quad 2878.52 \quad 2658.45 \\
\text{Total} \quad 100 \quad 1880 \\
\]

mol wt. mixture = 18.80 lb/lb mol

\[ \Delta H^o_{\text{rxn}} = \text{H}_2\text{O}(l) \to \text{CO}_2 \text{ products; } \Delta H^o_{\text{rxn}} = \text{H}_2\text{O} \text{ g + CO}_2 \text{ g products} \\
\Delta H^o_{\text{rxn}} = -[\Delta H^o_{\text{prod}} - \Delta H^o_{\text{react}}] = 1022.90 \text{ kJ/g mol} \\
\]

(a1) \[ \Delta H^o_{\text{rxn}} = \frac{-1022.90 \times 454 \text{ g mol}}{1.055 \text{ kJ} \times 18.80 \text{ lb}} = -23600 \text{ Btu/lb} \\
\text{HHV} = 23600 \text{ Btu/lb} \\
\]

(b1) \[ \Delta H^o_{\text{rxn}} = -925.71 \text{ kJ/g mol} \\
\]

Solutions Chapter 25

\[ \text{HHV} = 1160 \text{ Btu/ft}^3 \text{ at } 60^\circ\text{F}, 760 \text{ mm Hg} \]

(b2) \[ \Delta H^o_{\text{rxn}} = \frac{-925.71}{1.055} \times 18.80 = -21200 \text{ Btu/lb} \\
\text{LHV} = 21200 \text{ Btu/lb} \\
\]

(b3) \[ \Delta H^o_{\text{rxn}} = -398000 \text{ Btu/lb mol} \\
\text{LHV} = 398000 \text{ Btu/lb mol} \\
\]

25.43

Write the equation for the combustion for 1 gram as:

1 g of Fuel or food + Oxygen \rightarrow \text{CO}_2 \text{(g) + H}_2\text{O(l) + N}_2 \text{(g)}

Both the reactants and the products are at 25°C and 1 atm. The chemical energy released by the complete combustion of 1 g of food or fuel according to the above equation at standard conditions is the heat of combustion. Assume the \( \Delta H \) are additive. Then

\[ \Delta H_c = (17.1)(28) + (39.5)(10) + (14)(4) = 930 \text{ kJ} \]

The High Energy bar has (capital C for calorie)

220 Calories \( 1000 \text{ calories} = 4.184 \text{ J} \quad 1 \text{ kJ} = 921 \text{ kJ} \)

The values are close enough.
25.44
When the combustion results in a single component.

25.45

**Basis: 1 lb mixture**

Get the data for the $\Delta H_i$ in Btu/lb, not Btu/mol.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass fr., $\omega_i$</th>
<th>$\Delta H_i$ (Btu/lb)</th>
<th>$\Delta H$ (Btu)</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexachloroethane, C$_2$Cl$_6$</td>
<td>0.0487</td>
<td>828</td>
<td>40</td>
<td>58.44</td>
</tr>
<tr>
<td>Tetrachloroethene, C$_2$Cl$_4$</td>
<td>0.0503</td>
<td>2141</td>
<td>108</td>
<td>60.36</td>
</tr>
<tr>
<td>Chlorobenzene, C$_6$H$_5$Cl</td>
<td>0.2952</td>
<td>11,876</td>
<td>3,506</td>
<td>354.24</td>
</tr>
<tr>
<td>Toluene, C$_6$H$_5$</td>
<td>0.6058</td>
<td>18,246</td>
<td>11,053</td>
<td>726.96</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.000</td>
<td>14,707</td>
<td>1200.00</td>
<td></td>
</tr>
</tbody>
</table>

The Btu/lb are [14,707] from the heat of combustion data, a deviation of 3.2% from 15,200. For DuLong's equation, the component elements are needed.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>H</th>
<th>Cl</th>
<th>O</th>
<th>MW</th>
<th>Total (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_2$Cl$_6$</td>
<td>24</td>
<td>0</td>
<td>213</td>
<td>0</td>
<td>237.00</td>
<td></td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>0.10</td>
<td>0.00</td>
<td>0.90</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>5.84</td>
<td>0.00</td>
<td>52.60</td>
<td>0.00</td>
<td>58.44</td>
<td></td>
</tr>
<tr>
<td>C$_2$Cl$_4$</td>
<td>24</td>
<td>0</td>
<td>142</td>
<td>0</td>
<td>166.00</td>
<td></td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>0.14</td>
<td>0.00</td>
<td>0.86</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>8.45</td>
<td>0.00</td>
<td>51.91</td>
<td>0.00</td>
<td>60.36</td>
<td></td>
</tr>
<tr>
<td>C$_6$H$_5$Cl</td>
<td>72</td>
<td>5</td>
<td>35.5</td>
<td>0</td>
<td>112.50</td>
<td></td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>0.64</td>
<td>0.04</td>
<td>0.32</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>226.71</td>
<td>14.17</td>
<td>113.36</td>
<td>0.00</td>
<td>354.24</td>
<td></td>
</tr>
<tr>
<td>C$_6$H$_5$</td>
<td>84</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>9200</td>
<td></td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>0.91</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>661.53</td>
<td>65.43</td>
<td>0.00</td>
<td>0.00</td>
<td>726.91</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>902.53</td>
<td>79.60</td>
<td>217.87</td>
<td>0</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>0.75</td>
<td>0.07</td>
<td>0.18</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

HHV = 14,455 C + 62,028 H - 7753.5O + 4050 S (continued)
= (14,455)(0.75) + (62,028)(0.07) = 15,183 Btu/lb (the higher heating value) a deviation of 0.11%

25.46

The reactions are:

\[ \text{C}_8\text{H}_{18}(l) + 3 \text{ O}_2(g) \rightarrow 2 \text{ CO}_2(g) + 3 \text{ H}_2\text{O}(l) \]  

(1)

\[ \text{C}_4\text{H}_{10}(g) + 12.5 \text{ O}_2(g) \rightarrow 8 \text{ CO}_2(g) + 9 \text{ H}_2\text{O}(l) \]  

(2)

\[ \Delta H_{\text{rxn}} = -\left[ \sum \text{n}_p \Delta H_{\text{f, p}}^\circ - \sum \text{n}_r \Delta H_{\text{f, r}}^\circ \right] \]

For (1): \(-((2)(0) + (3)(0) - (1)(-1366.91)) = -1366.91 \text{ kJ/g mol C}_8\text{H}_{18}\)

For (2): \(-((8)(0) + (9)(0) - (12.5)(0) - (-1307.53)(4.184)) = -5470.71 \text{ kJ/g mol C}_4\text{H}_{10}\)

Note: the \(\Delta H_r = 1307.53 \text{ k cal/g mol for n-octane liquid is from Perry.}\)

Basis: 1 kg gasohol

<table>
<thead>
<tr>
<th>Component</th>
<th>mass fr. = kg</th>
<th>MW</th>
<th>g mol</th>
<th>(\Delta H^o_{\text{f}} \text{(kJ)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{C}<em>8\text{H}</em>{18}</td>
<td>0.10</td>
<td>46.05</td>
<td>2.17</td>
<td>-2,966</td>
</tr>
<tr>
<td>\text{C}<em>4\text{H}</em>{10}</td>
<td>0.90</td>
<td>114.14</td>
<td>7.89</td>
<td>-43,137</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.00</strong></td>
<td></td>
<td></td>
<td><strong>-46,103</strong></td>
</tr>
</tbody>
</table>

If the fuel were all octane

\[ 1 \text{ kg octane} \quad 1 \text{ kg mol octane} \quad 1000 \text{ g} \quad -5470.71 \text{ kJ} \]

\[ 114.14 \text{ kg octane} \quad 1 \text{ kg} \quad \text{g mol octane} = -47,930 \text{ kJ} \]

\[ -47,930 - (-46,103) \]

\[ \frac{-47,930}{-47,930} \times 100 \% = 3.8\% \]

25.47

Basis: 1 g mol dry cells

The heat of reaction is

\[ \Delta H^o_{\text{rxn}} = -\left[ \sum \text{n}_p \Delta H_{\text{f, p}}^\circ - \sum \text{n}_r \Delta H_{\text{f, r}}^\circ \right] \]

products - reactants

\[ = -((1)(-1.517) + 2.75(-393.51) + 3.42(-285.840)) \]

\[ = -6.67(-2,817 - 2.10) = -15,213 \text{ kJ/g mol cells} \]

For 100 g dry cells

\[ \frac{-15,213 \text{ kJ}}{1 \text{ g mol cells}} \times \frac{100 \text{ g dry cells}}{84.58 \text{ g dry cells}} = 1.80 \times 10^4 \text{ kJ} \]

25.48

Basis: 1 g mol yeast

The heat of formation is

\[ 3.92 \text{ C} + 6.5 \text{ H} + 1.94 \text{ O}_2 \rightarrow \text{C}_3\text{H}_8 \text{O}_{1.94} \]

The heat of combustion is for the reaction

\[ \text{C}_3\text{H}_8 \text{O}_{1.94} + 5.60 \text{ O}_2 \rightarrow 3.92 \text{ CO}_2(g) + 3.25 \text{ H}_2 \text{O}(l) \] (continued)
\[
-1,518 \text{ kJ} = - \left[ \sum n_i \Delta H^p_i \right]_{\text{product}} - \left[ \sum n_i \Delta H^p_i \right]_{\text{reactants}}
\]

\[
-1,518 = - \left[ (3.92)(-393.51) + (3.25)(-285.840) - 5.60(0) - (1)\Delta H^p_{\text{yr,prod}} \right]
\]

\[
\Delta H^p_{\text{yr,prod}} = -963.54 \text{ kJ/g mol}
\]

The molecular weight of \( C_{132}H_{272}O_{114} \) is 84.63. Per 100 g yeast:

\[
\Delta H^p_{\text{yr,prod}} = [-1139 \text{ kJ/100 g yeast}]
\]

---

### 25.49

**Basis:** The given data

<table>
<thead>
<tr>
<th>( \Delta H (\text{kJ/g mol}) )</th>
<th>g mol produced/g mol glucose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>-1330.51</td>
</tr>
<tr>
<td>Acetate</td>
<td>-887.01</td>
</tr>
<tr>
<td>Formate</td>
<td>-221.75</td>
</tr>
<tr>
<td>Lactate</td>
<td>-1330.51</td>
</tr>
<tr>
<td>Glucose</td>
<td>-2661.02</td>
</tr>
</tbody>
</table>

The enthalpy change in the solution was

\[
\Delta H_{\text{sol}} = \sum n_i \Delta H_i - \sum n_i \Delta H_i
\]

\[
= [(0.94)(-1330.51) + (1.05)(-887.01) + 1.76(-221.75) + 0.05(-1330.51)] - (1.00)(-2661.02) = [22.114 \text{ kJ/g mol glucose}]
\]

a. \[ \frac{22.17 \text{ kJ}}{g \text{ mol glucose}} \times \frac{1 \text{ g mol glucose}}{62 \text{ g cells}} = \frac{0.358 \text{ kJ/g cells}}{62 \text{ g cells}} \]
26.1

Assume that the furnace has to be ready to function at the operating temperature after 48 hours.

Oil required at idle \( \text{L used} \)

Operating for 48-hours: \( 270(48) = 12,960 \times 0.19 = 2,462 \)

Oil required for 6.5 hours of heating

Heating \( 60(6.5) \)

4,940 \( \times \) 0.19 = 930

Difference \( \$1,523 \)

The problems may have to do with excessive maintenance on shutting the furnace down and starting it up. The insulation may be damaged.

26.2

Nitrogen, in general, does not react with other chemical species during a combustion process, although some NOx forms, but its presence affects the outcome of the process because the sensible heat of nitrogen absorbs a large proportion of the energy released during the chemical process.

26.3

Moisture, in general, does not react chemically with any of the species present in the combustion chamber, but it absorbs some of the energy released during combustion, and it raises the dew point temperature of the combustion gases.

26.4

(a) reduces
(b) increases
(c) reduces

26.5

The reaction is:

\( \text{N}_2\text{H}_4(\ell) + \text{O}_2(g) \rightarrow \text{N}_2(g) + 2\text{H}_2\text{O}(g) \)

Calculate the material balance first:

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{N}_2\text{H}_4</td>
<td>\text{N}_2 \left( \frac{79}{21} \right) + 2 \left( \frac{79}{21} \right)</td>
</tr>
<tr>
<td>\text{O}_2</td>
<td>\text{O}_2</td>
</tr>
<tr>
<td>\text{N}_2</td>
<td>\text{H}_2\text{O}</td>
</tr>
</tbody>
</table>

The energy balance reduces to (with \( Q = 0 \)): \( \Delta H = 0 \), or \( \Delta H_{\text{products}} - \Delta H_{\text{reaction}} + \Delta H_{\text{ref}} = 0 \).

This solution uses the heats of combustion:

Heat of reaction

\[
\Delta H_{\text{ref}}^{\text{el}}(25) = -\left[ \sum \Delta H_{\text{products}}^\circ + \Sigma \Delta H_{\text{reaction}}^\circ \right] \\
= -\left[ 2(-10.8) + 0 \right] - \left\{ (-455.7)(1) + 0 \right\} \\
= [-21.6 + 455.7] = -23.97 \text{ k cal}
\]

Sensible heats:

\( \Delta H_{\text{products}} \) (continued)
Solutions Chapter 26

\[
\begin{align*}
\text{N}_2: & \quad 2 \left( \frac{79}{21} \right) (3.570 - 179) = 25.600 \text{ k cal} \\
\text{O}_2: & \quad 2 (3.745 - 175) = 7.140 \text{ k cal} \\
\text{N}_2\text{H}_4: & \quad 33.2 (100 - 25) = 2.49 \text{ k cal} \\
\sum & = 35.49 \text{ k cal}
\end{align*}
\]

\[\Delta H_{\text{rxn,app}} - \Delta H_{\text{rxn, (25)}} = 2.49 + 7.140 + 25.6 + 23.97 = 59.20 \text{ k cal}\]

Use trial and error

Assume 500°C:

\[\Delta H_{\text{rxn,app}}: \]

\[
\begin{align*}
\text{N}_2 & \quad 8.52 (3.396) = 29.0 \\
\text{O}_2 & \quad 1 (3.570) = 3.57 \\
\text{H}_2\text{O (g)} & \quad 2 (3.448) = 6.90 \\
& \quad 39.45 \text{ k cal}
\end{align*}
\]

39.45 - 59.20 = -19.75

Assume 1000°C:

\[
\begin{align*}
\text{N}_2 & \quad 8.52 (7.308) = 62.30 \\
\text{O}_2 & \quad 1 (7.741) = 7.74 \\
\text{H}_2\text{O (g)} & \quad 2 (9.01) = 18.02 \\
& \quad 88.06 \text{ kg cal}
\end{align*}
\]

88.06 - 59.20 = 28.86

Interpolate between 500°C and 1000°C:

\[
\frac{19.75}{28.86 - (-19.75)} = 0.406 \quad 0.406(500°C) = 203°C
\]

\[T = 500 + 203 \approx 700°C\]

Solutions Chapter 26

26.6

Basis: 20 ft³ C₄H₁₀ at 15.5 psia and 70°F (1 min)

\[\begin{align*}
F & = \text{C}_4\text{H}_{10} 100\% \\
\text{C}_4\text{H}_{10} & \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O}
\end{align*}\]

\[\text{C}_4\text{H}_{10} \quad \frac{13}{2} \text{O}_2 \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O}\]

\[
\begin{align*}
\text{C}_4\text{H}_{10} \quad \text{IN:} & \quad \frac{\text{pV}}{\text{RT}} = F = 15.5 \text{ psia} \quad \frac{20 \text{ ft}^3}{590°\text{R}} \quad \frac{1(\text{lb mol})}{(°\text{R})} \\
& = 0.0545 \text{ lb mol}
\end{align*}\]

Air IN:

\[
\begin{align*}
\text{O}_2 \quad \text{reqd} & \quad 0.0545 \left( \frac{13}{2} \right) = 0.354 \text{ lb mol} \\
\text{O}_2 \quad \text{xs} & \quad 0.0545 \left( \frac{13}{2} \right) (2) = 0.071 \\
\text{Total O}_2 & \quad 0.425 \\
\text{N}_2 \quad \text{in} & \quad 0.425 \left( \frac{79}{21} \right) = 1.599 \text{ lb mol}
\end{align*}\]

Material Balances

(continued)
Sensible heat of exiting gases

\[ \Delta H_{\text{CO}_2} = (0.218 \text{ lb mol})(36,953 \text{ Btu/lb mol}) = 8,056 \text{ Btu} \]

\[ \Delta H_{\text{H}_2} = (1.599)(24,560) = 32,721 \text{ Btu} \]

\[ \Delta H_{\text{H}_2\text{O}} = (0.273)(29,301) = 7,999 \text{ Btu} \]

\[ \Delta H_{\text{O}_2} = (0.070)(25,811) = 1,833 \text{ Btu} \]

\[ \Delta H = -62,349 + 50,159 - 8.5 = -12,198 \text{ Btu} \]

26.7

Steady state process, no reaction.

\[ \Delta H = \Delta H_{\text{h}} + \Delta H_{\text{f}} + \Delta H_{\text{reaction}} \]

Per g mol of C\text{C}_\text{H}_\text{O}_\text{S}

\[ \Delta H_{\text{h}} = 5(-241.826) + 4(-393.51) - (1(-124.73)) = -2658.44 \text{ kJ/g mol} \]

On the basis of 0.0545 lb mol C\text{C}_\text{H}_\text{O}_\text{S}

\[ 0.0545 \text{ lb mol} \times 454 \text{ g} = 2658.44 \text{ kJ} = 2658.44 \text{ Btu} \]

Sensible heat of entering C\text{C}_\text{H}_\text{O}_\text{S} (361 J/g mol)

\[ 0.0545 \text{ lb mol} \times 361 \text{ J} = 8.47 \text{ Btu} \]

<table>
<thead>
<tr>
<th>In</th>
<th>mass (lb)</th>
<th>(\Delta H) (Btu/lb)</th>
<th>(\Delta H) (Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>3000 (satd)</td>
<td>38.05</td>
<td>(1.14 \times 10^5)</td>
</tr>
<tr>
<td>(2)</td>
<td>F (satd)</td>
<td>38.05</td>
<td>38.05F</td>
</tr>
</tbody>
</table>
Out

(1) 3000 1469.2 $4.408 \times 10^6$
(1) F 1628.8 1628.8F

$\Delta H_{\text{out}} = \Delta H_{\text{in}} + Q$

$(1628.8F + 4.408 \times 10^6) - (38.05F + 1.14 \times 10^5) = 8 \times 10^6$

$F = 2316 \text{ lb/hr}$

26.8

Basis: 1 hr

The number of moles of flue gas is

$n_k = \frac{(1.3 \times 10^6 \text{ ft}^3 \times 1 \text{ atm} \times 1 \text{ lb mol}}{(1410 \text{ atm} \times 0.7302 \text{ ft}^3 \times 1 \text{ atm})} = 12.63 \text{ lb mol}$

26.9

Basis: 1 g mol $H_2(g)$

Assume $85^\circ C$ means the exit water is at $85^\circ C$, but the $H_2$ and $O_2$ enter at $25^\circ C$ for simplicity.

1 g mol $H_2(g)$ 25$^\circ C$

$\rightarrow O_2(g)$ 85$^\circ C$ 0.175 g mol
$H_2O(l)$ 85$^\circ C$ 0.65 g mol

0.5 g mol $O_2(g)$ 25$^\circ C$

$\rightarrow H_2(g)$ 85$^\circ C$ 0.35 g mol

The overall equation for the electro chemical reaction is

(continued)
Solutions Chapter 26

Anode: \[ \text{H}_2(g) \rightarrow 2\text{H}^+ + 2e^- \]
Cathode: \[ \frac{1}{2} \text{O}_2(g) + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O}(l) \]

Net reaction: \[ \text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) \]

Use the CD to get \( \Delta H \) for \( \text{O}_2 \) and \( \text{H}_2 \). The energy balance reduces to \( \Delta H = W \).

**Enthalpy in** Enthalpy out \( (\Delta H = \int C_p dT) \)
sensible heats: sensible heats:
\[ \Delta H \text{ of } \text{H}_2 = 0 \]
\[ \Delta H \text{ of } \text{H}_2\text{O}(l) = \frac{0.65 \times 4.18 \times 18 \times 85 - 25}{18 \text{ g} \times (\text{g} \times \text{C} \text{ mol})} = 2.937 \text{ kJ} \]
\[ \Delta H \text{ of } \text{O}_2 = 0 \]
\[ \Delta H \text{ of } \text{H}_2 = (0.35) (1.732) = 0.606 \]
\[ \Delta H \text{ of } \text{O}_2 = (0.175) (1.783) = 0.312 \]

\[ \Delta H^r \text{ of } \text{H}_2 = 0 \]
\[ \Delta H^r \text{ of } \text{O}_2 = 0 \]
\[ \Delta H^r (\text{kJ/g mol}) = -285.840 \text{ kJ/g mol} \]

\[ \Delta H^\text{rxn} = (0.65)[(-285.840) - 0] = -185.796 \text{ kJ/g mol } \text{H}_2 \]

\[ W = \Delta H^\text{rxn} - \Delta H^\text{in} + \Delta H^\text{in} = (0.606 + 0.312 + 2.937) - 0 + (-185.796) \]
\[ = -181.941 \text{ kJ} \]

\[ -181.941 \text{ kJ} \times 2.773 \times 10^{-4} \text{ kw} \text{h} = 0.0505 \text{ kWh} \]

26.10

The chemical formulas and combustion analyses are as follows:

**Combustion of iso-octane:**

\[ \text{C}_8\text{H}_{18} + \frac{12.5}{2} \text{O}_2 \rightarrow 8 \text{ CO}_2 + 9 \text{ H}_2\text{O} \]  \hspace{1cm} (1)

\[ \text{lb} = 114 + 400 = 514 \rightarrow 352 + 162 = 514 \]  \hspace{1cm} (2)

Combustion of ethyl alcohol:

\[ \text{C}_2\text{H}_5\text{OH} + 3 \text{ O}_2 \rightarrow 2 \text{ CO}_2 + 3 \text{ H}_2\text{O} \]  \hspace{1cm} (3)

\[ \text{lb} = 46 + 96 = 142 \rightarrow 88 + 54 = 142 \]  \hspace{1cm} (4)

Combustion of methyl alcohol:

\[ \text{CH}_3\text{OH} + 3/2 \text{ O}_2 \rightarrow \text{ CO}_2 + 2 \text{ H}_2\text{O} \]  \hspace{1cm} (5)

\[ \text{lb} = 32 + 48 = 80 \rightarrow 44 + 36 = 80 \]  \hspace{1cm} (6)

Combustion of methane:

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{ CO}_2 + 2 \text{ H}_2\text{O} \]

\[ \text{lb} = 16 + 32 = 80 \rightarrow 44 + 36 = 80 \]

**Results**

<table>
<thead>
<tr>
<th>Mol. wt.</th>
<th>lb per gal</th>
<th>per lb mol</th>
<th>per gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iso-Octane</td>
<td>114</td>
<td>5.793</td>
<td>2,173,000</td>
</tr>
<tr>
<td>Ethyl Alcohol</td>
<td>46</td>
<td>6.630</td>
<td>533,000</td>
</tr>
<tr>
<td>Methyl Alcohol</td>
<td>32</td>
<td>6.610</td>
<td>269,000</td>
</tr>
<tr>
<td>MTBE</td>
<td>88</td>
<td>6.2</td>
<td>1,328,800</td>
</tr>
<tr>
<td>CNG*</td>
<td>16</td>
<td>2.5*</td>
<td>341,000</td>
</tr>
</tbody>
</table>

*Effective density. Compressed natural gas dissolved in a suitable liquid.*

(continued)
Assume the exhaust gas has the same properties as air, or else the composition has to be known; $\Delta H$ data are from the CD.

$$\Delta H_{\text{meth}} = \left( \frac{n_{\text{H}} + n_{\text{CH}_4}}{\text{g mol}} \right) \left[ 19,132 \text{ J} / \text{g} \text{ mol} \right] \left( \frac{1}{1,055 \text{ J}} \right) = \left( n_{\text{CH}_4} + 11.61 \right)(8233) \text{ Btu}$$

$\Delta H$ IN at 130°F

$$\Delta H_{\text{meth}} = \left( n_{\text{CH}_4} + 11.61 \right)(857)(45.4) / 1,055 = 4282 \text{ Btu}$$

$8233 n_{\text{CH}_4} + 95,586 - 4,282 + n_{\text{CH}_4}(-3.802 \times 10^4) = 0$

$n_{\text{CH}_4} = 0.25 \text{ lb mol}$

The ft$^3$ at SC of CH$_4$ is [90/ min]

26.12

$\text{C}_3\text{H}_8 (g) + 9/2 \text{ O}_2 (g) \rightarrow 3 \text{ CO}_2 (g) + 3 \text{ H}_2\text{O} (g)$

Basis: 1 g mol C$_3$H$_8$ (g)

$\Delta E = 0 = -\Delta H + Q + W$ or $\Delta H = \Sigma \Delta H_{\text{prod}} - \Sigma \Delta H_{\text{react}} = 0$

(continued)
Solutions Chapter 26

Air in: req'd O₂: 9/2 g mol

\[ \text{xs 20\%} \quad (0.2) \quad (9/2) = 0.9 \text{ g mol} \]

N₂ in 5.4 \((79/21) = 20.31 \text{ g mol} \)

### Reactants

<table>
<thead>
<tr>
<th>g mol</th>
<th>Sensible heat</th>
<th>ΔHᵢₒ (kJ/g mol)</th>
<th>ΔHᵢₒ (kJ/g mol)</th>
<th>ΔH (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂H₆(g)</td>
<td>1</td>
<td>0</td>
<td>20.41</td>
<td>20.41</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>5.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₂(g)</td>
<td>20.31</td>
<td>0</td>
<td>0</td>
<td>20.41</td>
</tr>
</tbody>
</table>

### Products:

Assume T = 2000K

<table>
<thead>
<tr>
<th>g mol</th>
<th>ΔHᵢₒ (kJ/g mol)</th>
<th>ΔHᵢₒ (kJ/g mol)</th>
<th>ΔH (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂(g)</td>
<td>3</td>
<td>(92.466 - 912)</td>
<td>-393.51</td>
</tr>
<tr>
<td>H₂O(g)</td>
<td>3</td>
<td>(73.136 - 837)</td>
<td>-241.826</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>0.9</td>
<td>(59.914 - 732)</td>
<td>0</td>
</tr>
<tr>
<td>N₂(g)</td>
<td>20.31</td>
<td>(56.902 - 728)</td>
<td>0</td>
</tr>
</tbody>
</table>

Assume T = 2500K

<table>
<thead>
<tr>
<th>g mol</th>
<th>ΔHᵢₒ (kJ/g mol)</th>
<th>ΔHᵢₒ (kJ/g mol)</th>
<th>ΔH (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂(g)</td>
<td>3</td>
<td>(123.176 - 912)</td>
<td>-393.51</td>
</tr>
<tr>
<td>H₂O(g)</td>
<td>3</td>
<td>(98.867 - 837)</td>
<td>-241.826</td>
</tr>
<tr>
<td>O₂(g)</td>
<td>0.9</td>
<td>(79.119 - 732)</td>
<td>0</td>
</tr>
<tr>
<td>N₂(g)</td>
<td>20.31</td>
<td>(75.060 - 728)</td>
<td>0</td>
</tr>
</tbody>
</table>

By linear interpolation T = 2180K

Calculation T = 2250K, gives better precision \( T = 2217 \text{ K} \)

---

26.13

By making an adiabatic flame temperature calculation for each gas, the values, in order of increasing temperature, are found to be:

- CH₄ (3750°F)
- C₂H₆ (3820°F)
- C₄H₁₀ (3870°F)

Equilibrium aspects were not taken into account in the calculations. However, you can obtain the same relationships (but not the values of T) by looking at the values of ΔHᵢₒ.

---

26.14

Steps 1, 2, 3, and 4:

This is an open system with reaction. The process is in the steady state.

\[ \begin{align*}
F(g \text{ mol}) & \quad \text{CH}_4(g) \quad \text{H}_2 \text{O}(g) \quad \text{N}_2(g) \quad \text{O}_2(g) \quad \Sigma = P \\
100\% & \quad 1 \quad \text{mol} \quad \text{air} \quad 0.21 \quad 0.79 \quad 1.00 \\
T = 300K & \quad A(g \text{ mol}) \quad \text{O}_2 \quad \text{N}_2 \quad \Sigma = P \\
T = 25°C & \quad 1 \quad \text{mol} \quad \text{O}_2 \quad \text{N}_2 \\
\end{align*} \]

\[ \text{CH}_4(g) + 2 \text{O}_2(g) \rightarrow \text{CO}_2(g) + 2 \text{H}_2 \text{O}(g) \]

\[ \Delta H_i (kJ / g mol) = -74.84 \quad 0 \quad -393.51 \quad -241.826 \]

(continued)
Step 5: Basis: 1 g mol CH₄(g)

Step 4: Calculate the amount of entering air:

- O₂ required: 2 g mol
- O₂ entering: 2(1.10) = 2.20 g mol
- N₂ entering: 2.20 (0.79/0.21) = 8.28 g mol

Steps 5, 6, 7, 8, and 9

Calculate the amount of exit gas

<table>
<thead>
<tr>
<th>Balances (g mol)</th>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1</td>
<td>n₁CO₂</td>
</tr>
<tr>
<td>H</td>
<td>1(4)</td>
<td>n₂H₂O</td>
</tr>
<tr>
<td>O</td>
<td>2.20(2)</td>
<td>n₃O₂ + n₄H₂O + n₅CO₂(2)</td>
</tr>
<tr>
<td>N</td>
<td>8.28</td>
<td>n₅N</td>
</tr>
</tbody>
</table>

Summary of moles out:
- n₁CO₂ = 1 g mol
- n₅N = 8.28 g mol
- n₄H₂O = 2 g mol
- n₃O₂ = 0.20 g mol

The energy balance for an adiabatic process reduces to ΔH = 0 = \[ \sum_{\text{products}} n_i \Delta H_i - \sum_{\text{reactants}} n_i \Delta H_i \]. Because the outlet temperature is too calculated, if we use enthalpy tables for the gases, a trial and error solution is required. If we integrate heat capacity equations, solution of a cubic or quadratic equation in the outlet temperature is required (if truncate C_p equations).

<table>
<thead>
<tr>
<th>Compound</th>
<th>g mol</th>
<th>T</th>
<th>ΔH°(kJ/g mol)</th>
<th>ΔH°(kJ/g mol)</th>
<th>ΔH(kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
26.15

[Diagram showing reactions and mole flows]

Steady state process:

\[ \frac{\text{mol fr.}}{\text{g mol}} \]

\[ \text{CH}_4(g) \rightarrow 0.4 \]
\[ \text{CO}_2(g) \]
\[ \text{O}_2(g) \rightarrow 0.21 \]
\[ \text{N}_2(g) \rightarrow 0.79 \]
\[ 1.00 \]
\[ \text{Furnace} \]
\[ \text{CO}_2(g) \]
\[ \text{H}_2\text{O}(g) \]
\[ \text{N}_2(g) \]
\[ \text{O}_2(g) \]
\[ \frac{n_{\text{CO}_2}}{n_{\text{H}_2\text{O}}} \]
\[ \frac{n_{\text{N}_2}}{n_{\text{O}_2}} \]
\[ \Sigma = F \]

Basis: 1 g mol F

Calculation for xα air:

\[ \text{O}_2 \text{ red} \]
\[ g \text{ mol} \]
\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]
0.4(2) = 0.8
\[ \text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2 \]
0.4(1) = 0.2
\[ \text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} \]
0.2(1) = 0.1
\[ \text{xsO}_2: \]
1.1(3.0) = 3.3
\[ \text{Total O}_2 \text{ in:} \]
4.4
\[ \text{N}_2 \text{ in:} \]
4.4(3) = 16.55

Material balance for output (g mol)

\[ \text{CO}_2 \text{ (C balance)} \]
0.4 + 0.4 = 0.80
\[ \text{H}_2\text{O} \text{ (H}_2\text{ bal)} \]
0.4(2) + 0.2 = 1.0
\[ \text{O}_2 \text{ (O}_2\text{ bal)} \]
0.4(1) + 4.4 - 0.80 - 1.0(1) = 3.3 (the xs)

\[ \text{N}_2 \]
16.55

Energy balance reduces to \( Q = \Delta H \) and \( Q = 0 \) so \( \Delta H = 0 \)

Let \( T_{\text{ref}} = 25^\circ \text{C} \)

Let \( T = 1000^\circ \text{C} \)

Output | \( g \text{ mol} \) | \( \Delta H_f \) (cal/g mol) | \( \Delta H_{\text{ps}} \) (cal/g mol) | \( \Delta H \) (cal)
|---|---|---|---|
\( \text{CO}_2(g) \) | 0.8 | -94.052 | (11,846-217.9) | -65,939
\( \text{H}_2\text{O}(g) \) | 1.0 | -57.798 | (9210-200.3) | -48,788
\( \text{O}_2(g) \) | 16.55 | 0 | (7482-174) | +120,947
\( \text{N}_2(g) \) | 3.3 | 0 | (7916-175) | +25,545
Total | | | | +31,765

Input (stays same for each output \( T \))

\[ \text{CH}_4(g) \]
0.4
-17.889
0
-7,155.6
\[ \text{CO}(g) \]
0.4
-26,416
0
-10,566.4
\[ \text{H}_2(g) \]
0.2
0
0
0
\[ \text{O}_2(g) \]
4.4
0
0
0
\[ \text{N}_2(g) \]
16.55
0
0
0
Total
|-17,722

\( \Delta H = 31,765 - (-17,722) = 49,487 \) (too high)

Let \( T = 500^\circ \text{C} \)

Output

\| | \( g \text{ mol} \) | \( \Delta H_f \) (cal/g mol) | \( \Delta H_{\text{ps}} \) (cal/g mol) | \( \Delta H \) (cal)
|---|---|---|---|
\( \text{CO}_2(g) \) | 0.8 | -94,052 | (5340-217.9) | -71,144
\( \text{H}_2\text{O}(g) \) | 1.0 | -57,798 | (4254-200.3) | -53,744
\( \text{N}_2(g) \) | 16.55 | 0 | (3569-174) | +56,187
\( \text{O}_2(g) \) | 3.2 | 0 | (3745-175) | +11,781
Total | | | | -56,920

\( \Delta H = 56,920 - (-17,722) = 39,698 \) (too low)

(continued)
26.16

\[ Q = 0 \]

Fuel

100°F

\[ 20\% \text{xs air 60°F} \]

\[ \Delta H = \Delta H_{\text{fuel}} + \Delta H_{\text{air}} - \Delta H_{\text{excess}} = 0 \text{ so that } \Delta H_{\text{fuel}} = \Delta H_{\text{air}} - \Delta H_{\text{excess}} \]

\begin{enumerate}
  \item increase the inlet temperature of the fuel (increase \( \Delta H \) of reactants)
  \item increase the inlet temperature of the air (increase \( \Delta H \) of reactants)
  \item reduce the excess air (relative to the fuel) but still have complete combustion (the number of moles of \( N_2, O_2 \) are reduced), and use less energy to go from 77°F to the adiabatic reaction temperature)
  \item increase the concentration of CH₄ in the gas
  \item use oxygen enriched air
\end{enumerate}

Basis: 1 g mol CO; assume complete combustion because of the excess \( O_2 \)

Equation: \( CO + 0.5O_2 \rightarrow CO_2 \)

\( O_2 \) Required: \( 1 \text{ g mol } CO \times \frac{0.5 \text{ mol } O_2}{1 \text{ mol } CO} = 0.5 \text{ mol } O_2 \)

Excess \( O_2 \): \( (1+x)0.5 = \text{mols } O_2 \text{ in feed} \)

where \( x = \text{fraction excess } O_2 \)

Material Balance:

<table>
<thead>
<tr>
<th>Component</th>
<th>mols in</th>
<th>mols out</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1</td>
<td>( n_{CO_2} = 1 )</td>
</tr>
<tr>
<td>( O_2 )</td>
<td>0.5(1+x)</td>
<td>( n_{O_2} = 0.5x )</td>
</tr>
<tr>
<td>( N_2 )</td>
<td>0.5(1+x)(0.79/0.21)</td>
<td>( n_{N_2} = 1.88(1+x) )</td>
</tr>
</tbody>
</table>

Enthalpy Balance: (Using 25°C as the reference temperature)

Assume that \( Q \) is essentially zero. Then

\[ \text{(continued)} \]
\[ \Delta H_{\text{system}} = 0 \]

\[ \Delta H_{\text{out}} - \Delta H_{\text{in}} = 0 \]

\[ \Delta H_{\text{in}} = \sum \Delta H^\circ_r + \sum \int_{\text{ref}}^T C_p dT \]

\[ \Delta H_{\text{in}} = 1.0(\Delta H^\circ_{r,\text{C}_2\text{H}_6}) + 1.0(\Delta H_{\text{CO}_2,\text{ref}} - \Delta H_{\text{CO}_2,298\text{C}}) + (1 + 0.5x)(\Delta H_{\text{O}_2,\text{ref}} C - \Delta H_{\text{O}_2,298\text{C}}) + \]

\[ 1.88(1 + x)(\Delta H_{\text{H}_2,\text{ref}} C - \Delta H_{\text{H}_2,298\text{C}}) \]

\[ \Delta H_{\text{in}} = 1.0(-110520) + 1.0(7208.58 - 728) + (1 + 0.5x)(2744.92 - 732) + \]

\[ (1.88(1 + x)(2705.94 - 728) \]

\[ \Delta H_{\text{in}} = -102807.97 + 4724.99x \text{ J/mol} \]

\[ \Delta H_{\text{out}} = 1.0(\Delta H^\circ_{r,\text{C}_2\text{H}_6}) + 1.0(\Delta H_{\text{CO}_2,\text{ref}} - \Delta H_{\text{CO}_2,298\text{C}}) + 0.5x(\Delta H_{\text{O}_2,\text{ref}} C - \Delta H_{\text{O}_2,298\text{C}}) + \]

\[ 1.88(1 + x)(\Delta H_{\text{H}_2,\text{ref}} C - \Delta H_{\text{H}_2,298\text{C}}) \]

\[ \Delta H_{\text{out}} = 1.0(-393510) + 1.0(48474.44 - 912) + 0.5x(32428.44 - 732) + \]

\[ (1.88(1 + x)(30653.38 - 728) \]

\[ \Delta H_{\text{out}} = -289687.85 + 72107.93x \text{ J/mol} \]

\[ \Delta H_{\text{out}} - \Delta H_{\text{in}} = 0 = -289687.86 + 72107.93x - (-102807.97 + 4724.99x) \]

Solve for \(x\): \(x = 2.76\)

Percent Excess Air = 276%
and solve the polynomial equation obtained by integration via a computer code. The following is trial and error.

Assume $T = 2250$ K

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>$\Delta H (kJ/g mol)$</th>
<th>$\Delta H^* (kJ/g mol)$</th>
<th>$\Delta H (kJ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>99.0</td>
<td>(107.738 - .912)</td>
<td>-393.51</td>
<td>-28,381.72</td>
</tr>
<tr>
<td>H₂O</td>
<td>192.0</td>
<td>(85.855 - .837)</td>
<td>-241.83</td>
<td>-30,107.90</td>
</tr>
<tr>
<td>N₂</td>
<td>723.4</td>
<td>(65.981 - .728)</td>
<td>0</td>
<td>-47,206.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-11,285.60</td>
</tr>
</tbody>
</table>

Assume $T = 2500$ K

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>$\Delta H (kJ/g mol)$</th>
<th>$\Delta H^* (kJ/g mol)$</th>
<th>$\Delta H (kJ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>99.0</td>
<td>(123.176 - .912)</td>
<td>-393.51</td>
<td>-26,853.35</td>
</tr>
<tr>
<td>H₂O</td>
<td>192.0</td>
<td>(98.867 - .837)</td>
<td>-241.83</td>
<td>-27,608.60</td>
</tr>
<tr>
<td>N₂</td>
<td>723.4</td>
<td>(75.060 - .728)</td>
<td>0</td>
<td>-53,742.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-720.92</td>
</tr>
</tbody>
</table>

$T = \frac{(-11,285) - (-8429)}{(-11,285) - (-721)} = 2318$ K

b. Oil

Basis: 100 g oil = 0.438 g mol C₁₆H₃₄ (mol wt = 226.27)

$C₁₆H₃₄ + 24.5 O₂ → 16 CO₂ + 17 H₂O$

$S + O₂ → SO₂$

$S = 0.031$ g mol

Ignore the $\Delta H$ of the oil and $S$.

<table>
<thead>
<tr>
<th>In:</th>
<th>g mol</th>
<th>Out:</th>
<th>g mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ req'd</td>
<td>10.75</td>
<td>CO₂</td>
<td>7.008</td>
</tr>
<tr>
<td>N₂ in</td>
<td>40.36</td>
<td>H₂O</td>
<td>7.446</td>
</tr>
</tbody>
</table>

$\Delta H_{com} = -10,505.6$ cal/g.

$\Delta H_{rxn} = \frac{99 g}{g} \frac{-10,505.6 \text{ cal}}{4.184 \text{ J}} = -4351.59$ kJ

$\Delta H_{mol}$ for $S = \frac{-296.90 \text{ kJ}}{0.031 \text{ g mol}} = -9.20$ kJ

$\Delta H_{mol} = -4371.23$ kJ

Assume $T = 2250$ K

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>$\Delta H (kJ/g mol)$</th>
<th>$\Delta H^* (kJ/g mol)$</th>
<th>$\Delta H (kJ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>7.008</td>
<td>(107.738 - .912)</td>
<td>-393.51</td>
<td>-2009.08</td>
</tr>
<tr>
<td>H₂O</td>
<td>7.446</td>
<td>(85.855 - .837)</td>
<td>-241.826</td>
<td>-1167.59</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.031</td>
<td>(105.562 - .984)</td>
<td>-296.90</td>
<td>2633.61</td>
</tr>
<tr>
<td>N₂</td>
<td>40.36</td>
<td>(65.981 - .728)</td>
<td>0</td>
<td>-543.06</td>
</tr>
</tbody>
</table>

Assume $T = 2500$ K

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>$\Delta H (kJ/g mol)$</th>
<th>$\Delta H^* (kJ/g mol)$</th>
<th>$\Delta H (kJ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>7.008</td>
<td>(123.176 - .912)</td>
<td>-393.51</td>
<td>-1900.89</td>
</tr>
<tr>
<td>H₂O</td>
<td>7.446</td>
<td>(98.867 - .837)</td>
<td>-241.826</td>
<td>-1070.71</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.031</td>
<td>(119.971 - .984)</td>
<td>-296.90</td>
<td>-5.52</td>
</tr>
<tr>
<td>N₂</td>
<td>40.36</td>
<td>(75.060 - .728)</td>
<td>0</td>
<td>3000.04</td>
</tr>
</tbody>
</table>

$T = 2395$ K (continued)
c. Coke Basis: 100 g

\[ C = 95 \text{ g} \quad \text{ash} = 5 \text{ g} \]
\[ = 7.917 \text{ mol} \]
\[ C + O_2 \rightarrow CO_2 \]
\[ \text{Out:} \quad \text{O}_2 \text{ req'd} = 7.917 \text{ g mol} \quad \text{CO}_2 = 7.907 \text{ g mol} \]
\[ N_2 = 29.782 \text{ g mol} \quad N_2 = 29.782 \text{ g mol} \]

In:
\[ \Delta H_{\text{inlet}} \]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g or mol</th>
<th>C or ( \Delta H ) (kJ)</th>
<th>( \Delta T )</th>
<th>( \Delta H ) (kJ)</th>
<th>( \Delta H^r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>7.917</td>
<td>11 (J/g mol) (K)</td>
<td>-7</td>
<td>-0.6096</td>
<td>0</td>
</tr>
<tr>
<td>ash</td>
<td>5</td>
<td>1.15 (J/g) (°C)</td>
<td>-7</td>
<td>-0.040</td>
<td>?</td>
</tr>
<tr>
<td>O_2</td>
<td>7.917</td>
<td>(.527-.732)</td>
<td>-1.623</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>N_2</td>
<td>29.782</td>
<td>(.524-.728)</td>
<td>-6.075</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>-8.348</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Out:
Assume \( T = 2250 \text{ K} \)

\[ \Delta H_{\text{outlet}} \]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>mol</th>
<th>( \Delta H ) (kJ/g mol)</th>
<th>( \Delta H^r )</th>
<th>( \Delta H ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO_2</td>
<td>7.917</td>
<td>(107.738-.912)</td>
<td>-393.51</td>
<td>-2269.68</td>
</tr>
<tr>
<td>N_2</td>
<td>29.782</td>
<td>(65.981-.728)</td>
<td>0</td>
<td>1943.36</td>
</tr>
<tr>
<td>ash</td>
<td>5</td>
<td>C_p\Delta T = 1.15 (527-25)</td>
<td>?</td>
<td>2.80</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>-323.51</td>
<td></td>
</tr>
</tbody>
</table>

Assume \( T = 2500 \text{ K} \)

\[ \Delta H^r \text{ kJ/g mol} \]

\[ \Delta H^r (\text{kJ/g mol}) = -74.84 \quad 0 \quad -393.51 \quad -241.826 \]

Material Balance: Basis: 1 g mol CH_4 (= 16 g CH_4)
### Flow process, steady state, no Q, W, ΔPE, ΔKE

$\Delta H = 0$

$\Delta H_{\text{products}} + \Delta H_{\text{reactants}} = \Delta H_{\text{reaction}}$

(include the liquid water in the products and reactants)

Let $W = g$ mol liquid $H_2O$ at 310°F

$\Delta H_{\text{reactants}}$

$\Delta H_{\text{reactants}} = [(2)(-241.826) + (1)(-393.51)] - [0 + (1)(-74.84)]$

$= -877.162 + 74.84 = -802.322 \text{ kJ/g mol CH}_4$

<table>
<thead>
<tr>
<th>$\Delta H_{\text{products}}$</th>
<th>$\Delta H(J/g \text{mol})$</th>
<th>$g \text{ mol}$</th>
<th>$\Delta H(J)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CO}_2 (g)$</td>
<td>(6064-912)</td>
<td>1</td>
<td>5152</td>
</tr>
<tr>
<td>$\text{N}_2 (g)$</td>
<td>(4491-728)</td>
<td>7.9</td>
<td>27,728</td>
</tr>
<tr>
<td>$\text{O}_2 (g)$</td>
<td>(4578-732)</td>
<td>0.1</td>
<td>385</td>
</tr>
<tr>
<td>$H_2O(g)$ satd</td>
<td>(5220 - 837)</td>
<td>21.63</td>
<td>94,804</td>
</tr>
</tbody>
</table>

$H_2O(l)@310°F \quad [(279.92 - 45) \text{ Btu/ lb }] \quad W \quad 9826 \text{ W}$

$\Delta H_{H_2O(l)}$ at 77°F = $\frac{1 \text{ Btu}}{(\text{lb})(\text{°F})} (77 - 32) = 45 \text{ Btu/lb}$

$\frac{18 \text{ lb}}{1 \text{ lb mol}} \quad 1055 \text{ J} \quad 1 \text{ lb mol} \quad 454 \text{ g mol}$

Total = 128,077 + 9826 W

**NOTE:**

$\frac{n_{H_2O}}{n_{by \text{ lb}}} = \frac{p}{P_{H_2O}} = \frac{77.68}{110 - 77.68} = 2.40$ hence $n_{H_2O} = 9(2.40) = 21.63$

$\Delta H_{\text{products}}$

$\frac{\Delta H(J/g \text{mol})}{\text{g mol}} \quad \frac{\Delta H(J)}{

<table>
<thead>
<tr>
<th>$\text{CH}_4 (g)$</th>
<th>(561 - 879)</th>
<th>1</th>
<th>-318</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{O}_2 (g)$</td>
<td>(466 - 728)</td>
<td>2.1</td>
<td>-544</td>
</tr>
<tr>
<td>$\text{N}_2 (g)$</td>
<td>(466 - 728)</td>
<td>7.9</td>
<td>-2070</td>
</tr>
<tr>
<td>$H_2O (l)$</td>
<td>(157.95 - 45)</td>
<td></td>
<td>$\frac{18}{454}$ (1055) (W + 21.63-2)</td>
</tr>
</tbody>
</table>

128,077 + 9826 W + (-802,322) = -2942 + 4724.5 W + 92742 W = 149.8

(149.8) (18/16) = $168.5 \text{ lb H}_2O/\text{lb CH}_4$

### 26.20

**Assumptions**

1. The tank is adiabatic for the short period of time involved.
2. Both the reactants and products are ideal gases.
3. There is no work.
4. Combustion is complete. (continued)
5. Unsteady state process.
6. Closed system.

The reaction is \( H_2(g) + \frac{1}{2} O_2(g) \rightarrow H_2O(g) \)

The energy balance reduces to

\[
\Delta U = 0 = \Delta H - \Delta(pV)
\]

\[
\Delta U = \Delta H_{\text{prod}} - \Delta H_{\text{react}} + \Delta H^e(m)(25^\circ C) - V \Delta p = 0
\]

The final temperature comes from the value of \( \Delta U \).

**Basis:** 1 g mol of \( H_2 \)

**Reference temperature:** 25\(^\circ\)C

\[
\Delta H_{\text{react}}(25^\circ C) = \sum n_i \Delta H^e_i - \sum n_i \Delta H^f_i
\]

\[
= (1)(-241,820) - \left( \frac{1}{2} \right) 0 - (1)0 = -241,820 \text{ kJ/mol } H_2
\]

\[
\Delta H_{\text{prod}}(25^\circ C)
\]

All values are zero because \( \Delta T = 0 \) from the reference \( T \).

**Calculate \( \Delta H \) of the products at \( T \)**

If you integrate the heat capacity equations to get \( \Delta H_{\text{prod}} \), you will have to solve a cubic or quadratic equation (if you truncate the equation) in \( T \). Alternately you can use the tables for the combustion gases in the Appendix. Don’t forget to subtract \( \Delta H \) (25\(^\circ\)C) because the reference \( T \) for the tables is 0\(^\circ\)C.

If the gas is ideal, \( \Delta(pV) = R \Delta(nT) \). Note that \( n_1 = 3.38 \text{ g mol} \) and \( n_2 = 2.88 \text{ g mol} \), and \( T_{\text{final}} \) is the single unknown.

\[
\Delta(pV) = \frac{8.314 \text{ J}}{\text{(g mol)(K)}} \left[ (2.88 \text{ g mol})(T \text{ in K}) - 3.38(298) \right]
\]

\[
= 23.94 T - 8374 \text{ in J}
\]

\[
\Delta H_{\text{prod}} - \Delta(pV) = 241,820
\]

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>( \Delta H ) (kJ/g mol); ( T_{\text{ref}} = 298 )</th>
<th>3000K</th>
<th>3500K</th>
<th>3000K</th>
<th>3500K</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2O ) (g)</td>
<td>1</td>
<td>124.683</td>
<td>151.963</td>
<td>124.683</td>
<td>151.963</td>
<td></td>
</tr>
<tr>
<td>( N_2 ) (g)</td>
<td>1.88</td>
<td>92.784</td>
<td>111.403</td>
<td>174.434</td>
<td>209.438</td>
<td></td>
</tr>
<tr>
<td>(-\Delta(pV))</td>
<td></td>
<td>-63.446</td>
<td>-83.782</td>
<td>235.67</td>
<td>277.62</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>235.67</td>
<td>277.62</td>
<td></td>
</tr>
</tbody>
</table>

Linear interpolation to 241.820 gives \( T \approx 3045\text{K} \).

Assume ideal gas at 25\(^\circ\)C and 1 atm. Then the tank volume is

\[
3.38 \text{ g mol} \times 1 \text{ kg} = \frac{22.415 \text{ L}}{1000 \text{ g mol}} = 0.0758 \text{ L}
\]

To avoid calculating \( z \), assume ideal gas at final conditions (otherwise use Kay’s method). The final pressure is

\[
p = \frac{nRT}{V} = \frac{2.88 \times 10^{-3} \text{ g mol}}{(0.08206(L)(atm))(g \text{ mol})(K)(0.0758 \text{ L})} \approx 962 \text{ kPa}
\]

This pressure probably does not exceed the specifications for the tank.
26.21

Assumptions

(1) The reactants and products are ideal gases
(2) Combustion is complete
(3) The process is unsteady state, closed system

The reaction is

\[ \text{C}_7\text{H}_{18}(g) + 12.5 \text{ O}_2(g) \rightarrow 8 \text{ CO}_2(g) + 9 \text{ H}_2\text{O}(g) \]

The energy balance reduces to

\[ \Delta U = Q + W \quad \text{or} \quad Q = \Delta U - W \]

Let \( \Delta U = \Delta H_{\text{rea}} - \Delta H_{\text{rea}} + \Delta H_{\text{rea}}(25^\circ \text{C}) \)

If you want to calculate \( \Delta U_i \) for each compound,

\[ \Delta U_i = \Delta H_i - \Delta(pV)^i = \Delta H_i - R(298)(\Delta n) \]

for an ideal gas. For \( \text{C}_7\text{H}_{18} \), the correction is +19.8 J/g mol and for \( \text{H}_2\text{O} \) the correction is +1.24 J/g mol.

Number of initial moles

\[ n_{\text{init}} = \frac{(300 \text{ kPa})(0.8 \text{ m}^3)(\text{kg mol})(K)}{(8.314 \text{ kJ} / \text{mol} \cdot \text{K})(298 \text{ K})} = 0.0969 \text{ kg mol} \quad \text{or} \quad 96.9 \text{ g mol} \]

Let \( x = \text{ mol of C}_7\text{H}_{18} \). Then \( x + 12.5x + 12.5x(79/21) = 96.9 \); \( x = 1.602 \)

<table>
<thead>
<tr>
<th>Initial component g mol</th>
<th>Final component g mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{C}<em>7\text{H}</em>{18} )</td>
<td>1.602</td>
</tr>
<tr>
<td>( \text{O}_2 )</td>
<td>20.0</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>75.3</td>
</tr>
</tbody>
</table>

\( \Delta H_{\text{rea}}(25^\circ \text{C}) \)

\[ \Delta H_{\text{rea}}(25^\circ \text{C}) = \sum n_i \Delta H^0_i - \sum n_i \Delta H^0_p_i \]

\[ = (12.8)(-393.520) + (14.4)(-241.820)-(1.602)(-208.450) = -8.185 \text{ kJ} \]

\( \Delta H_{\text{rea}}(25^\circ \text{C}) = 0 \) because the reactants are at the reference temperature.

\( \Delta H_{\text{rea}}(1000 \text{ K}) \) Data from the tables in Appendix D6. Or use the integration of the heat capacity equations or the CD.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>( \Delta H(1000\text{K} - 298\text{K})) kJ/g mol</th>
<th>( \Delta H ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}_2 )</td>
<td>75.3</td>
<td>21.443</td>
<td>1,615</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>14.4</td>
<td>25.986</td>
<td>374</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>12.8</td>
<td>33.396</td>
<td>427</td>
</tr>
<tr>
<td>Total</td>
<td>102.5</td>
<td>2,416</td>
<td></td>
</tr>
</tbody>
</table>

The final volume is

\[ \frac{V}{p} = \frac{nRT}{p} = \frac{(0.1025)(8.314)(1000)}{300} = 2.841 \text{ m}^3/\text{kg mol} \]

\( = 2.841 \text{ L/g mol} \)

Work against the atmosphere on expansion (continued)
\[
W = -\int pdV = -p\Delta V = -\Delta pV = -RT\Delta(T)
\]
\[
= - \left[ 8.314 \text{(J/g mol)} \right] \left[ (102.5)(1000) - (96.9)(298) \right] \text{(g mol)} \text{(K)}
\]
\[
= -612.11 \times 10^3 \text{ J or } -612.11 \text{ kJ}
\]
\[
Q = [2.416 - 0 + (-8.185)] - [-612] = -5.157 \text{ kJ}
\]

Solutions Chapter 26

26.22

Open process, steady state

\[ Q = \Delta H = \Delta H_{\text{fus}} - \Delta H_{\text{res}} + \Delta H_{\text{ref}} \]

\[ \text{C}_4\text{H}_{10}(g) \to \text{C}_4\text{H}_6(g) + 2\text{H}_2(g) \]

Basis: 1 g mol butane gas

\[ Q = \Delta H_{\text{fus}} - \Delta H_{\text{res}} + \Delta H_{\text{ref}}(25^\circ C) \]

\[ \Delta H_f^o(\text{C}_4\text{H}_6)_{\text{gas}} = -165.5 \text{ kJ/g mol} \quad (-162.2 \text{ from the CD}) \]

\[ \Delta H_f^o(\text{C}_4\text{H}_8)_{\text{gas}} = -124.73 \text{ kJ/g mol} \]

\[ \Delta H_{\text{ref}} = (1)(-165.5) + (2)(0) - (1)(-124.73) = -40.77 \text{ kJ} \]

Sensible heats:

\[ T = 1000 \text{K} \quad T_{\text{ref}} = 25^\circ C (298 \text{K}) \]

\[ \Delta H = \int_{298}^{1000} C_p dT \]

\[ C_p = a + bT + cT^2 + dT^3 \]

\[ \therefore \Delta H = aT + \frac{b}{2} T^2 + \frac{c}{3} T^3 + \frac{d}{4} T^4 \]

\[ \Delta H_{\text{C}_4\text{H}_8} = 11.92T + 1.346 \times 10^{-1}T^2 - 4.767 \times 10^{-3}T^3 + 7.368 \times 10^{-4}T^4 \]

\[ \Delta H_{\text{C}_4\text{H}_8} = 91.92 \text{ kJ/g mol} \]

\[ \Delta H_{\text{C}_4\text{H}_6} = 92.3T + 1.394 \times 10^{-1}T^2 - 5.157 \times 10^{-3}T^3 + 8.745 \times 10^{-4}T^4 \]

(continued)
\[ \Delta H_{f, \text{butadiene}} = 121.0 \text{ kJ/g mol} \]

\[ \Delta H_{f, \text{H}_{2}} = 28.84 T + 3.825 \times 10^{-5} T^2 + 1.096 \times 10^{-6} T^3 - 2.175 \times 10^{-8} T^4 \]

\[ \Delta H_{f, \text{H}_{2}O} = 20.63 \text{ kJ/g mol} \]

\[ Q = \Delta H = 2(20.63) + l(91.92) - l(121.0) + (-40.77) = -28.59 \text{ kJ/g mol butadiene} \]

Alternately you can use tables of \( \Delta H \) values or the CD that accompanies the book to get the \( \Delta H_{\text{prod}} \) and \( \Delta H_{\text{react}} \). The answer for the enthalpy change is -25.3 kJ.

**Heat Transfer:**

\[ \Delta H_{\text{heat}} = [(165.5)l - (-147.6)l] + 133.18 - 121.0 = -5.72 \text{ kJ/g mol} \]

The actual heat load may be different because:

1. the reaction may not go to completion
2. side reactions are possible
3. the effect of pressure is not included
4. insulation may be bad

26.23

**Steps 1, 2, 3, and 4:**

This is a steady state problem involving an open system and reaction. All the temperatures for the stream flows are given and shown in the diagram. The reaction is

\[ \text{CH}_3\text{OH}(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{CO}(g) + \text{H}_2\text{O}(g) \]

\[ \Delta H_f (kJ/gmol): \quad -201.25 \quad 0 \quad -115.89 \quad -241.826 \]

---

**Step 5**

Basis: 1 g mol CH\(_3\)OH(g)

**Steps 6, 7, 8, and 9:**

The energy balance reduces to

\[ Q = \Delta H = \sum_{\text{products}} \Delta H_i - \sum_{\text{reactants}} \Delta H_i \]

We will use the heat capacity equations to calculate the sensible heats instead of the enthalpy tables. The balances will have the energy units of kJ.

\[ \Delta H_\text{products} = \int \left[ -115.89 + (10^{-3}) \left( 34.28 + 4.268 \times 10^{-2} T - 8.694 \times 10^{-4} T^2 \right) \right] dt \]

\[ + \int \left[ -241.826 + (10^{-3}) \left( 33.46 + 0.688 \times 10^{-2} T + 0.7604 \times 10^{-4} T^2 + 3.593 \times 10^{-6} T^3 \right) \right] dt \]

\[ = -115.89 \times 10^{-3} [5999 + 840.26 - 3.477] \]

\[ -241.826 \times 10^{-3} [5855.5 + 135.45 + 20.238 - 1.43] \]

\[ = -115.89 + 6.84 - 241.826 + 6.010 \]

\[ = -344.87 \text{ kJ} \]

(continued)
\[ \Delta H_{\text{reaction}} = 1 \left[ -201.25 \times (10^{-5}) \right]_{15}^{100} \left( 42.93 + 8.301 \times 10^{-5}T - 1.87 \times 10^{-5}T^2 - 8.03 \times 10^{-9}T^3 \right) dT \]
\[ + \frac{1}{2} \left[ 0 + (10^{-3}) \right]_{23}^{30} \left( 29.10 + 1.158 \times 10^{-5}T - 0.6076 \times 10^{-5}T^2 + 1.311 \times 10^{-8}T^3 \right) dT \]
\[ = \left[ -201.25 \times (10^{-5}) \right] \left( 3219.75 + 389.109 - 6.136 - 0.19996 \right) \]
\[ + \frac{1}{2} \left[ 0 + (10^{-3}) \right] \left( 2182.5 + 54.281 - 1.994 + 0.03265 \right) \]
\[ = -201.25 + 3.602 + 0 + 1.117 \]
\[ = -196.53 \text{ kJ} \]
\[ Q = \left( -344.87 - (-196.53) \right) = -148.34 \text{ kJ/g mol CH}_4\text{OH} \] (heat removed)

26.24

Steps 1, 2, 3, and 4

This is a steady state problem involving an open system and reaction. All the known data has been placed in the figure. The surroundings are an open system comprised of the water. \( \text{N}_2\text{H}_4 \) is liquid.

<table>
<thead>
<tr>
<th>H2O 400 kg/min, 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 50 \text{ kg mol} )</td>
</tr>
<tr>
<td>( 400 \text{ K} )</td>
</tr>
<tr>
<td>( \text{N}_2\text{H}_4 )</td>
</tr>
<tr>
<td>( 900 \text{ K} )</td>
</tr>
<tr>
<td>( \text{P} )</td>
</tr>
<tr>
<td>( \text{N}_2 ) 0.739</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} ) 0.174</td>
</tr>
<tr>
<td>( \text{O}_2 ) 0.087</td>
</tr>
<tr>
<td>( 1.000 )</td>
</tr>
</tbody>
</table>

Air Supplied = 476.2 kg mol

Steps 5, 6, 7, 8, and 9

The material balances (in kg mol) for the process give are:

<table>
<thead>
<tr>
<th>Balance</th>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{O} )</td>
<td>200</td>
<td>( n_{\text{H}<em>2\text{O}} + 2n</em>{\text{O}_2} )</td>
</tr>
<tr>
<td>( \text{N} )</td>
<td>( 50(2) + 2(376.3) )</td>
<td>( n_{\text{N}_2}(2) )</td>
</tr>
<tr>
<td>( \text{H} )</td>
<td>50(4)</td>
<td>( n_{\text{H}_2\text{O}}(2) )</td>
</tr>
</tbody>
</table>

The results are:

Out (kg mol)
Solutions Chapter 26

\[ n_{H_2O} = 100 \]
\[ n_{N_2} = 426.2 \]
\[ n_{O_2} = 50 \]
Total: 576.2

The energy balance can be reduced to

\[ Q = \Delta H \]

for both the water and combustion chamber. The reference state is 25°C and one atm. The first system is the combustion chamber.

System: Combustion Chamber

\[ Q = \Delta H_{product} - \Delta H_{reactants} = \sum_{product} n_i \Delta H_i - \sum_{reactants} n_i \Delta H_i \]

We can use the heat capacity equations or the enthalpy tables to get \( \Delta H_i \).

<table>
<thead>
<tr>
<th>Products</th>
<th>kg mol</th>
<th>( T )</th>
<th>( \Delta H^p_i ) (kJ/kg mol)</th>
<th>( \Delta H^vap_i ) (kJ/kg mol)</th>
<th>( \Delta H_i ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2O(g) )</td>
<td>100</td>
<td>900K</td>
<td>-241.826</td>
<td>(22,760-837)</td>
<td>-2.199 \times 10^7</td>
</tr>
<tr>
<td>( N_2(g) )</td>
<td>426.2</td>
<td>900K</td>
<td>0</td>
<td>(18,961-728)</td>
<td>0.777 \times 10^7</td>
</tr>
<tr>
<td>( O_2(g) )</td>
<td>50</td>
<td>900K</td>
<td>0</td>
<td>(19,970-732)</td>
<td>0.096 \times 10^7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1.266 \times 10^7</td>
</tr>
</tbody>
</table>

\[ \begin{align*}
\Delta H_{product} &= 3.658 \times 10^4 \text{ kJ} / 60 = 6.096 \times 10^2 \text{ kJ/min} \\
\Delta H_{reactants} &= \frac{1 \text{ min}}{400 \text{ kg}} \cdot 914 \text{ kJ/kg which corresponds to a mixture of liquid and vapor.} \\
\text{At one atm and } \Delta H &= 914 \text{ kJ/kg (relative to 25°C), the water can be a two phase system. The water vapor from the steam tables at 1 atm is } \Delta H \text{ of saturated water vapor} = 2675.6 \cdot 107 = 2569 \text{ kJ/kg, and } \Delta H \text{ for liquid water is 419.5 - 107 = 313 kJ/kg.}
\end{align*} \\
\frac{914}{313} (1-x) + 2569.6x \\
\text{x = 0.266 is a significant fraction of vapor}

Consequently, the exit line has to be quite large to accommodate the vapor and liquid flow rate which is: volume per kg = 0.266 (1.673) + 0.734 (0.001043) = 0.445 m³/kg. Multiply by 400 kg/min = 178 m³/min

26.25

Material balance

Assume inputs are at 77°F, the reference temperature

Basis: 100g mol fg.

(continued)
Solutions Chapter 26

\[ \text{CH}_4 \xrightarrow{77^\circ F} \text{before} \quad \text{after} \quad 7.8 \quad \text{CO}_2 \quad 8.7 \quad 490^\circ \text{F or} \quad 515^\circ \text{F} \]

\[ \text{H}_2\text{O} \quad \text{N}_2 \]

\[ \text{air} \quad 3.9 \quad 0.21 \quad \text{O}_2 \quad 1.9 \quad 0.72 \quad \text{N}_2 \quad 1.00 \]

Both before and after the energy balance for an open steady state process reduces to \( Q = \Delta H \). Assume that \( Q \) before = \( Q \) after.

Let \( P_b \) = the g mol of flue gas before the change in \( x \) as air.

\( P_a \) = the g mol of flue gas after the change in \( x \) as air.

The reaction is

\[ \text{CH}_4(g) + 2 \text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(g) \]

\( \Delta H^\circ_r (\text{kJ/g mol}) = -7484 \quad 0 \quad -393.51 \quad -241.826 \)

The respective material balances are:

**Case 1 - Before**

**Basis: 100 g mol P**

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>C: ( n_{\text{CH}_4} ) =</td>
<td>( n_{\text{CO}_2} ) = 7.8</td>
</tr>
<tr>
<td>H: ( 4n_{\text{CH}_4} ) =</td>
<td>( 2n_{\text{H}_2\text{O}} ) = 15.6</td>
</tr>
<tr>
<td>2O: 0.21A =</td>
<td>7.8 + 3.9 + 0.5(15.6) = 19.5</td>
</tr>
</tbody>
</table>

\[ A = 19.5/0.21 = 92.86 \]

\( n_{\text{N}_2} \) in = \( n_{\text{N}_2} \) out = 73.36

**Summary**

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 7.8 )</td>
<td>( \text{CH}_4 ) =</td>
</tr>
<tr>
<td>19.5</td>
<td>( \text{O}_2 ) = 3.9</td>
</tr>
<tr>
<td>73.36</td>
<td>( \text{N}_2 ) = 73.36</td>
</tr>
<tr>
<td>-</td>
<td>( \text{CO}_2 ) = 7.8</td>
</tr>
<tr>
<td>-</td>
<td>( \text{H}_2\text{O} ) = 15.6</td>
</tr>
<tr>
<td>100.66</td>
<td>100.66</td>
</tr>
</tbody>
</table>

**Case 1 - After Basis: 100 mol of P after**

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.7</td>
<td>( \text{CH}_4 ) =</td>
</tr>
<tr>
<td>19.3</td>
<td>( \text{O}_2 ) = 1.9</td>
</tr>
<tr>
<td>72.6</td>
<td>( \text{N}_2 ) = 72.6</td>
</tr>
<tr>
<td>-</td>
<td>( \text{CO}_2 ) = 8.7</td>
</tr>
<tr>
<td>-</td>
<td>( \text{H}_2\text{O} ) = 17.4</td>
</tr>
<tr>
<td>100.6</td>
<td>100.6</td>
</tr>
</tbody>
</table>

These values are good enough to get percents of each component.

**Energy Balances**

**Case 1 - Before**

Assume reactants enter at 25°C (298 K), the reference T.

(continues)
### Solutions Chapter 26

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>T(K)</th>
<th>$\Delta H^\circ_r$ (kJ/g mol)</th>
<th>$\Delta H^\circ_{f}$(kJ/g mol)</th>
<th>$\Delta H$(kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>7.8</td>
<td>298</td>
<td>-74.84</td>
<td>0</td>
<td>-583.752</td>
</tr>
<tr>
<td>O₂</td>
<td>9.5</td>
<td>298</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₂</td>
<td>73.36</td>
<td>298</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>100.66</td>
<td>298</td>
<td></td>
<td></td>
<td>-583.752</td>
</tr>
<tr>
<td>OUT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>7.8</td>
<td>541.5</td>
<td>-393.51</td>
<td>10.255</td>
<td>-2989.389</td>
</tr>
<tr>
<td>H₂O</td>
<td>15.6</td>
<td>541.5</td>
<td>-241.826</td>
<td>8.494</td>
<td>-3639.979</td>
</tr>
<tr>
<td>O₂</td>
<td>3.9</td>
<td>541.5</td>
<td>0</td>
<td>7.462</td>
<td>29.102</td>
</tr>
<tr>
<td>N₂</td>
<td>73.36</td>
<td>541.5</td>
<td>0</td>
<td>7.172</td>
<td>526.133</td>
</tr>
<tr>
<td></td>
<td>100.66</td>
<td>541.5</td>
<td></td>
<td></td>
<td>-6074.128</td>
</tr>
</tbody>
</table>

**Case II – After. Assume reactants enter at 25°C (298K). Let P = g mol kg final.**

<table>
<thead>
<tr>
<th>Comp.</th>
<th>g mol</th>
<th>T(K)</th>
<th>$\Delta H^\circ_r$ (kJ/g mol)</th>
<th>$\Delta H^\circ_{f}$(kJ/g mol)</th>
<th>$\Delta H$(kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>0.087P</td>
<td>298</td>
<td>-74.84</td>
<td>0</td>
<td>-6.511P</td>
</tr>
<tr>
<td>O₂</td>
<td>0.193P</td>
<td>298</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₂</td>
<td>0.726P</td>
<td>298</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.006P</td>
<td>298</td>
<td></td>
<td></td>
<td>-6.511P</td>
</tr>
<tr>
<td>OUT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>0.087P</td>
<td>527.6</td>
<td>-393.51</td>
<td>9.640</td>
<td>-33.397P</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.174P</td>
<td>527.6</td>
<td>-241.826</td>
<td>7.989</td>
<td>-40.688P</td>
</tr>
<tr>
<td>O₂</td>
<td>0.019P</td>
<td>527.6</td>
<td>0</td>
<td>7.021</td>
<td>0.133P</td>
</tr>
<tr>
<td>N₂</td>
<td>0.726P</td>
<td>527.6</td>
<td>0</td>
<td>6.757</td>
<td>4.906P</td>
</tr>
<tr>
<td></td>
<td>1.006P</td>
<td>527.6</td>
<td></td>
<td></td>
<td>-69.045P</td>
</tr>
</tbody>
</table>

$Q_{\text{before}} = \Delta H = -6074.128 - (-583.752) = -5490.4$ kJ

$Q_{\text{after}} = Q_{\text{before}} = -5490.4$ kJ = $\Delta H_{\text{out}} - \Delta H_{\text{in}} = [-69.045-(-6.511)]P_{\text{after}}$

$= -62.534 P_{\text{after}}$

$P_{\text{after}} = 87.80$ g mol.

$87.80 (0.087) = $\text{moles CH}_4$ after = 7.64$ g mol vs. 7.8 before

Energy used before × fraction saved is the savings

\[
\begin{align*}
\text{180,000 ft}^3 \text{ at SC} & \times \frac{1 \text{ lb mol}}{359 \text{ ft}^3} \times \frac{454 \text{ g}}{1 \text{ lb}} \times \frac{5490.4 \text{ kJ}}{1 \text{ Btu}} \times \frac{1 \text{ Btu}}{10^5 \text{ ft}^3} \\
& \times \frac{1 \text{ yr}}{8000 \text{ hr}} \times \frac{(7.80 - 7.64)}{7.80} = \$1.94 \times 10^3 \text{ yr}^{-1} \text{Btu}^{-1} \text{yr}^{-1}. \text{ Savings} \\
& \frac{31,000 \text{ yr}^{-1}}{1.94 \times 10^3 \text{ yr}^{-1} \text{Btu}^{-1} \text{yr}^{-1}} = 0.16 \text{ yr}^{-1}
\end{align*}
\]

26.26

First, we estimate the heat recovery from the exhaust gas when cooled from 1100°F to 350°F, which is 100°F above the temperature of 15 psig saturated steam. Note we could use 220°F to get the maximum recovery.

From the tables with the initial and final exhaust gas temperatures, 1100°F and 350°F respectively, we determine the approximate heat recovery to be 198 Btu/lb exhaust gas.

To get the pounds of gas:

Knowing that the specific volume of the flue gas (the specific volume of flue gas at a given temperature is very close to the specific volume of air at that temperature.) at 1100°F is 39.5 cu ft/lb, we convert the exhaust flow rate from 4225 cfm to lb/hr as follows:

\[
\text{Basis: 1 hr (continued)}
\]
Solutions Chapter 26

Exhaust flow rate = \( \frac{4225 \text{ (cu ft/min)}}{39.5 \text{ cu ft/lb}} \times 60 \text{ (min/hr)} \)

= 6420 lb/h

Then, rate of heat recovery = 6420 lb/h \times 198 Btu/lb

= 1.27 MBtu/hr (or \( 1.47 \times 10^6 \text{ Btu/hr if use 220°F water} \))

2. Next, we calculate the amount of steam generated from the exhaust heat recovered. We determine that with 220°F feedwater the heat absorbed in generating 15 psig saturated steam is 977 Btu/lb steam.

Steam generation = \( \frac{1.27 \text{ MBtu/hr}}{977 \text{ Btu/lb}} = 1300 \text{ lb/hr (or 1470 lb/hr if use 220°F water)} \)

Thus, steam generation from the fired boiler will be reduced from 2000 lb/h to 700 lb/hr.

3. The resulting annual fuel savings with 80% boiler efficiency based on the lower heating value of the #2 fuel oil (18,300 Btu/lb oil) and assuming 4500 hours of operation per year are calculated below:

Annual fuel savings = 1.27 MBtu/hr \times 4500 hr/yr

\[ = \frac{1.27 \times 4500}{0.8} \text{ MBtu/yr} \]

Knowing that the fuel oil density is about 7.02 lb/gal, we figure the annual fuel savings in gallons.

Annual fuel savings = \( \frac{7140 \text{ MBtu/yr}}{18,300 \text{ Btu/lb} \times 7.02 \text{ lb/gal}} \)

= 55,600 gal/yr

4. If the #2 fuel oil costs $0.50/gal,

Solutions Chapter 26

Annual savings = 55,600 gal/yr \times $0.50/gal

= $27,800 per year

The total cost of a waste heat recovery muffler and installation is about $20,000 for a 500 hp engine. In this case, the installation can be paid off in about two to three years.

26.27

Basis: 10.0 min

The thermodynamic properties are from the Chemical Engineer's Handbook. The attached plot is used for quicker interpolation using °F instead of K for temperature. The data for n-C7 based on liquid Cp's and ΔH's have been extrapolated from the handbook data.

The hot liquid will flash with no change in total enthalpy. Thus, the fraction vaporized has to be calculated.

To calculate fraction of liquid vaporized

\[ V = \text{Vapor rate} \]

\[ F = \text{Spill (feed) rate} \]

\[ \frac{V}{F} = \frac{h_v-h_f}{H_v-h_f} \]

\[ h_v = \text{Enthalpy of spilled liq} \]

\[ h_f = \text{Enthalpy of flashed liq} \]

\[ H_v = \text{Enthalpy of flashed vap} \]

\[ V \text{ and } F \text{ have mass or mole units} \]

Specific gravity of solvents at 400°F:

\[ \text{CH}_3\text{OH: } 0.529 \]

\[ n-C_7: 0.489 \]

(continued)
To calculate vapor

$$\Delta H_{\text{liquid in}} = \Delta H_{\text{liquid ext}} + \Delta H_{\text{vapor ext}}$$

$$m_{\text{Liquid in}} \Delta H_{\text{liquid in}} = m_{\text{ext}} \Delta H_{\text{vapor ext}} + m_{\text{vapor ext}} \Delta H_v$$

plus $$m_{\text{vapor}} = m_{\text{vapor ext}} + m_{\text{vapor}}$$

Spill Rates:

- CH$_3$OH 1000 gal/min (0.529)(8.35) lb/gal = 4417 lb/min
- n-C$_7$ 1000 gal/min (0.489)(8.35) lb/gal = 4083 lb/min

<table>
<thead>
<tr>
<th></th>
<th>$h_{\text{vapor}}$</th>
<th>$h_b$</th>
<th>$H_L$</th>
<th>$V_{\text{vapor}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KJ/kg</td>
<td>lb</td>
<td>lb/min</td>
<td></td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>1210</td>
<td>530</td>
<td>1730</td>
<td>2503</td>
</tr>
<tr>
<td>80°F</td>
<td>1210</td>
<td>605</td>
<td>1770</td>
<td>2793</td>
</tr>
<tr>
<td>BP</td>
<td>148°F</td>
<td>1210</td>
<td>708</td>
<td>1805</td>
</tr>
<tr>
<td>n-C$_7$</td>
<td>25°F</td>
<td>1030</td>
<td>465</td>
<td>840</td>
</tr>
<tr>
<td>80°F</td>
<td>1030</td>
<td>542</td>
<td>890</td>
<td>4083 (all vapor)</td>
</tr>
<tr>
<td>BP</td>
<td>209°F</td>
<td>1030</td>
<td>701</td>
<td>1022</td>
</tr>
</tbody>
</table>

(Note that all the n-heptane always flashes to vapor. Hydrocarbons generally have low heats of vaporization.) (continued)
To get volume of vapor

The lower flammable limits of the solvents are (LFL is concentration air). This would be used to get idea of excess (or deficit) of air.

For CH₃OH → 6.7%  n=C₇ → 1.05%

The volume of vapor is

\[ V_v = \text{specific volume of vapor} \]

\[ V_v = \frac{V_t \cdot V_d}{t} \text{ spill time} \]

and the volume of the maximum flammable vapor cloud is

\[ V_v = \frac{V_t \cdot V_d}{LFL} \]

The specific volumes are

Using \( v_v \) at 80°F

\[ v_v = \frac{RT}{p} = \frac{(10.73)(\text{ft}^3)(\text{Atm})^2}{(\text{lb mol})(\text{Atm})^2 (14.7)(\text{psia})^2 (\text{lb})} \]

= 12.32 \( \frac{\text{ft}^3}{\text{lb}} \) for CH₃OH

\[ v_v = \frac{(10.73)(540)}{(14.7)(98)} = 4.02 \quad \frac{\text{ft}^3}{\text{lb}} \text{ for n-C₇} \]

The vapor cloud volumes are:

For CH₃OH at 80°F

\[ \frac{(2793)(10)(min)(12.32)(\text{ft}^3)}{(min)(\text{lb})(0.067)} = 5.14(10^8) \text{ ft}^3 \]

For n-C₇

\[ \frac{(4083)(10)(4.02)}{(0.0105)} = 15.6(10^8) \text{ ft}^3 \]

Therefore, [choose methanol]

Use criteria of \( \Delta H \). Assume stoichiometric amount of air for 25°C input (input T makes little difference). Ignore sensible heats.

<table>
<thead>
<tr>
<th></th>
<th>nC₇</th>
<th>CH₃OH</th>
</tr>
</thead>
<tbody>
<tr>
<td>heats of combustion are</td>
<td>19,157</td>
<td>8,592</td>
</tr>
<tr>
<td>mass burned</td>
<td>4,083</td>
<td>2,503</td>
</tr>
<tr>
<td>energy released</td>
<td>78(10⁶)</td>
<td>21(10⁶)</td>
</tr>
<tr>
<td>Btu/lb</td>
<td></td>
<td>Btu</td>
</tr>
</tbody>
</table>

So, still choose CH₃OH.

26.28

Step 5

Basis: 1 kg mol CO₂ in Gross Feed F₁

\[ \text{25°C Fresh Feed} \]

\[ \begin{array}{c}
\text{CO}_2 \text{(g)} \\
\text{H}_2 \text{(g)} \\
\text{N}_2 \text{(g)}
\end{array} \]

\[ \text{1 atm} \]

\[ \text{B} \]

\[ \text{1 CO}_2 \]

\[ \text{3 H}_2 \]

\[ \text{N}_2 \]

\[ \text{90°C} \]

\[ \text{P} \]

\[ \text{R} \]

\[ \text{70°C} \]

\[ \text{CH}_3\text{OH(l)} \]

\[ \text{70°C} \]

\[ \text{H}_2\text{O(l)} \]

\[ \text{100°C} \]

\[ \text{CO}_2 \text{(g)} \]

\[ \text{H}_2 \text{(g)} \]

\[ \text{N}_2 \text{(g)} \]

\[ \text{25°C} = 298K \]

\[ \text{70°C} = 343K \]

\[ \text{100°C} = 373K \]

(continued)
Material Balance to get $N_2$ in gross feed to the reactor. Assume concentration is 2.0% (the maximum allowed).

$$0.02 = \frac{n_{n_2}}{1 + 3 + n_{n_2}} \quad n_{n_2}^e = 0.0816 \text{ mol/mol } F_1$$

**System:** Reactor plus separator

Steps 6 and 7

Number of equations (5): 4 element balances + fraction conversion

$$
\begin{align*}
(F_1) & = (P_2) + (P_3) + (P) \\
C: & \quad 1 = P_2 (1) + 0 + n_{CO_2}^p \\
H: & \quad 3(2) = P_2 (4) + 2P_3 + n_{H_2}^p (2) \\
O: & \quad 1(2) = P_2 (1) + P_3 (1) + n_{CO_2}^p (2) \\
N_2 & \quad 0.0816 = P_2 (0) + P_3 (0) + n_{n_2}^p \\
\end{align*}
$$

Species balance:

in - out + gen - consumed

CO$_2$ balance: 1 - $n_{CO_2}^p$ + 0 - 0.57(1)

Unknowns (5): $P_2, P_3, n_{CO_2}^p, n_{H_2}^p, n_{n_2}^p$

Note: $P = \sum n_i^p$ is redundant.

Solution of equations (all in kg mol)

$$
\begin{align*}
P_2 & = 0.57 \\
\frac{x_{CO_2}^p}{1.8016} & = 0.43 \\
P_3 & = 0.57
\end{align*}
$$

---

Solutions Chapter 26

$$
\begin{align*}
n_{CO_2}^e & = 0.43 \\
x_{CO_2}^p & = \frac{1.29}{1.8016} = 0.716 \\
n_{H_2}^e & = 1.29 \\
x_{H_2}^p & = \frac{0.0816}{1.8016} = 0.045 \\
P & = \sum n_i^p = 1.8016
\end{align*}
$$

**System:** mixing point before reactor (no reaction occurs)

Unknowns (2): $F$ and $R$; Equations (2): Total and $N_2$

Total: $F + R = 4.0816 = F_1$

Nitrogen: $N_2$: 0.005$F + x_{n_2}^p \quad R = 0.0816$

After $F$ and $R$ are calculated as below $F = F_1 - R$ (no reaction)

$F = 2.562 \text{ kg mol} \quad R = 1.520 \text{ kg mol}$

$$
\begin{align*}
n_{CO_2}^e & = 1 - 1.520(0.239) = 0.677 \text{ kg mol} \\
n_{H_2}^e & = 3 - 1.520(0.716) = 1.912 \text{ kg mol} \\
n_{n_2}^e & = 0.0816 - 1.520(0.045) = 0.0128
\end{align*}
$$

Check: 0.005 (2.526) = 0.0128

All mol values are in kg mol

**System:** sep. point after separator (continued)
Solutions Chapter 26

P_x = P - R & for each component

\[ n_{CO_x} = \frac{0.43}{1.802} \times 0.282 = 0.067 \]
\[ n_{NO_x} = \frac{1.29}{1.802} \times 0.282 = 0.236 \]
\[ n_{H_2} = \frac{0.816}{1.802} \times 0.282 = 0.0128 \]

Energy Balance (ref. 25°C) an overall system

\[ \Delta E = Q + W - \Delta H \]
\[ \Delta E = W = 0 \]
\[ Q = \Delta H = \Delta H_{\text{prod}} - \Delta H_{\text{react}} \]

**OUT**

<table>
<thead>
<tr>
<th>Comp.</th>
<th>kg mol</th>
<th>( \Delta H^r ) (kJ/kg mol)</th>
<th>( \Delta H_{\text{prod}} ) (kJ/kg mol)</th>
<th>( \Delta H ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°C</td>
<td>CH_3OH(ℓ)</td>
<td>0.57</td>
<td>-238.640</td>
<td>(70-25)(4.184)(680)(32)</td>
</tr>
<tr>
<td>70°C</td>
<td>H_2O(ℓ)</td>
<td>0.57</td>
<td>-285.840</td>
<td>(70-25)(4.184)(18)</td>
</tr>
<tr>
<td>100°C</td>
<td>CO_2(g) in P_x</td>
<td>0.067</td>
<td>-393.510</td>
<td>(3045-912)</td>
</tr>
<tr>
<td>100°C</td>
<td>H_2(g) in P_x</td>
<td>0.336</td>
<td>0</td>
<td>(2874-718)</td>
</tr>
<tr>
<td>100°C</td>
<td>N_2(g) in P_x</td>
<td>0.0128</td>
<td>0</td>
<td>(2910-728)</td>
</tr>
</tbody>
</table>

\[ Q = -320,157 \text{kJ} \] (heat removed)

The overall result is

\[ \frac{53,751 \text{kJ}}{2.562 \text{kg mol F}} = 20,980 \text{kJ/g mol fresh feed} \]

Solutions Chapter 26

26.29

Steady state, no W, no P, no K so Q = \( \Delta H \)

**Material balance**

\[ S = 9.0 \text{mol} \]
\[ O_2 = 9.5 \text{mol} \]
\[ N_2 = 81.5 \text{mol} \]

**Ref. T = 25°C = 298K**

\[ Q + W = \Delta H \]

**OUT**

Component | mol | \( T(K) \) | \( \Delta H^r \) (J/gmol) | \( \Delta H \) (J/gmol) | \( \Delta H \) (J) | Sensible heat

(continued)
### Solutions Chapter 26

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Standard Enthalpy Change ($\Delta H_{\text{rxn}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SO}_2(g)$</td>
<td>2.25 700K $-296,900$ (19,501-984) $-626,361.8$</td>
</tr>
<tr>
<td>$\text{SO}_3(g)$</td>
<td>6.75 700K $-395,180$ (27,154-1255) $-2,492,646.8$</td>
</tr>
<tr>
<td>$\text{N}_2(g)$</td>
<td>81.5 700K 0 (12,652-728) 971,806.0</td>
</tr>
<tr>
<td>$\text{O}_2(g)$</td>
<td>6.125 700K 0 (13,225-732) $76,519.6$</td>
</tr>
</tbody>
</table>

Let $T_{\text{ref}} = 25^\circ C$

\[
\begin{align*}
1\text{ hr} & 1025\text{ g} & 4.0\text{ J/hr g} & T_2 - 25^\circ C & 1\text{ hr} & 1025\text{ g} & 4.0\text{ J/hr g} & (25-25)\text{ °C} \\
+ 1\text{ hr} & 27.6\text{ kJ/L} & 2\text{ L} & 1000\text{ J} & 0 & \frac{(55,200 + 102,500)\text{ J}}{4,100\text{ J/°C}} & 38^\circ C, \text{ yes}
\end{align*}
\]

---

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Standard Enthalpy Change ($\Delta H_{\text{rxn}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SO}_2(g)$</td>
<td>9.0 400K $-296,900$ (5,234-984) $-2,633,850$</td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>9.5 400K 0 (3,752-732) 28,690</td>
</tr>
<tr>
<td>$\text{N}_2(g)$</td>
<td>81.5 400K 0 (3,695-728) $241,810.5$</td>
</tr>
</tbody>
</table>

\[
Q = \sum \Delta H_{\text{rxn}} - \sum \Delta H_{\text{ref}} = 32.52 \frac{kJ}{g \text{ mol}}
\]

---

### Problem 26.30

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Standard Enthalpy Change ($\Delta H_{\text{rxn}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SO}_2(g)$</td>
<td>2.25 700K $-296,900$ (19,501-984) $-626,361.8$</td>
</tr>
<tr>
<td>$\text{SO}_3(g)$</td>
<td>6.75 700K $-395,180$ (27,154-1255) $-2,492,646.8$</td>
</tr>
<tr>
<td>$\text{N}_2(g)$</td>
<td>81.5 700K 0 (12,652-728) 971,806.0</td>
</tr>
<tr>
<td>$\text{O}_2(g)$</td>
<td>6.125 700K 0 (13,225-732) $76,519.6$</td>
</tr>
</tbody>
</table>

Open steady state system: the inside of the cell.

\[
\Delta H = Q + W \quad Q = 0 \quad W = 0
\]

\[
\Delta H = 0
\]

\[
\Delta H_{\text{ref}} + \Delta H_{\text{rxn}} = 0
\]

\[
m_2C_p(T_2 - T_{\text{ref}}) - m_1C_p(T_1 - T_{\text{ref}}) + \Delta H_{\text{rxn}} = 0
\]

\[
T_2 = \frac{(55,200 + 102,500)\text{ J}}{4,100\text{ J/°C}} = 38^\circ C, \text{ yes}
\]
\( \Delta U = \Delta H - \Delta (pV) = 16 - [(700 \times 0.5339) - (2700 \times 0.1361)] = 9.7 \text{ kJ/kg} \)

or calculate use \( \Delta U \) directly from the CD.

If reversibility is assumed, \( W_{rev} \) can be calculated by selecting \((h, V)\) pairs along an isotherm and integrating the area under a plot of \( p \) vs \( V \). \( Q \) then can be calculated from \( Q = \Delta U - W \).

**State 2 to State 3 at constant \( V \)**

\( \Delta H = 2862 - 3558 = -696 \text{ kJ/kg} \)

\( \Delta U = -696 - [(400 \times 0.5339) - 700 \times (0.5339)] = -535.8 \text{ kJ/kg} \)

\( W_{rev} = 0 \) as \( \Delta V = 0 \)

\( Q = \Delta U = -535.8 \text{ kJ/kg} \)

**State 3 to State 4 at constant \( p \)**

\( \Delta H = 2733 - 2862 = -129 \text{ kJ/kg} \)

\( \Delta U = -129 - [(400 \times 0.4625) - (400 \times 0.5339)] = -100 \text{ kJ/kg} \)

\( W_{rev} = -p\Delta V = 40 \times (0.4625 - 0.5339) = 28.6 \text{ kJ/kg} \)

\( Q = \Delta U - W = -100 - (28.6) = -129 \text{ kJ/kg} \)

**State 4 to State 5 with \( Q = 0 \)**

\( \Delta H = 3285 - 2733 = 552 \text{ kJ/kg} \)

\( \Delta U = 552 - [(2700 \times 0.1161) - (400 \times 0.4625)] = 423.5 \text{ kJ/kg} \)

\( Q = 0 \)

---

**State 5 to State 1**

\( \Delta H = 3542 - 3285 = 257 \text{ kJ/kg} \)

\( \Delta U = 257 - [(2700 \times 0.1361) - (2700 \times 0.1161)] = 203 \text{ kJ/kg} \)

\( Q = ? \)

\( W_{rev} = ? \) (cannot be calculated because path is unknown)

**Check**

Is \( \Delta H \geq 0 \), yes; Is \( \Delta U \geq 0 \); \( \Delta U = 0.43 \) which is close enough?

---

**27.4**

**Basis:** 1 lb mol \( \text{H}_2\text{O} \)

<table>
<thead>
<tr>
<th>Initial State</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water at 212°F and 1 atm (enthalpy = ( H_1 ))</td>
<td>Saturated steam at 212°F and 1 atm (enthalpy = ( H_2 ))</td>
</tr>
</tbody>
</table>

a. Steady state open (flow) process: flow in a pipeline, negligible kinetic and potential energy changes. No work is done by the system or on the system so that \( W = 0 \), and,

\[ W = 0 \]

b. Closed (non-flow) process: The basic equation is:

\[ \Delta U_2 - \Delta U_1 = \Delta U = Q + W \]

(continued)
Because the work done is only a volume expansion and is reversible

\[ \dot{W} = -\int p \, dV = -p \Delta V = -\left( p \dot{V}_1 - p \dot{V}_3 \right) \]

Obtain \( \dot{V}_1, \dot{V}_3 \) from steam tables

\[ W = -p^r \left[ \frac{1}{R} \right] \left( \dot{V}_2 - \dot{V}_1 \right) = -\left( 14.7 \right) \left( 144 \right) \left( 26.799 \right) \left( 0.016719 \right) \]

\[ = -56.677 \text{ (ft)(lb)} \]
\[ \text{lb steam} = -72.85 \text{ lb} = -1.312 \text{ Btu} \]

Work is done against the atmosphere.

### 27.5

**Basis:** Adiabatic expansion with no work, a flow process.

\[ W = 0 \quad \text{irreversible expansion} \]

\[ Q = 0 \]

a. \( Q + W = 0 \quad \Delta H = 0 \)

An example is an ideal gas expanding through a restriction; \( H \) is a function of \( T \) only, and if \( \Delta H = 0, \Delta T = 0 \).

b. Expansion of a real gas is not isothermal

\[ \int dH = \int \left( \frac{dH}{dT} \right)_p \, dT + \int \left( \frac{dH}{dp} \right)_T \, dp = C_p \, dT + \int \left[ V - T \left( \frac{dV}{dT} \right)_p \right] \, dp = 0 \]

For a nonideal gas, \( C_p dT \) can be offset by the second term.

### 27.6

System: 1 lb mol of \( \text{N}_2 \) in the cylinder.

Compute the change in volume of the \( \text{N}_2 \). The initial volume is

\[ V_i = \frac{2nRT_i}{p_i} \]

\[ z = 1.00 \] (calculations not shown)

\[ V_i = \frac{1 \text{ lb mol} \left[ 10.73 \text{(psia)} \right] \left[ 760 \text{R} \right]}{\left[ \text{lb mol} \right] \left[ 14.7 \text{ psia} \right]} = 554.7 \text{ ft}^3 \]

\[ \Delta V = 0.5 \left( 554.7 \right) = 227.4 \text{ ft}^3/\text{lb mole} \]

a. While the \( \text{N}_2 \) compression is irreversible, the work done by the steam on the piston may be approximately reversible because \( p \) is constant and the reservoir is large so that the steam conditions are essentially constant with expansion on top of the piston. If so:

\[ W = -\int p dV = -p \Delta V = -\frac{70 \text{ lb}}{144 \text{ in}^2} \cdot \frac{227.4 \text{ ft}^3}{\text{lb mole}} \cdot \frac{1 \text{ Btu}}{778 \text{(ft)(lb)}} \]

\[ = -2946 \text{ Btu/lb mole} \]

b. The work done on the piston by the steam may not all be transferred to the \( \text{N}_2 \) because of the irreversibility of the compression of the \( \text{N}_2 \) by the piston. If it were reversible, then the work done on the \( \text{N}_2 \) would be computed as below.

\[ \Delta U + D \Delta E = Q + W \]

\[ Q = 0 \quad W = -2946 \text{ Btu} \]

(continued)
\[ \Delta PE (\text{of the piston}) = \] 

Calculate the change in height of the piston.

\[ A = \frac{\pi (\frac{10}{12})^2}{4} = 0.545 \text{ ft}^2 \]

\[ \Delta h \text{ of piston} = \frac{0.611 \text{ ft}^2}{0.545 \text{ ft}^2} = 1.12 \text{ ft} \]

\[ \Delta PE = mg\Delta h = \frac{10 \text{ lb} \times 32.2 \text{ ft}}{s^2} \left( \frac{\text{lb} \times \text{ft}^2}{s^2} \right) \left( \frac{1 \text{ ft}}{32.2 \text{ lb} \times \text{ft}} \right) = -0.014 \text{ Btu} \quad \text{(can be neglected)} \]

\[ \Delta U = 0 + 2946 + 0.014 = 2946 \text{ Btu} \]

If all of this energy were transferred to the N_2 on compression (unlikely), \( \Delta U \) of the N_2; otherwise, \( \Delta U \) of the piston and cylinder would go up and the \( \Delta U \) would be 2946 Btu/lb mol N_2; of the N_2 would not go up as much as 2946 Btu/lb mol N_2.

27.7

\[ \text{Efficiency} = \frac{\text{hp output}}{\text{hp input}} \times 100\% \]

\[ = \frac{24.6 \text{ hp}}{30 \text{ hp}} \times 100\% = 82\% \]

### Solutions Chapter 27

\[ 27.8 \]

\[ \text{Annual cost} = 300,000 \text{ kW} \times 6000 \text{ hr} \times 3.4128 \times 10^5 \text{ Btu} \times 5.110 \times 10^5 \text{ Btu} \times 0.40 \]

\[ = 1.69 \times 10^8 \text{ / yr} \]

\[ 27.9 \]

Basis: 100 g mol Fg

**Material balances**

**Chemical reaction equations**

(a) \( \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \) (g)

(b) \( \text{C}_2\text{H}_4 + 3\frac{1}{2}\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O} \)

(c) \( \text{C}_3\text{H}_6 + 4\frac{1}{2}\text{O}_2 \rightarrow 3\text{CO}_2 + 3\text{H}_2\text{O} \)

\[ \text{Excess O}_2: \quad 202.535 \cdot 1.40 \quad = 20.25 \text{ g mol} \]

Total O_2: \[ 202.535 + 20.25 = 222.79 \text{ g mol} \]

N_2 entering: \[ 222.79(79/21) = 538.11 \text{ g mol} \]

\[ \begin{array}{cccccc}
\text{g mol} & \text{req'd O}_2 & \text{CO}_2 \text{ produced} & \text{H}_2\text{O} \text{ produced} & \Delta H^\circ \text{(kJ/g mol)} \\
\text{CH}_4 & 96.4 & 192.8 & 96.4 & 192.8 & -74.84 \\
\text{C}_2\text{H}_4 & 2.01 & 7.035 & 4.02 & 6.03 & -84.667 \\
\text{C}_3\text{H}_6 & 0.99 & 2.7 & 1.8 & 1.8 & 20.41 \\
\text{N}_2 & 0.6 & 2.7 & 1.8 & 1.8 & 0 \\
\text{Total} & 202.535 & 102.22 & 200.63 & & \\
\end{array} \]

(continued)
Exit flue gas (T = 450°C)

<table>
<thead>
<tr>
<th></th>
<th>g mol</th>
<th>$\Delta H_{\text{mole}}$ (kJ/g mol)$^*$</th>
<th>$\Delta H$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>102.22</td>
<td>18.599</td>
<td>1,901.19</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>200.63</td>
<td>15.304</td>
<td>3,070.44</td>
</tr>
<tr>
<td>N$_2$</td>
<td>839.1</td>
<td>12.690</td>
<td>10,648.18</td>
</tr>
<tr>
<td>O$_2$</td>
<td>20.25</td>
<td>13.366</td>
<td>270.66</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>15,891</td>
</tr>
</tbody>
</table>

*From the CD

To get the LHV, Use the values from Appendix F to get the heat of reaction at SC with H$_2$O(g) as the product. O$_2$ and N$_2$ have 0 $\Delta H^e_p$.

Reaction (a):

$\Delta H^e_m = 96.4(-393.51) + 192.8(-241.826) - 96.4(-74.84) = -77,348$ kJ/100 g mol gas

Reaction (b):

$\Delta H^e_m = 4.02(-393.51) + 6.03(-241.826) - 2.01(-84.667) = -2,870$ kJ/100 g mol gas

Reaction (c):

$\Delta H^e_m = 1.8(-393.51) + 1.8(-241.826) - 0.6(20.41) = -1,131$ kJ/100 g mol gas

Total $\Delta H^e_m = -81,349$ kJ/100 g mol gas

LHV = 81,349 kJ/100 g mol

Efficiency = $100 - \frac{0.02(81,349 - 15,891)}{81,349 - 81,349} = 82%$

---

27.10

Basis: 1 second

Convert all of the data to J as needed. The process is steady state.

Electric output $500,000$ kW $\rightarrow 5 \times 10^8$ kJ

Energy with fuel input

$E_{\text{fuel}} = (64.6$ kg) $(28,400$ kJ/kg) $= 1.349 \times 10^8$ kJ

Heat added to the steam (system is boiler). Data are from the CD.

$Q = \Delta H = m_{\text{fuel}}(\bar{H}_{\text{out}} - \bar{H}_{\text{in}}) = 640(3,175.9 - 647.0) = 1.619 \times 10^8$ kJ

Boiler efficiency $= \frac{1.619 \times 10^8}{1.834 \times 10^8} (100) = 88.3%$

Gross plant efficiency $= \frac{5 \times 10^8}{1.834 \times 10^8} (100) = 27.2%$

Steam cycle efficiency $= \frac{5 \times 10^8}{1.619 \times 10^8} (100) = 30.9%$
The process is reversible (conversion of vapor to liquid at constant temperature and pressure).

a. Initially, all the H₂O is vapor (i.e., at the dew point) so the volume of liquid was 0.

b. \[ W = - \int_{V_1}^{V_2} p\,dV = -p \int_{V_1}^{V_2} (V_2 - V_1) = 400 \text{ kJ} \]

\[ 245.6 \text{ kPa} \left( V_2 - 3.654 \text{ m}^3 \right) \frac{1 \text{ J}}{1 \text{ kg} \cdot \text{m}^3} = 400 \text{ kJ} \]

\[ -(V_2 - 3.654) = 1.629 \]

\[ V_2 = 2.025 \text{ m}^3 \]

\[ \dot{V} = \frac{2.025 \text{ m}^3}{5 \text{ kg}} = (1 - x)(0.001067) + x(0.7308) = 0.4050 \text{ m}^3/\text{kg} \]

\[ \dot{V} = \frac{0.001067 \text{ m}^3 }{ \text{kg} } \]

The volume of liquid was \((1-x)(0.001067)(0.001067) = 0.0024 \text{ m}^3\) after compression.

\[ \Delta PE + \Delta KE + \int \dot{V} dp - \dot{W} + \dot{E}_c = 0 \]

Basis: 1 min (1000 L)

\[ \frac{1000 \text{ L}}{1000 \text{ L}} = 1 \text{ m}^3 \]

The density of water is 1000 kg/m³.

\[ \int \dot{V} dp = \dot{V} \Delta p \text{ for a liquid} \]

\[ m \dot{V} \Delta p = 10^3 \text{ kg} \cdot 10^2 \text{ m}^2/\text{kg} \cdot \left(290-140\right) \text{ N/m} \]

\[ \int \Delta \left(1 \text{ J} / (\text{N} \cdot \text{m}) \right) = 150 \text{ kJ} \]

\[ \Delta (PE) = 0 \quad \dot{W} = 0 \quad \Delta KE = 0 \]

\[ \dot{E}_c = -m \dot{V} \Delta p = -150 \text{ kJ/min} \]

(continued)
Solutions Chapter 27

To calculate the temperature change, for a throttling process the energy balance reduces to \( \Delta H = 0 \).

\[
\begin{align*}
\text{liquid} & \quad \Delta H = 20.8 \\
\text{at } 5^\circ C, 290 \text{ kPa} & \quad \Delta H = 20.8 \text{ at } 140 \text{ kPa}
\end{align*}
\]

\[
0 = \Delta H = \int C_p d\theta + \int \frac{dH}{dp} dp
\]

But the second term for a liquid is approximately zero, hence \( \Delta T \approx 0 \).

27.13

Process: flow, steady state  
System: feed water pump

\[
\Delta (\widehat{KE} + \widehat{PE}) + \int \dot{V} dp - \dot{W}_w + \dot{E}_v = 0
\]

Application of the general equation for the conservation of energy is not too useful since it reduces to, \( Q + \dot{W} = \Delta H \). By assuming a reversible process and applying the given efficiency factor, one obtains the work per time done on the system.

\[
\dot{W}_w = \int_{p_1}^{p_2} V dp
\]

If \( V \) is constant, \( \dot{W}_w = \dot{V} \Delta p \). \( p_2 = 500 \text{ psia} \) \( p_1 = 0.9 \text{ psia} \)

Basis: 100 gal/min

27.14

Mechanical energy balance:

\[
\Delta (\widehat{KE} + \widehat{PE}) = \int \dot{V} dp - \dot{W} + \dot{E}_v = 0
\]

The minimum work is the reversible work so \( \dot{E}_v = 0 \). Then

\[
\int \dot{V} dp = \dot{V} \Delta p
\]

because the fluid is incompressible, but \( \Delta p = 0 \). Thus the mechanical energy balance reduces to

\[
\dot{W}_w = \Delta (\widehat{KE} + \widehat{PE}) \eta_m
\]

If \( \dot{m} \) is the mass/time then, \( W = \text{work/time} = \text{power} \)

\[
W = (\widehat{KE}_t + \widehat{PE}_t) \dot{m}_t = (\widehat{KE}_1 + \widehat{PE}_1) \dot{m}_1 - (\widehat{KE}_t + \widehat{PE}_t) \dot{m}_t
\]

where the subscripts refer to the floors.

Basis: flows of water as shown in Figure in text (i.e., 1 min)

Take the first floor as the datum; \( \widehat{KE}_t = \frac{1}{2} \dot{V}^2, \widehat{PE} = gh \)

\[
\widehat{PE}_t = 0 \quad \widehat{KE}_t = \frac{1}{2} \left( \frac{60}{60} \right) = 0.5 \text{ ft}^2 / \text{s}
\]

(continued)
\[ \bar{PE}_1 = \frac{32.2 \text{ ft}^2}{s^2} \times \frac{30 \text{ ft}}{s} = \frac{966 \text{ ft}^3}{s^2} \]
\[ \bar{KE}_1 = \frac{1}{2} \left( \frac{600}{60} \right)^2 = 50.0 \text{ ft}^2/s \]

\[ \bar{PE}_2 = \frac{32.2 \text{ ft}^2}{s^2} \times \frac{60 \text{ ft}}{s} = \frac{1930 \text{ ft}^3}{s^2} \]
\[ \bar{KE}_2 = \frac{1}{2} \left( \frac{1200}{60} \right)^2 = 200.0 \text{ ft}^2/s \]

\[ m_1 = \frac{500 \text{ gal}}{\text{min}} \times \frac{0.1337 \text{ ft}^3}{\text{gal}} \times \frac{62.4 \text{ lbm}}{\text{ft}^3} \times \frac{1 \text{ min}}{60 \text{ s}} = 69.6 \text{ lbm/s} \]

\[ m_2 = \frac{200 \text{ gal}}{\text{min}} \times \frac{0.1337 \text{ ft}^3}{\text{gal}} \times \frac{62.4 \text{ lbm}}{\text{ft}^3} \times \frac{1 \text{ min}}{60 \text{ s}} = 27.5 \text{ lbm/s} \]

\[ m_3 = \frac{300 \text{ gal}}{\text{min}} \times \frac{0.1337 \text{ ft}^3}{\text{gal}} \times \frac{62.4 \text{ lbm}}{\text{ft}^3} \times \frac{1 \text{ min}}{60 \text{ s}} = 41.7 \text{ lbm/s} \]

\[ W = \left( (200 + 1930) (41.7) + (50 + 96.5) (27.8) - (0.5 + 0)(69.6) \right) \]

\[ \times \frac{(\text{lbm})(\text{ft}^2)}{(\text{s})(\text{ft}^2)} = 89,000 + 28,200 - 34.8 = 117,170 \frac{(\text{lbm})(\text{ft}^2)}{(\text{s})(\text{ft}^2)} \]

\[ 117,170 \frac{(\text{lbm})(\text{ft}^2)}{(\text{s})(\text{ft}^2)} \times \frac{1 \text{ hp}}{32 \frac{(\text{lbm})(\text{ft})}{(\text{s})(\text{ft}^2)}} \times \frac{550(\text{lbm})(\text{ft})}{5 \text{ s}} = 6.62 \text{ hp} \]

\[ \text{Process: flow, System: pump} \]

Basis: 1 kg

Use the steady state mechanical energy balance

\[ \Delta (\bar{KE} + \bar{PE}) + \int \dot{\bar{V}} dp - \dot{W} + \dot{E}_w = 0 \]

27.15

a. \( \Delta \bar{KE} = 0 \) Approximately

\[ \Delta \bar{PE} = \text{mg} \frac{1 \text{ kg}}{\text{gal}} \left| \frac{10 \text{ m}}{\text{s}^2} \right| \frac{1 \text{ J}}{(\text{kg})(\text{m})} = 98.0 \text{ J} \]

\[ \int \dot{\bar{V}} dp = \dot{V} \Delta p \text{ because } \dot{V} \text{ is essentially constant at } 10^{-3} \text{ m}^3/\text{kg} \]

\[ \frac{10^{-3} \text{ m}^3}{\text{kg}} \left( \frac{1150 - 101.3}{\text{kJ}} \right) \frac{1 \text{ J}}{\left( \text{kJ} \right) (\text{m})} = 1050 \text{ J/kg} \]

\[ \dot{E}_w = 60.0 \text{ J/kg} \]

\[ \dot{W}_\text{ideal} = 98.0 + 1050 + 60.0 = 1208 \text{ J/kg} \]

Actual work required = 1208 m J/kg

Basis: 1 min (continued)
27.16

The steady state mechanical energy balance is

\[ \Delta(\dot{KE} + \dot{PE}) + \int \dot{V} dp - \dot{W} + \dot{E}_v = 0 \]

System: Pipe above the pump discharge (120 ft long)

Assume

1. \( \Delta \dot{KE} = 0 \)
2. Discharge pressure is atmospheric so that \( p_2 = 0 \), and \( p_1 = 87.6 \) psi
3. \( \dot{V} \) is constant at 0.016 ft\(^3\)/lb

Basis: 1 lb water

Then

\[ \Delta \dot{PE} = 120(\text{ft})(\text{lb}_f)/\text{lb}_m. \] However, the level in discharge tank adds some extra height to 120 ft, say \( h \) ft

\[ \int_{h_{1a}}^{0} \dot{V} dp = (0.016)(0 - 87.6)(144) = -201.8(h)(\text{lb}_f)/\text{lb}_m \]

\( W = 0 \) for the system selected

\( \dot{E}_v = -(120 + x) - (-201.8) = 81.8 - x \)

27.17

Assume open, steady state process

The mechanical energy balance is per lb\(_m\)

\[ \Delta(\dot{KE} + \dot{PE}) + \int \dot{V} dp - \dot{W} + \dot{E}_v = 0 \]

System: A deaerator plus suction piping to pump

\[ \begin{align*}
\Delta \dot{KE} &= \frac{1}{2} \left( \frac{8 \text{ ft}}{\text{s}^2} \right) \left( \frac{(\text{lb}_f)(\text{ft}^2)}{32.2(\text{ft})(\text{lb}_m)} \right) = 0.994(\text{ft})(\text{lb}_f)/\text{lb}_m \text{ (Assumes no velocity in the deaerator)} \\
\Delta \dot{PE} &= \left( \frac{32.2 \text{ ft}}{\text{s}^2} \right) \left( \frac{(\text{lb}_f)(\text{ft}^2)}{32.2(\text{ft})(\text{lb}_m)} \right) (-h(\text{ft})) = -h(\text{ft})(\text{lb}_f)/\text{lb}_m \text{ (The reference for } h \text{ is at the water level)}
\end{align*} \]

(continued)
\[ \dot{V}\Delta p = \left( \begin{array}{c} 0.016 \text{ ft}^3 \\ \text{lb}_m \end{array} \right) \left( \begin{array}{c} 24 - 15 \text{ lb} \\ \text{in.}^2 \\ \text{lb}_m \end{array} \right) \left( \begin{array}{c} 144 \text{ in.}^2 \\ \text{ft}^3 \end{array} \right) = 20.77(\text{ft}^3)/(\text{lb}_m) \]

\[ \dot{W} = 0 \quad \dot{E}_v = 4(\text{ft})/(\text{lb}_m) 
- \Delta PE = \Delta KE + \dot{V}\Delta p + E_v 
\]

\[ h = 0.994 + 20.77 + 4 = 25.8 \text{ ft} \]

### 27.18
Basis 1 lb CO₂

The system is the compressor (open, steady state, no reaction). The steady state flow mechanical energy balance reduces to \( W = -\int Vdp \)

Use the CO₂ chart to find the relation between \( \dot{V} \) and \( p \).

At the final state the CO₂ is 0.37 gas and 0.63 liquid.

<table>
<thead>
<tr>
<th>( \dot{V}(\text{ft}^3/\text{lb}_m) )</th>
<th>( p ) (psia)</th>
<th>( \dot{V}(\text{ft}^3/\text{lb}_m) )</th>
<th>( p ) (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.5</td>
<td>6</td>
<td>0.5</td>
<td>220</td>
</tr>
<tr>
<td>10</td>
<td>11.5</td>
<td>0.3</td>
<td>330</td>
</tr>
<tr>
<td>6</td>
<td>19.5</td>
<td>0.2</td>
<td>460</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>0.15</td>
<td>600</td>
</tr>
<tr>
<td>1.5</td>
<td>66</td>
<td>0.10</td>
<td>600</td>
</tr>
<tr>
<td>1.0</td>
<td>110</td>
<td>0.05</td>
<td>600</td>
</tr>
</tbody>
</table>

Integrating we get 527

\[
\begin{align*}
\text{b.} & \quad -W = \frac{527(\text{ft}^3)}{(\text{lb}_m)(\text{in.}^2)} \left( \begin{array}{c} 144 \text{ in.}^2 \\ \text{ft}^2 \\ \text{Btu} \end{array} \right) \left( \begin{array}{c} 144 \text{ in.}^2 \\ \text{ft}^2 \\ \text{Btu} \end{array} \right) = \frac{98 \text{ Btu/} \text{lb}_m}{(\text{lb}_m)(\text{in.}^2)} \\
\text{c.} & \quad Q = \Delta H + W \\
\dot{H}_1 = 148 \text{ Btu/lb} \\
\dot{H}_2 = 73 \text{ Btu/lb} \\
Q = (73 - 148) - 98 = -173 \text{ Btu/lb} \\
\text{d.} & \quad \text{Cost} = \frac{98 \text{ Btu}}{\text{lb}_m} \left[ \frac{1}{0.85} \right] \frac{2.93 \times 10^{-4} \text{(kw)hr}}{1 \text{ Btu}} \left[ \frac{1 \text{(kW)hr}}{l(\text{kw})/\text{hr}} \right] = \$0.08 \]
\[
= \$2.70 \times 10^{-7}
\]
27.19

Basis: 1 second

\[ p_1 = 101.3 \text{ kPa} \]

\[ p_2 = 150 \text{ kPa} \]

\[ v_1 = 0 \]

\[ v_2 = 5 \text{ m/s} \]

\[ v = 80 \text{ m} \]

\[ \Delta \overline{PE} + \Delta \overline{KE} + \int_{h}^{p} \overline{Vdp} - \dot{W} + \dot{E}_v = 0 \]

\[ \Delta \overline{KE} = \frac{1}{2}(v_1^2 - v_2^2) = \frac{1}{2}(5^2 - 0^2) = 12.5 \frac{m^2}{s^2} = 12.5 \frac{J}{kg} \]

\[ \int_{h}^{p} \overline{Vdp} = \overline{V}(p_2 - p_1) = 1 \times 10^{-3} \frac{m^3}{kg} (150 - 101.3) \text{kPa} = 48.7 \times 10^{-3} \frac{J}{kg} \] (ignore)

\[ \Delta \overline{PE} = gh = 9.8(0-80) = -784 \frac{J}{kg} \]

\[ W_{\text{total}} = \frac{W_{\text{turbine}}}{\eta_{\text{turbine}}} = 200 \text{ kW} = 266.67 \frac{kJ}{s} \] work done by system

\[ \dot{m} = \frac{266.67 \frac{kJ}{s}}{(784 - 12.5) \frac{J}{kg}} = \frac{345.65 \text{ kg}}{s} \]

27.20

The Bernoulli equation is

\[ \frac{v_1^2}{2g} + h_1 + z_1 = \frac{v_2^2}{2g} + h_2 + z_2 \]

where \( \Delta p = h \)

For continuity flow between sections 1 and 2, \( Q_1 = Q_2 \)

\[ A_1 v_1 = A_2 v_2 \]

Solving the above two equations, we get

\[ Q = \frac{A_1 \sqrt{2g((h_1 - h_2) + (z_1 - z_2))}}{\sqrt{A_1^2 - A_2^2}} \]

\[ = \frac{A_1 A_2 \sqrt{2g(H + Z)}}{A_1^2 - A_2^2} \]

\[ Q = \frac{A_1 A_2 \sqrt{2g \Delta p}}{\sqrt{A_1^2 - A_2^2}} = C_A \frac{\sqrt{2g \Delta p}}{\sqrt{A_1^2 - A_2^2}} \]

where (continued)
Solutions Chapter 27

\[ C_d = \frac{A_1}{\sqrt{A_1^2 - A_2^2}} - 1 \]

\( C_d \) is usually determined by experiment.

27.21

**Basis: 1 second**

\[ Q = C_d \sqrt{2g \Delta p + z} \]  

(a)

Let \( z = 0 \).

\[ \dot{m} = \frac{Qm^2}{s} \]  

\( \dot{m} \) in kg/s

Multiply both sides of Equation (a) by \( \rho \)

\[ \dot{m} = C_d \sqrt{2\Delta p \rho} \]  

(b)

The units under the square root are

\[ \frac{g(m)}{s^2} \frac{\Delta p(m)}{s^2} \left( \frac{\rho(kg)}{(m^3)} \right)^{\frac{1}{2}} \left( \frac{kg}{s} \right)^{\frac{1}{2}} \frac{1}{m^2} \]

which is ok

If \( \Delta p \) is in the units of \( \text{Pa} \)

\[ \text{Pa} = \frac{N}{m^2} = \frac{(kg)(m)}{s^2} \frac{1}{m^2} \]

\[ \rho = \frac{P}{RT} \]

\[
\begin{array}{c|c|c|c|c|c|c|c|c|c|c}
307 \times 10^3 \text{ Pa} & \text{(g mol)}(K) & 16 \text{g CH}_4 & 1 \text{ atm} & = 1.95 \frac{\text{g}}{\text{cm}^3} \\
82.06(\text{cm}^3)(\text{atm}) & 303 \text{ K} & 1 \text{ g mol CH}_4 & 101.3 \text{ kPa} \\
\end{array}
\]

\[ \dot{m} = \frac{(0.55) [1(4 \times 10^{-4} \text{m})^3]}{4} \left[ \frac{2(1.95 \text{ g})}{(\text{cm}^3)} \right] \left[ \frac{1 \text{ kg}}{100 \text{ cm}^3} \right] \left[ \frac{100 \text{ cm}^3}{1 \text{ m}} \right] \frac{307 - 99 \text{ kPa}}{2} \]

\[ = 7.36 \times 10^{-3} \text{ kg/s} \]
28.1

\[ \text{Li} + \frac{1}{2} \text{Cl}_2(g) \rightarrow \text{LiCl}(s) \quad \Delta H^\circ_{\text{fus}} = -408.78 \text{kJ} / \text{g mol Li} \]

\[ \text{LiCl}(s) + 10 \text{H}_2\text{O}(l) \rightarrow \text{LiCl}[10\text{H}_2\text{O}] \quad \Delta H^\circ_{\text{soln}} = -32.84 \text{kJ} / \text{g mol LiCl} \]

\[ \text{Li} + \frac{1}{2} \text{Cl}_2(g) + 10 \text{H}_2\text{O}(l) \rightarrow \text{LiCl}[10\text{H}_2\text{O}] \quad \Delta H^\circ_{\text{soln}} = -441.62 \text{kJ} / \text{g mol LiCl}[10\text{H}_2\text{O}] \]

28.2

The reason the freezing works is because heat removed from the ice cream during the solution of the salt (for the \( \text{CaCl}_2 \cdot 6\text{H}_2\text{O} \), the resulting solution is with the attached water of hydration).

Note: A mixture of 3 g of ice to 1 g NaCl is 10 g mol H\(_2\)O to 1 g mol of NaCl. NaCl(s) + 10 H\(_2\)O \( \rightarrow \) NaCl [10 H\(_2\)O]

\[ \Delta H = (408.99) - (411.00) = 2.01 \text{kJ} / \text{g mol NaCl} \]

For the \( \text{CaCl}_2 \cdot 6\text{H}_2\text{O} \), you first decompose it and then dissolve it in the H\(_2\)O of hydration (it melts in effect).

\text{melt:} \quad \text{CaCl}_2 \cdot 6\text{H}_2\text{O} \rightarrow \text{CaCl}_2(s) + 6\text{H}_2\text{O}(l) \quad (a)

\text{dissolve:} \quad \text{CaCl}_2(s) + 6\text{H}_2\text{O} \rightarrow \text{CaCl}[6\text{H}_2\text{O}] \quad (b)

\[ \text{CaCl}_2 \cdot 6\text{H}_2\text{O} \rightarrow \text{CaCl}[6\text{H}_2\text{O}] \]

\[ \Delta H_a = [6(-285.840) + 1(-794.97)] - 2586.5 = -76.49 \text{kJ} \]

\[ \Delta H_b = (-854.4) - (-794.97) = 59.40 \quad \Delta H_{\text{wet}} = 17.06 \text{kJ} \]

28.3

Reference: 25°C and 1 atm for compounds

a. Integral heat of solution for 1 mol Na\(_2\)CO\(_3\) (MW = 106.0)

<table>
<thead>
<tr>
<th>Moles H(_2)O added</th>
<th>( \Delta H^\circ_r (\text{J} / \text{g mol}) )</th>
<th>Integral ( \Delta H^\circ_{\text{soln}} (\text{J/g mol}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1130.92</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>-1163.70</td>
<td>-32.78</td>
</tr>
<tr>
<td>20</td>
<td>-1162.78</td>
<td>-31.86</td>
</tr>
<tr>
<td>25</td>
<td>-1161.98</td>
<td>-31.06</td>
</tr>
<tr>
<td>40</td>
<td>-1160.22</td>
<td>-29.30</td>
</tr>
<tr>
<td>75</td>
<td>-1158.00</td>
<td>-27.01</td>
</tr>
<tr>
<td>100</td>
<td>-1157.17</td>
<td>-26.25</td>
</tr>
<tr>
<td>200</td>
<td>-1155.50</td>
<td>-24.58</td>
</tr>
<tr>
<td>400</td>
<td>-1154.37</td>
<td>-23.45</td>
</tr>
</tbody>
</table>

(continued)
b. The initial components are at 25°C. The heat capacity of the solution can be assumed to be that of water (although in Perry, a solution of 4% Na₂CO₃ has a heat capacity of 95% of that of water)

\[
C_p = \frac{1 \text{ cal}}{(g)(^\circ C)} \times \frac{18 \text{ g } H_2O}{1 \text{ g mol } H_2O} \times \frac{4.184 \text{ J}}{1 \text{ cal}} = \frac{75.3 \text{ J}}{(\text{g mol})(^\circ C)} \quad \text{(or 71.5 J/g mol (°C))}
\]

If the process is batch, assume \(\Delta U = \Delta H\).

\[
\begin{align*}
143 \text{ kg } Na_2CO_3 \cdot 10H_2O & = 1 \text{ kg mol } Na_2CO_3 \times \frac{286 \text{ kg } Na_2CO_3 \cdot 10H_2O}{1 \text{ kg mol } Na_2CO_3} = 0.50 \text{ kg mol } Na_2CO_3 \\
180 \text{ kg } H_2O & = 10 \text{ kg mol } H_2O \\
\text{Basis: } 1 \text{ g mol } Na_2CO_3
\end{align*}
\]

The final solution contains 20 kg mol of water and 0.5 kg mol Na₂CO₃ or 40 kg mol H₂O per kg mol of Na₂CO₃. From the table \(\Delta H^\circ_{\text{solution}} = -1160.22 \text{ kJ/g mol } Na_2CO_3\).
### a.

<table>
<thead>
<tr>
<th>HNO₃ (moles)</th>
<th>ΔH (J)</th>
<th>moles of soln</th>
<th>ΔH/mol soln (J/g mol soln)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>3,375</td>
<td>1.0</td>
<td>3,375</td>
</tr>
<tr>
<td>0.1</td>
<td>230</td>
<td>1.1</td>
<td>210</td>
</tr>
<tr>
<td>0.2</td>
<td>-1,660</td>
<td>1.2</td>
<td>-1,385</td>
</tr>
<tr>
<td>0.3</td>
<td>-2,920</td>
<td>1.3</td>
<td>-2,245</td>
</tr>
<tr>
<td>0.5</td>
<td>-3,980</td>
<td>1.5</td>
<td>-2,655</td>
</tr>
<tr>
<td>0.67</td>
<td>-6,150</td>
<td>1.67</td>
<td>-3,680</td>
</tr>
<tr>
<td>1.0</td>
<td>-8,830</td>
<td>2.0</td>
<td>-4,415</td>
</tr>
<tr>
<td>1.5</td>
<td>-10,735</td>
<td>2.5</td>
<td>-4,295</td>
</tr>
<tr>
<td>2.0</td>
<td>-12,865</td>
<td>3.0</td>
<td>-4,290</td>
</tr>
<tr>
<td>3.0</td>
<td>-14,610</td>
<td>4.0</td>
<td>-3,650</td>
</tr>
<tr>
<td>4.0</td>
<td>-14,465</td>
<td>5.0</td>
<td>-2,895</td>
</tr>
<tr>
<td>5.0</td>
<td>-14,320</td>
<td>6.0</td>
<td>-2,385</td>
</tr>
<tr>
<td>10.0</td>
<td>-6,915</td>
<td>11.0</td>
<td>-630</td>
</tr>
<tr>
<td>20.0</td>
<td>-12,705</td>
<td>21.0</td>
<td>605</td>
</tr>
</tbody>
</table>

Plot the enthalpy per mole of solution from the table above as a function of the wt. % HNO₃ from the first table.

### b.

4 moles H₂O to 4 moles HNO₃ is a 50 mole % solution of acid.

33 mole % + 60 mole % → 50 mole %

A B F

Basis: 8 mol final solution (F)

If the process is batch, assume ΔU = ΔH.

Overall balance: A + B = F = 8

HNO₃ balance: 0.333 A + 0.60 B = 8 (0.50)

0.333 A + 0.60 (8 - A) = 4

Solving: A = 3 mol (1 mol HNO₃, 2 mol H₂O)

B = 5 mol (3 mol HNO₃, 2 mol H₂O)

The problem asks for the heat absorber on mixing the two solutions, A and B. The enthalpy data come from the table in the problem statement.

(continued)
Solutions Chapter 28

\[ Q = \Delta H = \Delta H_f - (\Delta H_A + \Delta H_B) \]

A: ratio is \(2\) mol H\(_2\)O/mol HNO\(_3\) = \(-20,290\) J/g mol HNO\(_3\)

B: ratio is 0.67 mol H\(_2\)O/mol HNO\(_3\) = \(-10,880\) J/g mol HNO\(_3\)

F: ratio is \(1\) mol H\(_2\)O/mol HNO\(_3\) = \(-14,230\) J/g mol HNO\(_3\)

\[ Q = \left(\frac{14,230}{g\ mol\ HNO_3}\right) \left(\frac{4\ g\ mol\ HNO_3}{1\ g\ mol\ HNO_3}\right) - \frac{20,290}{J/g\ mol\ HNO_3} \left(\frac{3\ g\ mol\ HNO_3}{g\ mol\ HNO_3}\right) \]

\[ Q = -3,390\ J \]

28.5

\[ Q = \Delta H^{\infty} = \Delta H^{\infty,20\%}\ \text{soln} - \Delta H_{\text{CaCl}_2} \]

a. Conversion of 20 wt% to moles:

Basis: 100 g solution

\[ 20\ g\ \text{CaCl}_2 \cdot \frac{1\ g\ \text{mol\ CaCl}_2}{111.05\ g\ \text{CaCl}_2} = 0.18\ g\ \text{mol\ CaCl}_2 \]

\[ 80\ g\ H_2O \cdot \frac{1\ g\ \text{mol\ H}_2O}{18\ g\ H_2O} = 4.44\ g\ \text{mol\ H}_2O \]

\(0.18/4.44\) = 24.7 g mol H\(_2\)O/g mol CaCl\(_2\)

If the process is batch, assume \(\Delta U = \Delta H\).

\[ \Delta H^{\infty} = \left(\frac{-208.3\ \text{kcal}}{\text{g mol CaCl}_2}\right) \cdot \left(\frac{190.0\ \text{kcal}}{\text{g mol CaCl}_2}\right) = -18.3\ \text{kcal} \]

28.6

a. \(Q = 0\) (ideal solution)

b. Basis: 900 kg H\(_2\)O and 63 kg HNO\(_3\)

MW: H\(_2\)O = 18, HNO\(_3\) = 63.0

\[ \frac{900}{18} = 50\ \text{kg mol H}_2\text{O} = 1\ \text{kg mol HNO}_3 \]

Reference conditions 25°C and 1 atm.

If the process is batch, assume \(\Delta U = \Delta H\).

\[ \text{HNO}_3(\ell) + 50\ \text{H}_2\text{O}(\ell) \rightarrow \text{HNO}_3[50\ \text{H}_2\text{O}] \] (continued)
\[ \Delta H_{\text{solution}} = (-205.978) \cdot 0 - (-173.234) = -32.744 \text{ kJ/kg HNO}_3 \]

The energy balance reduces to \(Q = \Delta H = \Delta H_{\text{solution}}\)

\[Q = (50) \cdot (-32.944) = -1637.2 \text{ kJ}\]

28.7

Calculate the initial enthalpy. Use \(H_2SO_4\) enthalpy concentration chart.

<table>
<thead>
<tr>
<th>Comp. (lb)</th>
<th>%H_2SO_4</th>
<th>kg H_2SO_4</th>
<th>T(°F)</th>
<th>(\Delta H) Btu/Lb</th>
<th>(\Delta H)(kJ/kg)</th>
<th>(\Delta H)(kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>20</td>
<td>50</td>
<td>220</td>
<td>90</td>
<td>209.16</td>
<td>52,290</td>
</tr>
<tr>
<td>100</td>
<td>98</td>
<td>98</td>
<td>310 K (98°F)</td>
<td>14</td>
<td>32.54</td>
<td>3,253.6</td>
</tr>
<tr>
<td>Total</td>
<td>148</td>
<td>100%</td>
<td></td>
<td></td>
<td>55,543</td>
<td></td>
</tr>
</tbody>
</table>

Final \(H_2SO_4\) concentration in a closed system:

\[
\frac{148}{350} (100) = 42.3\%
\]

Final specific enthalpy:

\[
\frac{55,543 \text{ kJ}}{350 \text{ kg}} = 1.6055 \text{ kJ/lb}
\]

From the chart: \(T \approx 242°F \Rightarrow 117°C\) or \(390 \text{ K}\)

The composition of the liquid is \(43\) to \(44\% H_2SO_4\)

If the system is closed, then the final state is two phase.

28.8

Assume the system is closed, but \(\Delta U = \Delta H\).

Data from the \(H_2SO_4\) enthalpy concentration chart. The initial states are:

\[
\begin{align*}
\text{Comp.} & \quad \text{T(K)} & \text{TPD} & \% \text{H}_2\text{SO}_4 & \% \text{H}_2\text{O} & \text{ke H}_2\text{SO}_4 & \text{ke H}_2\text{O} & \Delta \hat{H} \text{(Btu/lb)} & \Delta \hat{H} \text{(kJ/kg)} & \Delta \hat{H} \text{(kJ)} \\
\text{20\% H}_2\text{SO}_4 & 340 & 152 & 20 & 50 & 100 & 400 & 40 & 92.9 & 46,450 \\
\text{96\% H}_2\text{SO}_4 & 310 & 96 & 96 & 4 & 288 & 12 & -10 & -23.2 & -6,960 \\
\text{Steam} & 400 & 260 & 0 & 100 & 0 & 100 & 2799.7 & 272,970 \\
\text{Total} & 388 & 512 & & & & 2799.4 & 312,460
\end{align*}
\]

b. The final concentration of the mixture is (total is 900 kg)

\[
\% \text{H}_2\text{SO}_4 = \frac{388}{900} (100) = 43\%
\]

\%

\[
\text{H}_2\text{O} = 100 - 43 = 57\%
\]

a. The energy balance reduces to \(\Delta H = 0\), or \(\Delta H_{\text{final}} = \Delta H_{\text{initial}}\). The specific enthalpy of the final solution is \(312,460 \text{ kJ/900 kg} = 347.2 \text{ kJ/kg}\)

(continued)
From the H$_2$SO$_4$ enthalpy – concentration chart for these two conditions,

T $\approx$ 25°F or 395 K

The concentration of the liquid is 53% H$_2$SO$_4$

28.9

This problem can be solved using the charts in Appendix I for NH$_3$ and H$_2$SO$_4$, but the readings will not be very accurate. It is better to go to a reference book (or the internet) to get data for NH$_3$, and use Table H1 for H$_2$SO$_4$.

Preliminary calculations for NH$_3$:

<table>
<thead>
<tr>
<th>g</th>
<th>MW</th>
<th>g mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$OH</td>
<td>15</td>
<td>35.05</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>85</td>
<td>18.02</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>5.145</td>
</tr>
</tbody>
</table>

The energy balance will reduce to $Q = \Delta H$ if the system is open and $Q = \Delta U$ if the system is closed, but we can assume for a closed system $\Delta U = \Delta H$.

$\Delta H = \Sigma \Delta H_{products} + \Sigma \Delta H_{reactants} + \Delta H_{solution}$

Reference conditions 25°C and 1 atm

$\Delta H_{rxn}$: The reaction is calculated from (on the basis of 0.428 g mol NH$_3$)

$2 \text{NH}_3(g) + \text{H}_2\text{SO}_4(l) \rightarrow (\text{NH}_4)_2\text{SO}_4(c)$

$\Delta H_{rxn}(\text{kJ/g mol})$: -46.191 -811.32 -1179.3

$\Delta H_{rxn} = [(0.428)(-46.191) + (0.428)(0.5)(-811.32)]$

= -58.98 kJ

The data for NH$_3$ come from the LaRoche Industries website rather than Appendix I.

$\Delta H_{products}$: The products are at the reference conditions so that $\Delta H_{products} = 0$.

$\Delta H_{reaction}$: The H$_2$SO$_4$ is at 25°C and 1 atm, hence its $\Delta H = 0$. The NH$_3$ is at 1 atm where the temperature is 171°F (77°C). The $\Delta H$ from 77°C to 25°C (331K to 298K) for a 7.29% (by weight) solution of NH$_3$ in water requires data for the heat capacity which is not available, hence use the value for the water alone (92.71 g or 0.0927 kg).

Use data from the steam tables or the CD.

$\Delta H_{solution}$ of NH$_3$:

Each compound has an associated heat of solution. The values in the LaRoche tables are for 7.2% by weight NH$_3$. (continued)
<table>
<thead>
<tr>
<th>Weight %</th>
<th>T(°C)</th>
<th>(°C)</th>
<th>ΔH (Btu/lb solution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2</td>
<td>170.8</td>
<td>77</td>
<td>116.1</td>
</tr>
<tr>
<td>0</td>
<td>213</td>
<td>100</td>
<td>181.0</td>
</tr>
</tbody>
</table>

The values of ΔH in Btu/lb have to be adjusted to 25°C, and the difference taken. Convert first to kJ.

7.29% solution: \[
\frac{116.1 \text{ Btu}}{1 \text{ lb solution}} \times \frac{1 \text{ Btu}}{1 \text{ kg solution}} \times \frac{0.454 \text{ kg}}{1 \text{ lb}} = 269.7 \text{ kJ/kg solution}
\]

0% solution: \[
\frac{181.0 \text{ Btu}}{1 \text{ lb solution}} \times \frac{1 \text{ Btu}}{1 \text{ kg solution}} \times \frac{0.454 \text{ kg}}{1 \text{ lb}} = 420.61 \text{ kJ/kg solution}
\]

Assume you can calculate the ΔH from T to 25°C using only the ΔH of water.

170.8 – 77 (92.7% H₂O): \[
\frac{0.0927 \text{ kg}}{100 \text{ g solution}} \times \frac{219 \text{ kJ}}{1 \text{ kg}} = 20.3 \text{ kJ/100 g solution}
\]

213 – 77 (100% H₂O): \[
\frac{0.100 \text{ kg}}{100 \text{ g solution}} \times \frac{317.7 \text{ kJ}}{1 \text{ kg}} = 31.8 \text{ kJ/100 g solution}
\]

7.29% solution: \[26.97 \text{ kJ/100 g solution} – 20.3 \text{ kJ/100 g solution} = 6.67 \text{ kJ/g solution}\]

0% solution: \[42.06 \text{ kJ/100 g solution} – 31.8 \text{ kJ/100 g solution} = 10.26 \text{ kJ/g solution}\]

Heat of solution = 6.67 – 10.26 = -3.59 kJ/100 g NH₄SO₄ solution

The g moles of H₂SO₄ needed to react with the 0.428 g mole of NH₄ are 0.5 (0.428) = 0.214 g mol H₂SO₄. The H₂SO₄ solution is 1 mol H₂SO₄ per 3 mol H₂O. From the table in Appendix H, \[ΔH_{\text{solution}} = 48.998 \text{ kJ/g mol H₂SO₄}\]

\[ΔH_{\text{solution}} = (-48.998)(0.214) = -10.49 \text{ kJ/100 g NH₄SO₄ solution}\]

The heat of solution of the (NH₄)₂SO₄ in [5.145 + (3)(0.214)] mol of H₂O is not

\[\Delta H_{\text{known}} = \left[\left(-1173.1\right) - \left(-1179.3\right)\right] \text{ kJ/mole(NH₄)₂SO₄} \times \frac{0.5(0.428) \text{ g mol(NH₄)₂SO₄}}{\text{g mol(NH₄)₂SO₄}} = 1.33 \text{ kJ per 100 g NH₄SO₄ solution}\]

\[\Sigma ΔH_{\text{known}} = -3.59 - 10.49 + 1.33 = -12.75 \text{ kJ}\]

\[Q = ΔH = 0 - 10.66 + (-58.98) + (-12.75) = -82.39 \text{ kJ}\]
28.10 Heat of solution data have been taken from NBS Circular 500.

(a) Basis: 17 lb of NH₃ = 1 lb mol of NH₃

Reference temperature = 77°F → 25°C

To convert from kilocalories per gram mole to British thermal units per pound mole, multiply by 1800.

<table>
<thead>
<tr>
<th>Description</th>
<th>State</th>
<th>$-\Delta H^\circ_r$ (kcal/g mol)</th>
<th>$-\Delta H^\circ_r$ (Btu/lb mol)</th>
<th>$-\Delta H^\circ_{mix}$ (Btu/lb mol)</th>
<th>Weight % NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>0H₂O</td>
<td>g</td>
<td>11.04</td>
<td>19,900</td>
<td>8,500†</td>
<td>100</td>
</tr>
<tr>
<td>1H₂O</td>
<td>aq</td>
<td>18.1</td>
<td>32,600</td>
<td>12,700</td>
<td>48.5</td>
</tr>
<tr>
<td>2H₂O</td>
<td>aq</td>
<td>18.7</td>
<td>33,600</td>
<td>13,700</td>
<td>32.0</td>
</tr>
<tr>
<td>3H₂O</td>
<td>aq</td>
<td>18.87</td>
<td>34,000</td>
<td>14,100</td>
<td>23.9</td>
</tr>
<tr>
<td>4H₂O</td>
<td>aq</td>
<td>18.99</td>
<td>34,200</td>
<td>14,300</td>
<td>19.1</td>
</tr>
<tr>
<td>5H₂O</td>
<td>aq</td>
<td>19.07</td>
<td>34,350</td>
<td>14,450</td>
<td>15.9</td>
</tr>
<tr>
<td>10H₂O</td>
<td>aq</td>
<td>19.23</td>
<td>34,600</td>
<td>14,700</td>
<td>8.63</td>
</tr>
<tr>
<td>20H₂O</td>
<td>aq</td>
<td>19.27</td>
<td>34,700</td>
<td>14,800</td>
<td>4.51</td>
</tr>
<tr>
<td>30H₂O</td>
<td>aq</td>
<td>19.28</td>
<td>34,700</td>
<td>14,800</td>
<td>3.05</td>
</tr>
<tr>
<td>40H₂O</td>
<td>aq</td>
<td>19.28</td>
<td>34,700</td>
<td>14,800</td>
<td>2.30</td>
</tr>
<tr>
<td>50H₂O</td>
<td>aq</td>
<td>19.29</td>
<td>34,750</td>
<td>14,850</td>
<td>1.85</td>
</tr>
<tr>
<td>100H₂O</td>
<td>aq</td>
<td>19.30</td>
<td>34,750</td>
<td>14,850</td>
<td>0.94</td>
</tr>
<tr>
<td>200H₂O</td>
<td>aq</td>
<td>19.32</td>
<td>34,800</td>
<td>14,900</td>
<td>0.47</td>
</tr>
<tr>
<td>∞H₂O</td>
<td>aq</td>
<td>19.32</td>
<td>34,800</td>
<td>14,900</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† Represents latent heat of condensation

Standard heats of solution have been calculated from the cumulative data as follows:

$$\Delta H^\circ_{sol} = \Delta H^\circ_r - \Delta H^\circ_{mix}$$

For example, for NH₃[1 H₂O]:

$$\Delta H^\circ_{sol} = -32,600 - (-19,900)$$
$$= -12,700 \text{ Btu/lb mol NH}_3$$

Weight percents have been computed as follows:

$$\text{wt \% NH}_3 = \frac{\text{lb NH}_3(100)}{\text{lb H}_2\text{O} + \text{lb NH}_3}$$

$$\text{wt \% NH}_3 \text{ for } 1 \text{ H}_2\text{O} = \frac{17(100)}{18(1) + 17} = 48.5\%$$

The heat of solution values shown in Fig. 1 are equivalent to the cooling duty required.
Solutions Chapter 28

(b) This part of the problem requires that a new basis be selected, 100 gal of solution. Additional data concerning densities of NH₄OH are shown in the table below. Sample calculations are as follows:

\[
density \text{ (lb/100 gal)} = \frac{(sp \text{ gr soln})(62.4 \text{ lb/ft}^3)(1.003)(100)}{7.48 \text{ gal/ft}^3}
\]

Note: 1.003 is the specific gravity of water at 77°F.

density at 32.0% NH₃ = \( \frac{0.889(62.4)(1.003)(100)}{7.48} \) = 741 lb/100 gal

cooling req'd \( = \left( \frac{\text{lb mol NH}_3}{\text{Btu/100 gal}} \right) \left( -\Delta H^\circ_{\text{rxn}} \frac{\text{Btu}}{\text{lb mol NH}_3} \right) \)

for 100 gal = 13.94(13,700) = 191,000 Btu/100 gal soln

32.0 NH₃ soln

These data are portrayed in Fig. b.

---

Basis: 100 gal of solution at concentrations and densities shown:

<table>
<thead>
<tr>
<th>% NH₃</th>
<th>sp gr* at 4°C</th>
<th>Density (lb/100 gal)</th>
<th>lb NH₃/100 gal</th>
<th>lb mol NH₃/100 gal</th>
<th>( -\Delta H^\circ_{\text{rxn}} ) (Btu mol NH₃)</th>
<th>Cooling Req'd per 100 gal (Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.0</td>
<td>0.889</td>
<td>761</td>
<td>127</td>
<td>13.94</td>
<td>13,700</td>
<td>191,000</td>
</tr>
<tr>
<td>19.2</td>
<td>0.914</td>
<td>761</td>
<td>185</td>
<td>10.30</td>
<td>14,100</td>
<td>111,000</td>
</tr>
<tr>
<td>15.3</td>
<td>0.929</td>
<td>774</td>
<td>148</td>
<td>8.70</td>
<td>14,450</td>
<td>106,000</td>
</tr>
<tr>
<td>13.3</td>
<td>0.940</td>
<td>784</td>
<td>124.7</td>
<td>7.32</td>
<td>14,800</td>
<td>60,000</td>
</tr>
<tr>
<td>11.5</td>
<td>0.963</td>
<td>805</td>
<td>99.4</td>
<td>6.08</td>
<td>14,700</td>
<td>60,000</td>
</tr>
<tr>
<td>10.3</td>
<td>0.981</td>
<td>819</td>
<td>72.0</td>
<td>5.18</td>
<td>14,900</td>
<td>32,200</td>
</tr>
<tr>
<td>9.46</td>
<td>1.000</td>
<td>826</td>
<td>60</td>
<td>4.66</td>
<td>14,900</td>
<td>16,600</td>
</tr>
<tr>
<td>0.0</td>
<td></td>
<td>834</td>
<td>0</td>
<td>0</td>
<td>14,900</td>
<td>0</td>
</tr>
</tbody>
</table>


(c) Basis: 100 gal of solution at 10.5% NH₃

\[ \Delta E = \Delta U = mC\Delta T = mC\Delta T = 72,000 \text{ Btu/100 gal} \]

sp gr soln = 0.955

(continued)
Solutions Chapter 28

\[ m = \frac{0.955 \times (6.24)(1.003)(100)}{7.48} = 800 \text{ lb} \]

\[ C_p \text{ NH}_3 \text{ soln} = 10.5 \% \text{ NH}_3 \text{ soln} = 4.261 \text{ J/(g)(°C)} \]

\[ = 1.02 \text{ Btu/(lb)(°F)} \]

\[ \Delta T = \frac{\Delta H}{mC_p} = \frac{72,000}{800(1.02)} = 88° \text{F} \]

\[ T_{\text{final}} = 77 + 88 = 165° \text{F} \]

28.11

Open system, steady state

An energy balance shows \( Q = \Delta H \).

Enthalpy values from H-x chart for NaOH

<table>
<thead>
<tr>
<th>Comp.</th>
<th>( \Delta H, \text{ Btu/lb sol'n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% (70°F)</td>
<td>35</td>
</tr>
<tr>
<td>40% (100°F)</td>
<td>94</td>
</tr>
<tr>
<td>H_2O vapor (212°F)</td>
<td>1150</td>
</tr>
</tbody>
</table>

28.12

Use the enthalpy concentration diagram for H_2SO_4 (found in Appendix 1) for the enthalpy data.

Basis: 1000 lb 50% solution at 100°F

\[ \text{Ice at 32°F} \]

\[ 80\% \text{ H}_2\text{SO}_4 \text{ at 100°F} \]

\[ 20\% \text{ H}_2\text{SO}_4 \text{ at 100°F} \]

\[ 50\% \text{ H}_2\text{SO}_4 \text{ at 100°F} \]

From Appendix 1: (continued)
**Solutions Chapter 28**

<table>
<thead>
<tr>
<th>Conc.</th>
<th>temp. (°F)</th>
<th>ΔH (Btu/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>100</td>
<td>-88</td>
</tr>
<tr>
<td>20%</td>
<td>100</td>
<td>-4</td>
</tr>
<tr>
<td>50%</td>
<td>100</td>
<td>-85</td>
</tr>
</tbody>
</table>

ΔH of ice = -144 Btu/lb (or negative of the heat of fusion at 32°F, the reference for the H₂SO₄ chart)

Assume closed system with ΔU = ΔH.

**Material Balance:**

Let total lb of 80% H₂SO₄ = x
Let total lb of 20% H₂SO₄ = y
Let total lb of ice = z

**Material Balances:**

H₂SO₄ : \(0.8x + 0.2y + 0z = 500\)
H₂O : \(0.2x + 0.8y + z = 500\)

**Energy balance** (Q = 0 = ΔH = Hᵣ₋₄ - Hᵣₐ)

\[88x + 4y + 114z = 85,000\]

A summary table can now be completed as follows based on the solution of the three equations using Polymath.

<table>
<thead>
<tr>
<th>Component</th>
<th>80% H₂SO₄ (lb)</th>
<th>20% H₂SO₄</th>
<th>Ice (lb)</th>
<th>Final sol'n</th>
<th>Wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂SO₄</td>
<td>475</td>
<td>24.6</td>
<td>0</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>H₂O</td>
<td>119</td>
<td>98.4</td>
<td>282</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>594</td>
<td>123</td>
<td>282</td>
<td>1000</td>
<td>100</td>
</tr>
</tbody>
</table>

**28.13**

The concentration lies on a line joining the coordinates of 0% H₂SO₄, ΔH = 1180, and 30% H₂SO₄ and 70°F. The intersection of this line with the boiling point line = 28%.

**28.14**

**Basis:** 1000 lb 10% NaOH at 100°F

<table>
<thead>
<tr>
<th></th>
<th>Conc.</th>
<th>lb NaOH</th>
<th>lb H₂O</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>10%</td>
<td>100</td>
<td>900</td>
<td>1000</td>
</tr>
<tr>
<td>Added</td>
<td>73%</td>
<td>0.73 m</td>
<td>0.27 m</td>
<td>m</td>
</tr>
<tr>
<td>Final</td>
<td>30%</td>
<td>100+0.73 m</td>
<td>900+0.27 m</td>
<td>1000+m</td>
</tr>
</tbody>
</table>

\[100.0 + 0.73 m = 0.30 \text{ } 1000.0 + m = 465 \text{ lb 73% NaOH added}\]

**b.** Reference State: liquid water at 32°F under its own vapor pressure (ΔH = 0 Btu/lb)

Enthalpy values from NaOH on H-x chart

\[Q = \Delta H = \Delta H_{30\%} - [\Delta H_{10\%} + \Delta H_{73\%}]\]

(continued)
### Solutions Chapter 28

<table>
<thead>
<tr>
<th>Cons.</th>
<th>Temp</th>
<th>lb so/ft</th>
<th>ΔH, Btu/lb</th>
<th>ΔH, Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>100°F</td>
<td>1000</td>
<td>61</td>
<td>61,000</td>
</tr>
<tr>
<td>73</td>
<td>200°F</td>
<td>465</td>
<td>371</td>
<td>172,600</td>
</tr>
<tr>
<td>30</td>
<td>70°F</td>
<td>1465</td>
<td>37</td>
<td>54,200</td>
</tr>
</tbody>
</table>

\[
Q = \Delta H = (54,200) - (61,000 + 172,600) = -179,400 \text{ Btu}
\]

Heat remove = 179,400 Btu

---

### 28.15

**Basis:** 1 hour, Data from NH₃ – H₂O chart

**a. Material Balances:**

- Overall:
  \[
  10,000 = L + V
  \]
- NH₃:
  \[
  8,000 = L_{\text{NH}_3} + V_{\text{NH}_3}
  \]
- H₂O:
  \[
  2,000 = L_{\text{H}_2\text{O}} + V_{\text{H}_2\text{O}}
  \]

**Enthalpy Balance:**

\[
\Delta H_r = Q = \Delta H_L + \Delta H_V
\]

By assuming values of \( x \):

<table>
<thead>
<tr>
<th>( x )</th>
<th>( x )</th>
<th>( \Delta H_L )</th>
<th>( \Delta H_V )</th>
<th>( (\Delta H_V) ) calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>0.9993</td>
<td>-31.7</td>
<td>550.7</td>
<td>661.2</td>
</tr>
<tr>
<td>0.65</td>
<td>0.9987</td>
<td>-34.1</td>
<td>552.4</td>
<td>508</td>
</tr>
<tr>
<td>0.67</td>
<td>0.9989</td>
<td>-33.1</td>
<td>551.8</td>
<td>554</td>
</tr>
</tbody>
</table>

\( x_{\text{sat.}} = 67\% \)
29.1

a. Dew point = 10°C

b. \( \%RH = \frac{P_{aw} \cdot 100}{P_{sat}} \cdot 100 = \frac{1.27 \text{ kPa}}{3.356 \text{ kPa}} \cdot 100 = 38\% \)

c. \( \gamma = \frac{P_{aw}}{P_{sat}} = \frac{1.27}{101.3 - 1.27} = \frac{18}{29} = 0.79 \text{ kg H}_{2}\text{O/kg air} \)

29.2

Assume \( P_t = 760 \text{ mm Hg} \)

a. \( P_{v,\text{O}} @120^\circ F = 87.58 \text{ mm Hg} \)

b. \( \gamma = \frac{(18)(87.58)}{(29)(672.42)} = 0.081 \text{ lb H}_{2}\text{O/lb dry air} \)

c. \( \dot{V} = (0.730)(120) + 336\left(\frac{1}{29} + \frac{0.081}{18}\right) = 16.51 \text{ ft}^3 \text{ at } 120^\circ \text{F and 1 atm} \)

d. \( \dot{V} = (2.80)(10^{-3})T_k + 4.56\times10^{-3}(9\%T_k) \)

At saturation at 40°C

\( \gamma = \frac{(46)(10.90)}{(44)(100 - 10)} = 0.228 \text{ g A/g C} \)

\( \dot{V} = (2.80)(10^{-3})(313.15) + 4.56\times10^{-3}(0.116) = 0.877 \text{ m}^3/\text{kg C} \)

29.3

Refer to the text for specific equations and definitions.

29.4

Let \( A = \text{alcohol and C = CO}_2 \). MW of \( A = 46; \) MW of \( C = 44. \)

At 40°C, \( P_a = 134.26 \text{ mm Hg or } 17.90 \text{ kPa} \)

a. \( P_a = 0.10 (100) = 10 \text{ kPa} \)

b. \( \%RS = \frac{P_a}{P_s}(100) = \frac{10}{17.90}(100) = 55.9\% \)

c. \( C_v = 1.00 + 1.88(9\%) = 1.00 + 1.88 (0.116) = 1.22 \text{ J/(K) (g C)} \)

29.5

They are almost parallel to each other.
29.6
When the air is saturated.

29.7
Draw a horizontal line until it intersects with the saturation curve. The temperature at the intersection is the dew-point temperature.

29.8
When the air is saturated (100% relative humidity).

29.9
Condenses water from the air in humid climates.

29.10
The two temperatures are approximately equal at atmospheric temperatures and pressure.

29.11
Because a horizontal line on the psychrometric chart represents a process in which the moisture content (the humidity) constant, and the moisture content of air remains constant during a heating or cooling process.

29.12
If by "air" is meant wet air, \( H = \frac{0.02}{0.98} = 0.204 \text{ lb } H_2O \text{ lb dry air} \)

From the SI humidity chart
a. Dew point = 25.2°C
b. %RH ≈ 59%

29.13
a. From Humidity Chart, where \( t_{DB} = 90°C (194°F) \) and \( t_{WB} = 46°C (115°F) \) \( H = 0.049 \text{ kg } H_2O/\text{kg air} \). Upon cooling to 43°C (109°F), no condensation occurs, therefore \( H \) is constant.

\[
\frac{0.049 \text{ kg } H_2O}{1 \text{ kg air}} \times \frac{29 \text{ kg air}}{1 \text{ kg mol } H_2O} \times \frac{1 \text{ kg mol } H_2O}{18 \text{ kg } H_2O} = 0.079 \text{ kg mol } H_2O/\text{kg mol air}
\]

b. Final pressure \( = 100 \left( \frac{273 + 43}{273 + 90} \right) = 87.1 \text{ kPa} \)

c. At saturation: \( 0.079 = \frac{p_{s,v,o}}{87.1 - p_{s,v,o}} \); solving \( p_{s,v,o} = 6.38 \text{ kPa} \)

At the dew point, the vapor pressure of pure water is equal to 6.38 kPa. Dew point = 57°C (136°F)

The same answer can be obtained by proceeding to the dew point at constant \( H \) on a humidity chart for the correct pressure.
29.14

From the SI chart at the intersection of $T_{db} = 30^\circ C$ and $RH = 65\%$

$\gamma = 0.0174 \text{ kg H}_2\text{O/kg dry air}$

29.15

The state in the problem is defined by $T_{db} = 82^\circ F$ and $T_{wb} = 70^\circ F$. The total pressure is 14.696 psia. From the psychrometric chart you can get the necessary values. At the intersection of the DB line and the WB line read:

a. $\gamma = 0.014 \text{ lb water/lb dry air}$

b. Read: $RH = 56\%$

c. The vapor pressure of water $p_{v,o}$ at 82$^\circ F$ is (from the steam tables) = 0.5409 psia

d. From the humidity chart, the dewpoint is 65$^\circ F$

e. The enthalpy comes from following the WB line to the left (34.2) less the enthalpy deviation of -0.1 Btu/lb dry air.

$H = 34.1 \text{ Btu/lb dry air}$

f. The specific volume at the initial point is

$-14 \text{ ft}^3$/lb dry air

29.16

Basis: 1 lb dry air

Data from the humidity chart.

Initial state:

$T_{db} = 180^\circ F$ and $T_{wb} = 120^\circ F$

$\gamma = 0.0637 \text{ lb H}_2\text{O/lb dry air}$

$H_{saturated} \approx 120 \text{ Btu/lb dry air}$

$S_{H_{saturated}} \approx -1.5 \text{ Btu/lb dry air}$

$H = 118.5 \text{ Btu/lb dry air}$

Final state

$T_{db} = 115^\circ F, T_{wb} = ?, H = 0.0657 \text{ lb H}_2\text{O/lb dry air}$

$H_{saturated} \approx 101 \text{ Btu/lb dry air}$

$\Delta H = 101 - 118.5 = -17.5 \text{ Btu/lb dry air}$

29.17

State: $T_{db} = 80^\circ F$  $RH = 65\%$

Basis: 1 lb dry air

$\gamma$ from the humidity chart is 0.0142 lb H$_2$O/lb dry air
29.18

From the humidity chart
Humidity = 0.0105 kg/kg dry air
Wet bulb temperature = 21.5°C
Humid volume = 0.88 m³/kg dry air
Dew point = 14.7°C
Specific enthalpy = 63 - 0.5 = 62.5 kJ/kg dry air

29.19

From the humidity chart
Relative humidity = 30%
Specific enthalpy = 76.5 - 0.65 = 75.85 kJ/kg dry air

29.20

From the humidity chart
Dry bulb temperature = 33.7°C
Wet bulb temperature = 27°C
Relative humidity = 60%
Humid volume = 0.897 m³/kg dry air
Enthalpy = 85.1 - 0.34 = 84.76 kJ/kg

29.21

Basis: 1 lb bone dry air (BDA)

Data from psychometric chart (BDA = bone dry air).

a. @ 1, Dew point = 23°C

b. @ 1, humidity = 0.018 kg H₂O/kg dry air

b. @ 1, Relative humidity = \( \frac{H}{H_2} = \frac{0.018}{0.033} \times 100 = 54.5\% \)

c. @ 1, Relative humidity = \( \frac{H}{H_2} = \frac{0.018}{0.033} \times 100 = 54.5\% \)

d. \( \Delta H = Q + W \)
\( W = 0 \)
Q = \( \Delta H_2 - \Delta H_1 = (141.5 - 3.6) \frac{kJ}{kg \text{ BDA}} - (79.0 - 0.3) \frac{kJ}{kg \text{ BDA}} = 59.2 \frac{kJ}{kg \text{ BDA}} \)
\( m = \frac{V}{V} = \frac{100 \text{ m}^3 \text{ entering air}}{0.89 \text{ m}^3} = 112.36 \text{ kg BDA} \)
Q = \( \frac{59.2 \text{ kJ}}{112.36 \text{ kg BDA}} = 6.651.7 \text{ kJ} \)
e. Adiabatic cooling by evaporation yields a saturated humidity of 0.041 kg H₂O/kg BDA.

(continued)
### Solutions Chapter 29

<table>
<thead>
<tr>
<th>0.041 kg H₂O - 0.018 kg H₂O</th>
<th>112.36 kg BDA</th>
<th>2.58 kg H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg BDA</td>
<td>110 m³ air</td>
<td>100 m³</td>
</tr>
</tbody>
</table>

\[ T_{exit} = 0 \degree C \]

#### 29.22

**Basis:** 1 lb dry air

- Assume \( p_T = 760 \text{ mm Hg} \)
- \( p_{H₂O} @ 120\degree F = 87.58 \text{ mm Hg} \)
- 
  \[ H = \frac{(183)(87.58)}{(29)(672.42)} = 0.081 \text{ lb H₂O/lb dry air} \]
- From psychrometric chart, sat'd volume @ 120°F = 16.52(R)/lb dry air
- From psychrometric chart, adiabatic cooling temp = wet bulb temp = 77°F
- \( h @ 120\degree F \) (DP = 60°F) = 0.0110 lb H₂O/lb air
- \( h_{sat} @ 82\degree F = 0.0237 \text{ lb H₂O/lb air} \)
- \( \% \text{ sat} = \frac{(0.0110)(100)}{(0.0237)} = 46.2\% \)
- \( H_{sat} @ 60\degree F = 0.01101 \text{ lb H₂O/lb dry air} \)
- \( H_{sat} @ 40\degree F = 0.00515 \text{ lb H₂O/lb dry air} \)
- \( 0.01101 - 0.00515 = 0.00586 \)

From the SI psychrometric chart at 29°C and 40% relative humidity read

\[ T_{wb} = 19.3\degree C \]

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature, which is the lowest temperature that can be obtained on an evaporative cooler. That is,

\[ T_{wb} = 19.3\degree C \]

#### 29.24

Excess dryness in the air feels uncomfortable.

#### 29.25

To reduce the relative humidity so the air will not feel so damp.

#### 29.26

Yes.

#### 29.27

- The humidity of the entering air at 225°F DB and 110°F WB is obtained from the humidity chart.
  (continued)
Humidity = \frac{0.031 \text{ lb } H_2O}{\text{lb dry air}}

Assume the exit air to be saturated at 125°F.

Humidity = \frac{0.0955 \text{ lb } H_2O}{\text{lb dry air}}

b. Basis: 1 hr

10 tons/1 day = \frac{2000 \text{ lb}}{24 \text{ hr/ton}} = 835 \text{ lb/hr}

Water in = (0.1) (835) = 83.5 \text{ lb/hr}

Water out = \frac{(0.9)}{(835)} \text{ lb dry grain} \times \frac{1 \text{ lb } H_2O}{99 \text{ lb dry grain}} = 7.59 \text{ lb/hr}

\text{lb } H_2O \text{ removed/hr} = \text{water in} - \text{water out} = 83.5 - 7.59 = 75.9 \text{ lb } H_2O/\text{hr}

c. Product output = \left[ \frac{(0.9)}{(835)} \text{ lb dry grain} + \frac{7.59 \text{ lb } H_2O}{\text{hr}} \right] \left( \frac{24 \text{ hr}}{1 \text{ day}} \right) = 18,200 \text{ lb/day}

d. \frac{7.59 \text{ lb } H_2O/hr}{(0.0955 - 0.0310) \text{ lb } H_2O/\text{lb BDA}} = 1175 \text{ lb BDA/hr}

Q = \Delta H = \text{Enthalpy out} - \text{Enthalpy in}

= \Delta H_{\text{air}} + \Delta H_{\text{dry grain}} + \Delta H_{\text{water}}

= 1175 \text{ lb BDA/hr} \left[ \frac{136.5 \text{ Btu}}{\text{lb BDA}} - (92.25 - 2.25) \text{ Btu/} \text{lb BDA} \right]

+ (0.9)(835) \text{ lb dry grain} \left( \frac{0.18 \text{ Btu}}{\text{lb} \ (\degree F)} \right) \left( \frac{(110 - 70) \degree F}{\text{lb}} \right)

29.28

Assume in this problem

1. Steady operating conditions
2. Dry air and water vapor are ideal gases
3. \( \Delta KE = \Delta PE = W = 0 \)
4. The mixing is adiabatic (Q = 0)

Data from the humidity chart:

Stream 1:

\( H_1 = 110.3 \text{ kJ/kg dry air} \)

\( \eta = 0.0272 \text{ kg } H_2O/\text{kg dry air} \)

Stream 2:

\( H_2 = 50.9 \text{ kJ/kg dry air} \)

\( \eta_2 = 0.0130 \text{ kg } H_2O/\text{kg dry air} \)

The specific humidity and the enthalpy of the mixture can be determined from mass and energy balances for the adiabatic mixing of the two streams:

Basis: 1 kg dry air

Total Mass balance: 8 + 6 = 14 kg total

(continued)
Solutions Chapter 29

Water mass balance:

\[ 8(0.0272) + 6(0.0130) = 14 \] (mixtures)

b. \( \omega = 0.0211 \text{ kg H}_2\text{O/kg dry air} \)

Energy balance (\( \Delta H = 0 \))

\[ 8(110.3) + 6(50.9) = 14 \] (mixtures)

\[ H = 84.8 \text{ kJ/kg dry air} \]

These two properties fix the state of the mixture. Other properties of the mixture are determined from the psychrometric chart.

d. \( T = 30.7^\circ C \)

c. \( RH = 75.1\% \)

Data from Humidity Chart

Solutions Chapter 29

Energy Balance:

\[ \Delta H_{\text{air out}} - \Delta H_{\text{air in}} = \Delta H_{\text{water in}} - \Delta H_{\text{water out}} \]

Basis: 1 lb dry air

Ref. temp. = 85°F

\[ \Delta H_{\text{air}} = \Delta H_{\text{H}_2\text{O}} \]

\[ \frac{0.24 \text{ Btu}}{(\text{lb}) (\text{°F})} = \frac{0.45 \text{ Btu}}{(\text{lb}) (\text{°F})} \]

\[ \Delta H_{\text{H}_2\text{O}} = \Delta H_{\text{H}_2\text{O}} + \Delta H_{\text{H}_2\text{O} \text{ in}} \]

\[ \frac{1040 \text{ Btu}}{\text{lb}} \boldsymbol{0.0129 \text{ lb}} \]

\[ -0 \]

\[ = \frac{1 \text{ Btu}}{(\text{lb}) (\text{°F})} \]

\[ m = 1.136 \text{ lb H}_2\text{O/lb air or 0.915 lb air/ lb H}_2\text{O} \]

c. \% \text{ H}_2\text{O} vaporized = \frac{0.0129}{1.136} \times 100 = 1.14\%

29.30

Basis: 180 kg/hr of product

Material Balance

Dry product = \frac{92 \text{ kg dry P}}{100 \text{ kg P}} \times 1 \text{ hr} = 166 \text{ kg dry P/hr}

a. Water removed from solid: (continued)
Solutions Chapter 29

\[
\ln = \frac{1.35 \text{ kg H}_2\text{O} / 1.00 \text{ kg dry F}}{166 \text{ kg/hr dry F} / (0.08) (180) \text{ kg/hr}} = 207.5 - 14.4 = 193 \text{ kg H}_2\text{O/hr}
\]

Basis: 1 BDA

Water picked up in dryer

\[
\begin{align*}
\text{out} & : \quad \frac{0.0571 \text{ kg H}_2\text{O}}{\text{kg BDA}} \quad \frac{0.0083 \text{ kg H}_2\text{O}}{\text{kg BDA}} \\
\text{in} & : \quad \frac{0.0488 \text{ kg H}_2\text{O}}{\text{kg BDA}}
\end{align*}
\]

\[
\begin{align*}
\text{kg BDA} & = \frac{193 \text{ kg H}_2\text{O}}{0.0488 \text{ kg H}_2\text{O/kg BDA}} = 3955 \text{ kg BDA/hr} \\
\text{hr} & = \frac{0.0488 \text{ kg H}_2\text{O/kg BDA}}{193 \text{ kg H}_2\text{O}} = 0.0026 \\
\end{align*}
\]

b. Energy balance

\[
\Delta H (\text{kJ/kg BDA})
\]

Air:

- air in (21°C, 52% RH):
  \[58.2\] 
- air out (53°C, 60% RH):
  \[219.7\]

\[
\Delta H = 161.5 \text{ kJ/kg BDA}
\]

Basis: 1 hr

\[
\Delta H = (161.6)(3955) = 6.387 \times 10^5 \text{ kJ}
\]

Solid (ref. 21°C)

Solutions Chapter 29

\[
\text{solid out: } \Delta \tilde{H} = \int_{T_1}^{T_2} C_p dT = 0.18 \text{ cal/}^\circ \text{C} \cdot \text{mol} \cdot \text{cal/g} \cdot \text{cal/}^\circ \text{C} \cdot \text{g} = 16.57 \text{ kJ/kg P}
\]

\[
\text{solid in: } \Delta \tilde{H} = 0 \text{ (because of reference temperature)}
\]

Basis: 1 hr

\[
\Delta H = (16.57)(180) = 2983 \text{ kJ}
\]

If the dryer and reheater are insulated, then for the system

\[
Q = W = \Delta H \text{ and } W = 0
\]

\[
Q_{\text{reheater}} = 2983 + 6.387 \times 10^5 = 6.42 \times 10^5 \text{ kJ/hr}
\]

29.31

Initial air: \(T_{\text{DB}} = 38^\circ \text{C}, T_{\text{WB}} = 27^\circ \text{C}\),

\[
H_1 = 0.0175 \text{ kg/kg dry air}
\]

Air from scrubber: \(T = 24^\circ \text{C}, RH = 100\%, RH_2 = 0.0188 \text{ kg/kg dry air}\)

Heated to 93°C: \(H_2 = 0.0188\)

From drier: \(T_{\text{DB}} = 49^\circ \text{C}, H_4 = 0.0377\)

\((1000 \text{ kg/hr}) (0.05) = 50.0 \text{ kg H}_2\text{O to be evaporated}\)

\[
50.0(0.0377 - 0.0188) = 2650 \text{ kg dry air/hr}
\]

\[
2650 (0.0377) = 100 \text{ kg H}_2\text{O/hr}
\]

\[
V_0 \left( \frac{2650 + 100}{29} \right) \left( \frac{22.4}{18} \right) \left( \frac{273 + 49}{273} \right) = 2560 \text{ m}^3 \text{ at } 49^\circ \text{C and 1 atm}
\]

(continued)
Heat supplied:

\[ Q = [(2650) \times (1.00) + 100 \times (0.200)] (93 - 24) = 1.84 \times 10^5 \text{ kJ/hr} \]

Water at 93°C has \( p^* = 79.4 \text{ kPa} \)

\[ h_s = \frac{(18)}{(29)(101.3 - 79.4)} = 2.25 \text{ kg H}_2\text{O/kg dry air} \]

\[ \left(\frac{0.0188}{2.25}\right) \times (100) = 0.83\% \text{ RH air from heater} \]

Answers:

a. \( H = 0.0175 \)  
   b. \( H = 0.0188 \)  
   c. \( 2650 \text{ kg dry air/hr} \)  
   d. \( 100 \% \)  
   e. \( 2560 \text{ m}^3/\text{hr} \)

29.32

**Step 5:** Basis: 1 hr

Assume:

1. \( \Delta P E = \Delta K E = W = 0 \),
2. No reaction occurs,
3. open, steady state process,
4. ideal gas behavior

Data:

**Entrance air (in)**

- \( H \) (kJ/kg dry air) = 50.5
- \( \gamma \) (kg H\(_2\)O/kg dry air) = 0.00587
- \( \dot{V} \) (m\(^3\)/kg dry air) = 0.88

Assume the properties of the wet penicillin are the same as those of water. \( \Delta H_{\text{m}} \) at 34°C = 2420.25 kJ/kg water. Let \( P \) = kg dry penicillin per hour, and \( F \) = kg dry air/hr.

**Steps 3 and 4**

**Steps 6 and 7:**

The exit conditions for the air are not known, but the \( \gamma \) and \( H \) are related on the humidity chart hence only one is unknown. \( P \) (dry penicillin is unknown).

The balances are water, dry air, and dry penicillin.

**Steps 8 and 9**

<table>
<thead>
<tr>
<th>( T_{\text{wa}} ) (°C)</th>
<th>( \gamma ) (kg H(_2)O/kg dry air)</th>
<th>( \dot{H} ) (kJ/kg dry air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.009</td>
<td>57.0</td>
</tr>
<tr>
<td>21</td>
<td>0.010</td>
<td>60.6</td>
</tr>
<tr>
<td>22</td>
<td>0.0115</td>
<td>64.0</td>
</tr>
</tbody>
</table>

(continued)
Water balance: 5114 (0.009 - 0.00587) = water evaporated = 16.0 kg  
5114 (0.010 - 0.00587) = 21.1 kg  
5114 (0.0115 - 0.00587) = 28.8 kg  

Energy balance: 5114 (57.0 - 50.5) / (2420.25) = 13.73 kg  
5114 (60.5 - 50.5) / (2420.25) = 21.1 kg  
5114 (64.0 - 50.5) / (2420.25) = 28.5 kg  

The solution is very sensitive to the values read from the psychometric chart. Assume the final Twa = 21 or 22°C. 

a. Water evaporated = 28.5 kg  
b. ∆H (21°C) = 51,140 kJ/kg dry air = 51,140 kJ/hr  
c.  

Steps 6 and 7  
Unknowns P, exit Twa  
Equations air, water  

Steps 8 and 9  
Water balance on air gives water evaporated (5114) (0.010-0.00587) = 21.1 kg H₂O  
Energy balance: 60.5 - 50.5 (5114) + 21.1 (2420.25) = 0  
0.80 → 0.60  
Use 21°C  
21.1 kg H₂O evap = P \[\left[\frac{0.80 - 0.50}{0.20 - 0.50}\right] = 3P\]  

P = \[\frac{21.1}{3}\] = 7 kg/hr  

29.33  
Steps 1, 2, 3, and 4  
The process will be assumed to be a steady state, open, continuous one with 5L flowing in (in the material balance the air is invariant). All of the data for the stream flows and compositions have been placed on the figure. The lungs will be the system.  

\[
\begin{align*}
5 \text{ L air, 25°C} & \quad \text{Lungs} & 5 \text{ L air, 37°C} \\
\text{P} & = 0.95 \text{ kPa} & \text{P} & = 6.27 \text{ kPa} \\
\text{P}_{\text{H}_2\text{O}} & = 96.05 \text{ kPa} & \text{P}_{\text{H}_2\text{O}} & = 90.73 \text{ kPa} \\
t_{\text{air}} & = 97.0 \text{ kPa} & t_{\text{tot}} & = 97.0 \text{ kPa} \\
\text{P}_{\text{H}_2\text{O}} & = 3.17 \text{ kPa} & \text{P}_{\text{H}_2\text{O}} & = 3.17(0.3) = 0.95 \text{ kPa} \\
\end{align*}
\]

Step 5: Basis: 5 L air → 1 min  
Steps 6, 7, 8, and 9:  
Material balances  
\[
\ln n_{\text{H}_2\text{O}} = \frac{96.05 \text{ kPa}}{1 \text{ atm}} \cdot \frac{\text{5 L}}{101.3 \text{ kPa}} = 0.194 \text{ g mol} \\
\]

Out:  
\[n_{\text{H}_2\text{O}} = 0.194 \text{ g mol}\]  

(continued)
Solutions Chapter 29

\[ n_{H_2O} = 0.194 \left( \frac{6.27}{90.73} \right) = 0.0134 \text{ g mol} \]

Energy balance

The energy balance reduces to \( Q = \Delta H \). The reference temperature will be 25°C. Assume the increase in water vapor comes from water vaporized at 37°C \( (\Delta H_{\text{vap}} = 2414.3 \text{ kJ/kg}). \)

\( \Delta H_{\text{air}} \): Both the air and water enter at 25°C so \( \Delta H = 0 \) for both the input streams.

\[ \Delta H_{\text{air}} = 0.194 \int_{25}^{40} (27.2 + 0.0041 T_v) dT = 66.2 \text{ J} \]

\[ \Delta H_{H_2O} = 1.92 \times 10^{-3} \int_{34}^{40} (34.4 + 0.0063 T_v) dT \]

\[ + (0.0134 - 1.92 \times 10^{-3}) (2414.3)(18) = 499 \text{ J} \]

\( Q = \Delta H = 499 + 66.2 = 565 \text{ J/min or } 53.9 \text{ kJ/hr} \)

29.34

\[ \]
Solutions Chapter 29

Air out = \( \frac{1.00 \text{ lb mol}}{0.0261} \) = 2,930 lb mol dry air out

\[ \begin{align*}
\text{H}_2\text{O out} &= \frac{0.0292 \text{ lb mol}}{0.0261} \frac{2220 \text{ lb mol}}{18} = 138 \text{ mol H}_2\text{O out} \\
\text{Total mol out} &= 3068 \text{ total mol out}
\end{align*} \]

\[ \begin{align*}
\text{Air Recirculated} &= \frac{3068}{359} \frac{580}{492} = 1,300,000 \text{ ft}^3 \text{ wet air exiting/ton DW}
\end{align*} \]

Water balance: \((0.0031)(1) + (0.0292)(W) = (0.0075)(1+W)\)

\[ \begin{align*}
0.0292 W &= 0.0075 \\
-0.0075 W &= -0.0031 \\
0.0217 W &= 0.0044
\end{align*} \]

\[ \begin{align*}
R &= \frac{0.0044}{0.0217} = 0.203 \text{ lb}
\end{align*} \]

\[ \begin{align*}
\text{Recirculation} &= \frac{0.203}{1.203} = 16.8\% \text{ of gas out is recirculated}
\end{align*} \]

29.35

Adiabatic operation removes 425,000 Btu/hr from the process.

Basis: 1 hr

The energy balance is \( \Delta H = 0 \) overall.

a. For the process:

\[ \begin{align*}
T_{\text{in}} &= 100^\circ \text{F} \\
T_{\text{out}} &= 234^\circ \text{F} \\
R\% &= 1.3\%
\end{align*} \]

b. Temperature leaving the cooler is 61°F (dew point constant \( R \))

c. (continued)
d. \[ \Delta H = (72 - 27) \text{ Btu/lb BDA} = 45 \]

<table>
<thead>
<tr>
<th>425,000 Btu</th>
<th>1 lb BDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 Btu/hr</td>
<td>9450 BDA/hr</td>
</tr>
</tbody>
</table>
30.1

To variables (2 streams + Q) 2 (c + 1) + 1 = 2c + 5
Constraints
indept. material balances  c
energy balance  1  c + 1
Net d.f.  c + 4

30.2

Total variables (2 streams + Q) 2 (c + 2) + 1 = 2c + 5
Constraints
indept. material balances  c
energy balance  1  c + 1
Net d.f.  c + 4

Conventional specifications of variables are the entering stream (c + 2), and the temperature (1) of the exit stream. In some instances Q (1) may be specified rather than the outlet temperature.

30.3

Assume the feed is a single phase stream not the same as any of the other streams.

Total variables (5 streams + Q) 5 (c + 2) + 1 = 5c + 11
Constraints:
Indep. material balances  c
Energy balance  1
Equilibrium relations  c
T same in each phase  1
p same in each phase  1  2c + 3
Net d.f.  3c + 8

30.4

The components are 6: CH₄, CO₂, CO, H₂O, N₂, O₂. Hence, the total no. of variables is for 3 streams + Q 3 (4 + 2) + 1 = 19

We can reduce these variables by |

Note: the true number of phase rule components = 4 (continued)
30.6

Assume phase equilibrium exists if more than one phase occurs. With \( r \) reactions, we have \( \xi_1, \xi_2, \ldots, \xi_r \) values specified.

\[
\begin{align*}
C + 2 & \rightarrow C + 2 \\
\text{r+1 specifications} (\xi_1, \xi_2, \ldots, \xi_r, 0)
\end{align*}
\]

We trade \( r \) equilibrium relations for the \( r \) extent of reactions, and the degrees of freedom are \( C + 2 - (r + 1) = C - r + 1 \).

30.7

24 variables - (3) (5) equations = 9 less 4 specifications = 5 more specifications (the equations are energy, mass, equilibria.)

30.8

a. A set of differential equation can be written for each stage for each component (and total material).

For the steady state, you can write overall balances:
- total mass balance
- \( \text{NH}_3 \) balance
- \( \text{H}_2\text{O} \) balance
- sum of mass fraction balances for \( F, D, B \)

If a basis is picked, such as \( F = 100 \), 2 unknowns exist, \( D \) and \( B \), and two independent equations exist; hence the system is determinate. (continued)
For the sequence of stages, each stage would have:
- Total material balance
- Component material balances
- Equilibrium relations
- Sum of mass (mole) fraction relations

In total, there would be 6 independent equations and 8 unknown variables on the top stage. The bottom stage would have 7 independent equations and 7 unknowns. Starting at the bottom, each successive stage would be determinate until the top was reached. Without equilibrium relations holding and without knowing enthalpies as a function of concentration, the number of unknowns would exceed the number of independent equations.

b. Examine unit 1 in as much as no feedback of information occurs. If unit 1 is not determinate, the entire system will not be determinate. The balances for unit 1 are:

\[ \text{total alcohol merts equilibrium} \]
\[ y_b + y_a = 0.90 \]

The unknowns are 5

\[ V_1, L_1, S_0, Y_{10}, Y_{1a} \]

Thus, the subsystem is not determinate.

30.9

\[ N_e = 3 (5 + 2) \]

\[ N_s = \]

Material balances 5
Vapor-liquid equilibria relations 4
(One pair, \( x_{35} = K x_{25} \), is known)
Basic Block Diagram for the Flowsheet

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equations</th>
<th>Stream Variables</th>
<th>Unit Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixer</td>
<td>5</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Reactor</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Cooler</td>
<td>8</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Valve</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Flash</td>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Bleed</td>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Compressor</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

Streams Leaving

<table>
<thead>
<tr>
<th>Stream variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Water</td>
</tr>
<tr>
<td>Product</td>
</tr>
<tr>
<td>Bleed Stream</td>
</tr>
</tbody>
</table>
31.1

\[ \Delta H = 145.36 \text{kJ/kg} \]

\[ \Delta H = 2727.4 \text{kJ/kg} \]

\[ \Delta H = 604.3 \text{kJ/kg} \]

Data

\( W \) (interpolating from SI steam tables)

\[ \Delta H_w = \frac{2644.0 \text{kJ}}{\text{kg}} + \frac{(2738.8 - 2644.0) \text{kJ}}{(394 - 350) \text{K}} = 2727.4 \text{kJ/kg} \]

\( F \)

\[ \Delta H_F = \frac{62.5 \text{Btu/lb}}{0.4536 \text{kg}} = \frac{145.36 \text{kJ}}{\text{kg}} \]

\( P \)

\[ \Delta H_P = \frac{-19.0 \text{Btu/lb}}{0.4536 \text{kg}} = -44.19 \text{kJ/kg} \]

Unknowns: \( W, P, S, C \)

Balances: \( \text{H}_2\text{SO}_4, \text{H}_2\text{O} \) (or overall), energy

\[ \text{H}_2\text{SO}_4 \text{ Balance:} \]

<table>
<thead>
<tr>
<th>F kg Feed</th>
<th>P kg Product</th>
<th>80 kg \text{H}_2\text{SO}_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kg \text{H}_2\text{SO}_4</td>
<td>20 kg</td>
<td>100 kg Feed</td>
</tr>
<tr>
<td>100 kg Feed</td>
<td>100 kg Product</td>
<td></td>
</tr>
</tbody>
</table>

0.2 (100 kg) = 0.8 P

P = 25 kg

Overall Mass Balance:

\( F_{\text{kg feed}} + S_{\text{kg steam}} = W_{\text{kg vapor}} + P_{\text{kg product}} + C_{\text{kg condensate}} \)

\( F + S = W + P + C \)

\( F = W + P \)

\( 100 \text{ kg} = W + 25 \text{ kg} \) hence \( W = 75 \text{ kg H}_2\text{O} \) vapor

Overall Energy Balance Reduces to (Open System, Steady State):

\[ \Delta H = 0 \]

\[ m (\Delta H_C - \Delta H_s) + (m_w \Delta H_w + m_p \Delta H_p) - m_f \Delta H_f = 0 \]

\[ m = \frac{188,914.751 \text{kJ}}{88.5 \text{kg steam}} = 1,129.5 \text{ kg feed} \]
### 31.3

**Basis:** 1 hr

**Eqn. No.**

1. **Turbine Material Balance**
   
   \[ A = B + C \]

2. **Turbine Energy Balance**
   
   \[
   \frac{200,000}{hr} = \frac{1482A - 1406B - 1164C}{Br\text{u}}\text{ Btu} \times \frac{1\text{ hp}}{2.55 \times 10^7\text{ Btu/hr}}
   \]

   \[ 20,000 = \frac{(B/30) + (C/8)}{} \]

3. **600-psi Material Balance**
   
   \[ B = 100,000 + 100,000 + D + 30,000 \]

   \[ B = D + 230,000 \]

4. **50-psi Material Balance**
   
   \[ F + D + 30,000 = E \]

5. **50-psi Energy Balance**

\[ 1,380 D + 30,000 (1,300) + 218 F = 1,210 E \]

6. **Deaerator Material Balance**
   
   \[ E + C + 200,000 = A + F \]

7. **Deaerator Energy Balance**
   
   \[ 1,210 E + 68 (C + 200,000) = 218 (A + F) \]

There are 7 eqns. and 6 unknowns.

Combine \((4) \& (6)): A - C - D = 230,000 \]

" \((4) \& (7)): 218 A - 68 C - 218 D - 992 E = 20,140,000 \]

" \((4) \& (5)): 1162 D + 32,460,000 = 992 E \]

Combine \((8) \& (1)): B - D = 230,000 \]

" \((9) \& (1)): 218 (B + C) - 68 C - 218 D - 992 E = 20,140,000 \]

" \((10) \& (12)): 218 B + 150 C - 1380 D = 52,600,000 \]

Solving eqns. \((2), (11) \& (13)) simultaneously:

\[
\begin{align*}
B &= 240,266 \text{ lb/hr} \\
C &= 95,929 \text{ lb/hr} \\
D &= 10,266 \text{ lb/hr} \\
E &= 44,747 \text{ lb/hr} \\
F &= 4,481 \text{ lb/hr} \\
A &= 336,195 \text{ lb/hr}
\end{align*}
\]

Substituting \(D\) in eqn. 10:

" \(D \& E\) in eqn. 4:

" \(B \& C\) in eqn. 1:
A calciner presents a classic choice between air preheat and waste-heat boilers. The goal is to reduce the consumption of natural gas. Only about the 50 x 10^6 Btu/hr are being absorbed into the process. A rough calculation gives

\[
\text{(Btu/hr)}(10^6) = 200,000 \times 0.5 \times (500 - 200)^\circ F = 254,000 \\
\text{Water vaporization} = 20,000 \times 970 = 19,400 \\
\text{Water heating} = 20,000 \times 0.5 \times (1,000 - 500) = 50,000 \\
\text{Total} = 254,000 + 19,400 + 50,000 = 323,400
\]

About 150 x 10^6 are available in the fuel.

Preheating the air

Preheating the air to 560°F will cool the flue gas to about 500°F, and no condensation should occur. The duty of the preheater would be 400,000 x 0.24 (560 - 60) = 48 million Btu/hr. The exhaust flue gas from the air preheater could be used to generate steam or to preheat feed (in a direct-contact fluid bed, for example), and the product solids might also be put to use. Either holds the potential for another 20 million Btu/hr savings if a sue can be found for the recovered steam or heat.

Waste heat boiler

About 52,000 lb/hr of 630-psig steam could be generated. This could be used to preheat the feed and perhaps do some of the water vaporization, but his amounts to replacing the calciner—a high-capital-cost route. The steam could also be used to preheat the combustion air to about 450°F. This would utilize 400,000 x 0.24 x (450 - 60) = 37.4 million Btu/hr.

Capital costs of the respective equipment must be considered. Usually the capital cost for air preheat systems are less. In addition, credits are sure, since fuel is conserved directly. The value of the heat saved does not depend on the overall site steam balance. On the other hand, steam is more flexible and far more portable than large volumes of hot gas. Preheated combustion air changes the combustion characteristics and the radiant-heat distribution of a furnace and can increase emissions of nitrogen oxides. The addition of hot-air ducts can sometimes cause access problems under a furnace and may in fact become uneconomical for furnaces with a large number of wall burners.
### Solutions Chapter 31

**Basis:** 1 g mol CaCO₃

\[
\Delta H_{\text{CaO}} = \frac{111 \text{ J}}{\text{g mol}} \left( \frac{900 - 25}{\text{°C}} \right) = 97.125 \text{ kJ/g mol CaCO}_3
\]

Let \( X \) be the g mol CH₄/g mol CaCO₃

CaO gas + CaCO₃ gas + air → Reactions

\[
[(1)(97.125) + 0] - [0 + 0 + 0] + [(1)(177.8) + X(-890.36)] = 0
\]

\[
X = 0.309 \text{ g mol CH}_4/\text{g mol CaCO}_3
\]

\[
\begin{align*}
1 \text{ g mol CaCO}_3 & \quad 100 \text{ g mol CaCO}_3 \\
0.309 \text{ g mol CH}_4 & \quad 16 \text{ g mol CH}_4
\end{align*}
\]

\[
1 \times 10^3 \text{ kg CaCO}_3
\]

\[
20.5 \text{ kg CaCO}_3/\text{kg CH}_4
\]

### 31.6

**Basis:** 1 hr

**Material balance**

<table>
<thead>
<tr>
<th>In</th>
<th>lb</th>
<th>Out</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt (16,000)(.07)</td>
<td>= 1,120</td>
<td>Salt</td>
<td>= 1,120</td>
</tr>
<tr>
<td>Water 16,000 - 1,120</td>
<td>= 14,880</td>
<td>Water soin 1,120 - ( \frac{1,120}{0.4} )</td>
<td>= 1,680</td>
</tr>
<tr>
<td>Water evap. 14,880 - 1,680</td>
<td>= 13,200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) **Energy balance**

**Basis:** 180°F, liq. H₂O

<table>
<thead>
<tr>
<th>In</th>
<th>Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>7% Solution = (0.92)(16,000)(T - 180)</td>
<td>= 14,720 (T - 180)</td>
</tr>
</tbody>
</table>

**Out**

\[
\begin{align*}
\text{Steam } \Delta H_{\text{vap}} &= (15,000)(959) = 14,400,000 \\
\text{Liq. H}_2\text{O} &= (15,000)(1.0)(230 - 180) = 750,000 \\
\text{Condensate} &= 15,000(230 - 180) = 750,000 \\
\text{Conc. salt soln} &= \quad 0
\end{align*}
\]

\[15,150,000 + 14,720 (T-180)\]

T = 90°F

The above analysis ignores the heat of solution effects as the NaCl becomes more concentrated.

(b) 2,800 lb 40% NaCl produced/hr
<table>
<thead>
<tr>
<th>Component</th>
<th>Flowrate (lb/hr)</th>
<th>Composition</th>
<th>Energy (Btu/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed A</td>
<td>15000</td>
<td>H₂O, O₂</td>
<td>-160000</td>
</tr>
<tr>
<td>Feed B</td>
<td>30000</td>
<td>H₂O, O₂</td>
<td>-320000</td>
</tr>
<tr>
<td>Condensate</td>
<td>60000</td>
<td>H₂O, O₂</td>
<td>-160000</td>
</tr>
<tr>
<td>Out</td>
<td>400000</td>
<td>H₂O</td>
<td>-400000</td>
</tr>
<tr>
<td>Stream 1</td>
<td>225000</td>
<td>H₂O</td>
<td>-225000</td>
</tr>
<tr>
<td>Stream 2</td>
<td>300000</td>
<td>H₂O</td>
<td>-300000</td>
</tr>
<tr>
<td>Stream 3</td>
<td>125000</td>
<td>H₂O</td>
<td>-125000</td>
</tr>
</tbody>
</table>

**Energy Balance on Condenser 1**

\[ \text{In} \quad \text{W} = 15 \text{lb H₂O} \quad \text{In} \quad \text{W} = 400000 \text{Btu/hr} \]

\[ \text{Out} \quad \text{W} = 400000 \text{Btu/hr} \quad \text{Out} \quad \text{W} = 10 \text{lb H₂O} \]

**Steam In/Out**

\[ \text{Steam In} = 1 \text{lb H₂O} \quad \text{Steam Out} = 2 \text{lb H₂O} \]

**Energy Balance on Column 1**

\[ \text{In} \quad \text{W} = 30000 \text{Btu/hr} \quad \text{In} \quad \text{W} = 400000 \text{Btu/hr} \]

\[ \text{Out} \quad \text{W} = 400000 \text{Btu/hr} \quad \text{Out} \quad \text{W} = 400000 \text{Btu/hr} \]

**Product Out**

\[ \text{Product Out} = 1 \text{lb H₂O} \]

**Energy Balance on Column 2**

\[ \text{In} \quad \text{W} = 30000 \text{Btu/hr} \quad \text{In} \quad \text{W} = 400000 \text{Btu/hr} \]

\[ \text{Out} \quad \text{W} = 400000 \text{Btu/hr} \quad \text{Out} \quad \text{W} = 400000 \text{Btu/hr} \]

**Product Out**

\[ \text{Product Out} = 1 \text{lb H₂O} \]
since on condenser II:

\[ W = \text{lb H}_2\text{O}/\text{hr}; \quad \text{Reference temperature} = 172^\circ \text{F} \]

\[
\begin{align*}
\text{In} & \quad \text{Out} \\
4200(0.72)(172 - 172) + (4200)(650) &= 2725000 \\
W'(1.0)(30 - 172) &= -92W' \\
\text{Condensate} & \quad \text{Cooling H}_2\text{O} \quad W'(1.0)(172 - 150) = -42W' \\
-92W' + 2725000 &= -36000 \\
50W &= 2761000 \\
W &= 55200 \text{ lb H}_2\text{O}/\text{hr} \\
\frac{55200 \text{ lb H}_2\text{O}}{50 \text{ gal}} &= 1104 \text{ gal H}_2\text{O}/\text{hr} \\

\text{since on heat exchanger II:} \\
\quad W = \text{lb H}_2\text{O}/\text{hr}; \quad \text{Reference temperature} = 80^\circ \text{F} \\
\begin{align*}
\text{In} & \quad \text{Out} \\
1050(0.72)(160 - 80) &= 60500 \\
W'(1.0)(80 - 80) &= 0 \\
\text{Product} & \quad \text{Cooling H}_2\text{O} \quad W'(1.0)(190 - 80) = 50W' \\
60500 + 50W' &= 15120 \\
50W' + 15120 &= 60500 \\
W &= 907 \text{ lb H}_2\text{O}/\text{hr} \quad \text{or} \quad 109 \text{ gal H}_2\text{O}/\text{hr} \\

\text{Phase 2: Energy Balances} \\
(a) \quad \text{Energy balance on heat exchanger III (Fig. E5.15b)}: \\
\text{Feed} \quad 10000 \text{ lb at } 90^\circ \text{F} \\
\text{Heat Exchanger III} \quad 8333 \text{ lb at } 70^\circ \text{F} \\
\text{Reference Temperature} = 80^\circ \text{F} \\
\text{Out} \quad 10000 \text{ lb at } 210^\circ \text{F} \\
\begin{align*}
\text{Feed} & \quad (10000)(0.90)(80 - 80) = 0 \text{ Btu} \\
\text{Bottoms} & \quad (8333)(1.0)(210 - 80) = 1884000 \text{ Btu} \\
\text{Out} & \quad (10000)(0.90)(170 - 80) = 8640000 \text{ Btu} \\
\text{Bottoms} & \quad (8333)(1.0)(T - 80) = 8333T - 666000 + 864000 \\
886000 &= 8333T \\
T &= 106.5^\circ \text{F} \\

(b) \quad \text{Energy balance around heat exchanger III inlet, and overhead vapor and reflux line from 1:} \\
\text{Reference temperature} = 176^\circ \text{F} \\
\begin{align*}
\text{In} & \quad \text{Out} \\
\text{Feed} & \quad 10000(0.90)(80 - 176) = -921000 \text{ Btu} \\
\text{Bottoms to} & \quad \text{vanillin plant} \quad 8333(1.0)(106.5 - 176) = -579000 \text{ Btu} \\
\text{Refux} & \quad 5000(0.85)(176 - 176) = 0 \text{ Btu} \\
\text{Vapor} & \quad 6667(0.85)(176 - 176) + 6667(0.75) = 450000 \text{ Btu} \\
\text{Steam} & \quad \Delta H_{\text{H}_2\text{O}} = -921000 \text{ Btu} \\
\Delta H_{\text{H}_2\text{O}} &= -921000 = 3921000 \text{ Btu/hr} \\
\Delta H_{\text{V}} &= 3921000 = 3921000 \text{ Btu/hr} \\
\Delta H_{\text{V}} &= 4842000 \text{ Btu/hr}
31.8

(a) Compute heat of reaction for \( C_7H_{16}(g) \rightarrow C_7H_{16}(g) + 4 H_2(g) \)

\[ \Delta H^\circ_{\text{rxn}} (\text{kJ/mol}) = -224.4 \quad +12.00 \quad 0 \]

mol wt.: 100 92 2.016

\[ \Delta H^\circ_{\text{rxn}} = 12.00 - (-224.4) = 236.4 \text{ kJ/mol heptane} \]

Basis: 100 kg n-C7H16

Material balance:

\[
\begin{array}{ccc}
\text{kg} & \text{kg mol} \\
\hline
\text{In: n-C7H16} & 100 & 1.00 \\
\text{Out: toluene (1.00) (0.15) (92) =} & 13.8 & 0.15 \\
H_2 (1.00) (0.15) (4) (2.02) = & 1.21 & 0.60 \\
n-C7H16 (100) (0.85) = & 85.0 & 0.85 \\
& 100.0 & \\
\end{array}
\]

Energy Balance on reactor: \( \Delta H_{\text{prod}} - \Delta H_{\text{reac}} + \Delta H_{\text{rxn}} = Q \)

\[ \text{kJ} \]

\[ \Delta H_{\text{in: n-C7H16 vapor}} = 100 (1.88) (425 - 98.6) = 61,360 \]

\[ \Delta H_{\text{out: n-C7H16 vapor}} \]

(b) Energy Balance on extractor (ref. 25°C)

\[
\begin{array}{ccc}
\text{kg} \\
\hline
\text{In: n-C7H16} & 85.0 (2.13) (18 - 25) & -1,267 \\
toluene & 13.8 (2.22) (18 - 25) & 215 \\
solvent & 138 (1.67) (38 - 25) & 2,996 \\
\end{array}
\]

(continued)
Solutions Chapter 31

Out: n-C\textsubscript{7}H\textsubscript{16} 85 (2.13) (T - 25)

- toluene 13.8 (2.22) (T - 25) 442.15 (T - 25)
- solvent 138 (1.67) (T - 25)

Heat of Solution: (-23 kJ/kg) (13.8) -317

\[ \Delta H_{\text{prod}} - \Delta H_{\text{heat}} + \Delta H_{\text{soln}} = 0 \]

\[ 442.15 (T - 25) - 1.514 + (-317) = 0 \]

\[ T = 29.14^\circ C \]

(c) Energy Balance on heat exchanger: (ref. 29.14\(^\circ\)C)

(Imagine fresh solvent is negligible in quantity.)

\[ \text{kJ} \]

In:
- toluene 13.8 (2.22) (29.14 - 29.14) 0
- solvent 138 (1.67) (29.14 - 29.14) 0

Out:
- toluene 13.8 (2.22) (T - 29.14) 20,940
- solvent 138 (1.67) (120 - 29.14) 20,940

\[ 20,940 = 2040 + 261 (T - 29.14) \]

\[ T = 102^\circ C \]

Solutions Chapter 31

(d) Energy Balance on still: (ref. 111\(^\circ\)C, i.e., where \(\Delta H_{\text{vap}}\) for toluene is given)

Assume the toluene vapor leaves at 120\(^\circ\)C.

\[ \text{kJ} \]

In:
- Solvent 138 (1.67) (100 - 111) -2,535
- Toluene 13.8 (2.22) (100 - 111) -337

-2,872

Out:
- solvent 138 (1.67) (120 - 111) 2074
- Toluene 13.8 (2.30) (120 - 111) 286

2360

\(\Delta H_{\text{vap}}\) of toluene assuming all entering the still vaporizes:

\[ 13.8 \text{ (364) 5023} \]

\[ Q = \Delta H = \Delta H_{\text{cool}} - \Delta H_{\text{in}} + \Delta H_{\text{vap}} = 2360 - (-2872) + 5023 = 10,260 \text{ kJ/100 kg} \]

= 103 kJ/kg n-heptane

31.9

Base temp. = 70\(^\circ\)F

a. Material Balance:

Benzene: (100,000) (0.50) = 50,000 lb

Toluene: (100,000) (0.40) = 40,000 lb

o-Xylene: (100,000) (0.10) = 10,000 lb

(continued)
Solutions Chapter 31

Tower 1: overhead = 50,000/0.96 = 52,100 lb Bz + toluene

Residue: 47,900 lb

Tower: 2 residue = 10,000/0.99 = 10,000 lb o-xyl + tol.

overhead = 47,900 - 10,100 = 37,800 lb toluene

Calculation of T_1

heat exchanger:

[(175 - 70) (0.45) (52,100) = 2,460,000 Btu above 70°F
(75 - 70) (0.45) (52,100) = 117,000 Btu in exit ΔH from tower 1

heat lost = 2,460,000 - 117,000 = 2,343,000 Btu

temp. rise = 2,343000/(0.46) (100,000) = 50.6°F

T_1 = 70 + 50.6 = 120.6°F

b). Tower 1:

ΔH content of stream: (100,000) (0.46) (185 - 70) = 4,830,000

ΔH of reflux: (6) (2,460,000) = 14,740,000

ΔH in (Btu) = 19,570,000

ΔH of residue: (220 - 70) (0.48) (47,900) = 3,450,000

ΔH of liquid: (175 - 70) (7) (52,100) (0.45) = 17,240,000

ΔH of vaporization: (93.2) (1.8) (7) (52,100) = 61,400,000

ΔH of vapor: (0.285) (179 - 175) (7) (52,100) = 417,000

ΔH out (Btu):

82,507,000

ΔH supplied by reboiler in tower 1:

82,507,000 - 19,570,000 = 62,937,000 Btu

b2. Tower 2

in: charge 3,450,000

Reflex: (6) (37,800) (0.30) (230 - 70) = 10,880,000

ht. in: (Btu) 14,330,000

Water used = 212,000 + 352,000 + 33,200 + 3550

= 600,750 gal/day

d. Heat Balance on Tower 1:

charge: 4,830,000 cond: 61,857,000

steam: 62,937,000 Bz + tol: 2,460,000

residue: 3,450,000

total (Btu): 67,767,000 = 67,767,000

31.10

An important question to consider before attempting to solve the material and energy balances in a process is the feasibility of the flow sheet. The specified variables and data must contain enough information to solve the mass and energy balances written for the components of the flow sheet, and in particular must not overspecify or underspecify the problem as whole or for any component by providing more or fewer know state variables than there are design equations. If the flowsheet contains recycle streams, verification of the necessary data can become quite involved.

(continued)
The feasibility of the flow sheet itself is not determined solely by the given data and the energy and material balances of the system. One must examine the flow sheet to make sure that a solution is technically feasible, i.e., will the flow sheet produce the desired results or has something been overlooked (ignoring the fact that there are always problems in producing the desired results when actually building a process and trying to get it started.) Spotting mistakes is only partly an analytical process; it often requires familiarity with the units that make up the process and the materials that are being processed.

In the problem presented one major mistake is readily identified by examination of the flow sheet. Heat exchanger number three is overspecified. The incoming cold stream A and the exiting hot stream B cannot both be at the same temperature.

Another heat exchanger, using water as a coolant for B, is necessary.

### 31.11

<table>
<thead>
<tr>
<th>from regenerator</th>
<th>700°C</th>
<th>to H.E. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>H.E. 3</td>
<td>38°C</td>
<td>B</td>
</tr>
<tr>
<td>H.E. 3'</td>
<td>38°C</td>
<td></td>
</tr>
</tbody>
</table>

A more critical view of the process must examine what the water vapor in the gas does in the SO₂ adsorption process. SO₂ and water form a sulfuric acid mist that is almost impossible to absorb and is highly corrosive. 97% H₂SO₄ is used as an absorbant in the acid tower precisely because it has an extremely low partial pressure of water vapor. Any acid mist formed would circulate through the process, not be absorbed, and corrode the equipment, eventually escaping with the cleaned stack gases, a more harmful pollutant than SO₂ alone. Thus one should be sure that no water can contact the SO₂.

Barring leaks, the only source of water to the process is the incoming stack gas which undoubtedly contains water vapor from the combustion process:

\[
\text{Basis: } 100 \text{ kg coal kg mol H₂}
\]

\[
(5.2 \text{ kg H}) \left( \frac{\text{kg mol} \ H_2}{2 \text{ kg H}} \right) = 2.6 \text{ kg mol } H_2
\]

2.6 kg mol H₂ is equivalent to

\[
2.6 \text{ kg mol H₂O} \left( \frac{18 \text{ kg}}{1 \text{ kg mol}} \right) = 47 \text{ kg H₂O/100 kg coal}
\]

To check whether or not water vapor will be present in the stack gas, the weight fraction of the water vapor in the combustion gases can be assumed to be equivalent to the weight fraction of water vapor in saturated air at a given temperature, assuming the stack gas approximates air in composition. The total amount of stack gas per 100 kg of coal is:

Basis: 100 kg coal

\[
76.6 \text{ kg C} \left( \frac{\text{kg mol}}{12 \text{ kg}} \right) = 6.4 \text{ kg mol C}
\]

\[
5.2 \text{ kg H} \left( \frac{\text{kg mol} \ H_2}{2 \text{ kg } H_2} \right) = 2.6 \text{ kg mol H₂}
\]

\[
6.2 \text{ kg O} \left( \frac{\text{kg mol} \ O_2}{32 \text{ kg } O_2} \right) = 0.19 \text{ kg mol O₂}
\]

\[
2.3 \text{ kg S} \left( \frac{\text{kg mol}}{32 \text{ kg}} \right) = 0.072 \text{ kg mol S}
\]

N and ash do not burn so that there is 90 kg of combusted material/100 kg coal.

(continued)
Solutions Chapter 31

Air required:

\[
\begin{align*}
C + O_2 & \rightarrow CO_2 \\
H_2 + \frac{1}{2} O_2 & + H_2O \\
S + O_2 & \rightarrow SO_2
\end{align*}
\]

\[
\begin{align*}
6.4 & \text{C} \\
1/2(2.6) & \text{H}_2 \\
0.072 & \text{S}
\end{align*}
\]

\[
8.42
\]

\[
0.19 \text{ mol O}_2 \text{ in coal}
\]

\[
8.23 \text{ mol O}_2 \text{ required from air}
\]

\[
\begin{align*}
8.23 & \text{ kg mol O}_2 \quad \text{1 kg mol air} \quad 29 \text{ kg air} \left(\frac{1.18}{0.21} \text{ kg mol O}_2 \text{ per kg mol air}\right) \\
& = 1340 \text{ kg dry air}
\end{align*}
\]

Total weight of combustion gases = 90 + 1340 = 1430 kg

Weight fraction of water vapor = \[
\frac{47}{1430} = 0.033
\]

Thus, the weight fraction of the water vapor is approximately 0.033, even assuming the air used for combustion is completely dry. Saturated air, even at 60\(^\circ\)C, has a partial water pressure of 49.4 mm Hg. Then the weight fraction of water, assuming ideal gases is

\[
\frac{P_{H_2O}}{P_{air}} = \frac{149.4 \text{ kg mol H}_2O}{(760 - 149.4) \text{ kg mol dry air}} \quad \frac{1 \text{ kg mol dry air}}{29 \text{ kg dry air}}
\]

\[
\begin{align*}
18 \text{ kg H}_2O & = 0.15 \text{ kg H}_2O \\
\text{1 kg mol H}_2O & = \frac{0.15 \text{ kg H}_2O}{\text{1 kg mol H}_2O}
\end{align*}
\]

Looking at the sorbent, the sorbent-air and stack gas streams will mix. Some water vapor will enter the Regenerator. If only 0.1% of the water vapor reaches the Regenerator

\[
\begin{align*}
2.6 & \text{ kg mol H}_2O \quad 18 \text{ kg H}_2O \\
100 & \text{ kg coal} \quad 1000 & \text{ kg mol H}_2O \quad 4.7 \times 10^{-2} \text{ kg}
\end{align*}
\]

4.7 \times 10^{-2} \text{ kg H}_2O \quad 2000 \text{ kg} \quad 340 \text{ metric ton coal}

\[
\begin{align*}
100 & \text{ kg coal} \quad 1 \text{ metric ton coal} \\
& = 320 \text{ kg H}_2O/hr
\end{align*}
\]

H\(_2\)O + SO\(_3\) \rightarrow H\(_2\)SO\(_4\), so that the equivalent sulfuric acid is

\[
\begin{align*}
320 & \text{ kg H}_2O \\
1 & \text{ kg mol H}_2SO_4 \\
98 & \text{ kg H}_2SO_4 \\
18 & \text{ kg per kg mol H}_2O \quad 1 \text{ kg mol H}_2O \quad 1 \text{ kg mol H}_2SO_4 = 1740\text{ kg H}_2SO_4 \\
\text{hr}
\end{align*}
\]

Thus, the flow sheet is not feasible unless the water vapor can be eliminated from entering the absorber.

31.12

a. (NH\(_4\))\(_2\)SO\(_4\) = (22)(500) = 11,000

Benzol = (15)(500) = 7,500

Toluol = (5)(500) = 2,500

Pyridine = (3)(500) = 1,500

Phenol = (5)(500) = 2,500

Naphthalene = (7)(500) = 3,500

Cresols = (20)(500) = 10,000

Pitch = (40)(500) = 20,000

Coke = (1500)(500) = 750,000

Gas = 5,000,000 cu ft = 199,670

\[
\frac{34}{132} \times 11,000 = 2830 \text{ lb NH}_3 \text{ removed as (NH}_4)_2\text{SO}_4
\]

\[
\text{NH}_3 = \frac{36}{132} \times 22 \times 500 = 3000 \text{ lb}
\]

b. Basis: 80\(^\circ\)C = 178\(^\circ\)F

(continued)
### Solutions Chapter 31

#### Primary tower

<table>
<thead>
<tr>
<th>Compound</th>
<th>Heat in</th>
<th>$\times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>20,000(0.65)(5.25)</td>
<td>6.83</td>
</tr>
<tr>
<td>Cresols</td>
<td>10,000(0.55)(219)+181+(0.5)(306)</td>
<td>4.54</td>
</tr>
<tr>
<td>Toluene</td>
<td>2,500(0.83)(54)+155.9+(0.35)(471)</td>
<td>0.87</td>
</tr>
<tr>
<td>Benzene</td>
<td>7,500(0.30)(525)</td>
<td>1.18</td>
</tr>
<tr>
<td>Phenol</td>
<td>2,500(0.56)(183)+162+(0.45)(342)</td>
<td>1.05</td>
</tr>
<tr>
<td>Pyridine</td>
<td>1,500(0.41)(61.2)+193.5+(0.28)(463.8)</td>
<td>0.52</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>3,500(0.282)(0.4)+64.05+(0.40)(247.7) + 136+(0.35)(277)</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.38 Btu</td>
</tr>
</tbody>
</table>

#### Heat Out

<table>
<thead>
<tr>
<th>Compound</th>
<th>Heat in</th>
<th>$\times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>20,000(0.65)(475)</td>
<td>6.18</td>
</tr>
<tr>
<td>Cresols</td>
<td>10,000(0.55)(219)+181+(0.5)(104.2)</td>
<td>3.54</td>
</tr>
<tr>
<td>Toluene</td>
<td>2,500(0.53)(54)+155.9+(0.35)(70.1)</td>
<td>0.52</td>
</tr>
<tr>
<td>Benzene</td>
<td>7,500(0.30)(124.1)</td>
<td>0.28</td>
</tr>
<tr>
<td>Phenol</td>
<td>2,500(0.56)(183.6)+162+(0.45)(41.4)</td>
<td>0.71</td>
</tr>
<tr>
<td>Pyridine</td>
<td>1,500(0.41)(61.1)+193.2+(0.28)(163.9)</td>
<td>0.40</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>3,500(0.282)(0.36)+64.05+(0.40)(225)</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Total $16.38-12.17 \times 10^6 = 4.21 \times 10^6$ Btu lost in primary tower.

#### Secondary tower

<table>
<thead>
<tr>
<th>Compound</th>
<th>Heat out</th>
<th>$\times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Toluene</td>
<td>2,500(0.53)(54)+155.9+(0.35)(21.6)</td>
<td>0.48</td>
</tr>
</tbody>
</table>

### Solutions Chapter 31

#### Bevzene

- $0.28$

- Loss $= (0.80-0.48) \times 10^{-6}$
- $0.80 \text{ Btu} = 0.32 \times 10^{-6} \text{ Btu}$

#### Toluene

- $0.52$
- Loss $= (0.80-0.48) \times 10^{-6}$
- $0.80 \text{ Btu} = 0.32 \times 10^{-6} \text{ Btu}$

#### c. 2500 lb Phenol

- $2500 = 26.6 \text{ lb mol}$
- $94$
- $26.6 \text{ lb mol NaOH (100% solution)}$
- $26.6 \times 40 \frac{H}{H} = 2660 \text{ lb 40% NaOH required}$

#### d. $\text{C}_3\text{H}_5\text{N} (\text{MW} = 79)$

- $(1500)(98) = 3720 \text{ lb 50% H}_2\text{SO}_4$
- $(79)(5)$

#### c. Pyridine: $\text{H}_2\text{SO}_4 + 2 \text{ NaOH} + \text{Na}_2\text{SO}_4 + 2\text{ H}_2\text{O} + \text{Pyridine}$

- $(1860) \frac{98}{(142)} = 2700 \text{ lb Na}_2\text{SO}_4$
- Phenol $= (13.3)(142) = 1890 \text{ lb}$
- Total $\text{Na}_2\text{SO}_4 = 4590 \text{ lb}$

### f. $10,000 \times (500) = 5,000,000 \text{ cu ft}$

- $(500)(2000)(300) = 300,000,000 \text{ Btu}$
- $\frac{300,000,000}{555} = 540,000 \text{ cu ft}$

(continued)
### 31.13

**COM1 (GCOMP)**  
**INLET = FEED**  
**OUTLET =**

- **S001**  
  - **OUTLET PRESSURE, PSIA = 100.00**  
  - **OUTLET TEMP, DEG F = 282.22**  
  - **ISENTROPIC TEMP, DEG F = 324.40**  
  - **ISENTROPIC HORSEPOWER = 276.2**  
  - **INDICATED HORSEPOWER = 223.6**  
  - **BRAKE HORSEPOWER = 279.5**  
  - **DISPLACEMENT, CFH = 98957.1**  
  - **VOLUMETRIC EFFICIENCY = .8912**

**HEAT = HEATR**  
**-INLET = S001**,  
**OUTLET = S002**

- **OUTLET TEMP = 100.00 DEG F**,  
- **PRESSURE DROP = 2.00 PSI**  
- **DUTY = -.5683E+06 BTU/HR**

**COM2 (GCOMP)**  
**INLET = S002**  
**OUTLET = OUT**

- **OUTLET PRESSURE, PSIA = 569.00**  
- **OUTLET TEMP, DEG F = 382.02**  
- **ISENTROPIC TEMP, DEG F = 453.14**  
- **ISENTROPIC HORSEPOWER = 441.0**  
- **INDICATED HORSEPOWER = 351.3**  
- **BRAKE HORSEPOWER = 439.1**  
- **DISPLACEMENT, CFH = 33777.4**  
- **VOLUMETRIC EFFICIENCY = .8013**

### 31.14

#### 50% Recycle

<table>
<thead>
<tr>
<th>STREAM NAME:</th>
<th>FEED</th>
<th>OUT</th>
<th>S001</th>
<th>S002</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LBMOl/Hr</td>
<td>LBMOl/Hr</td>
<td>LBMOl/Hr</td>
<td>LBMOl/Hr</td>
</tr>
<tr>
<td>1 METHANE</td>
<td>.03163</td>
<td>3.11682</td>
<td>3.10100</td>
<td>.01582</td>
</tr>
<tr>
<td>2 ETHANE</td>
<td>2.1331</td>
<td>3.32579</td>
<td>3.21911</td>
<td>.10666</td>
</tr>
<tr>
<td>3 PROPANE</td>
<td>3.51170</td>
<td>15.8752</td>
<td>14.1188</td>
<td>1.75585</td>
</tr>
<tr>
<td>4 N-BUTANE</td>
<td>10.8815</td>
<td>15.0000</td>
<td>9.55772</td>
<td>5.44074</td>
</tr>
<tr>
<td>6 1,3-BUTADINE</td>
<td>63.4611</td>
<td>95.0000</td>
<td>63.2610</td>
<td>31.7305</td>
</tr>
<tr>
<td>TOTAL LB/MOL</td>
<td>91.2500</td>
<td>153.318</td>
<td>107.681</td>
<td>45.6250</td>
</tr>
<tr>
<td>TOTAL LB/HR</td>
<td>4964.56</td>
<td>8038.45</td>
<td>5555.51</td>
<td>2482.28</td>
</tr>
<tr>
<td>1000 BTU/HR</td>
<td>-794.83</td>
<td>509.26</td>
<td>64.43</td>
<td>-397.42</td>
</tr>
<tr>
<td>DEGREES F</td>
<td>41.00</td>
<td>185.00</td>
<td>41.00</td>
<td>41.00</td>
</tr>
<tr>
<td>PSA</td>
<td>25.00</td>
<td>100.00</td>
<td>25.00</td>
<td>100.00</td>
</tr>
<tr>
<td>DENSITY, LB/FT3</td>
<td>38.9928</td>
<td>.8313</td>
<td>.2504</td>
<td>.0000</td>
</tr>
<tr>
<td>MOLE FRACT VAPOR</td>
<td>0.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

**STREAM NAME: S001**

- **LBMOl/Hr**
- **LBMOl/Hr**

- **1 METHANE**
- **3.13263**
- **.01582**

- **2 ETHANE**
- **3.43242**
- **.10666**

- **3 PROPANE**
- **17.6305**
- **1.75585**

- **4 N-BUTANE**
- **20.4392**
- **5.44074**

- **5 ISO-BUTENE**
- **27.5738**
- **6.37538**

- **6 1,3-BUTADINE**
- **26.722**
- **31.7305**

- **TOTAL LB/MOL**
- **98.931**
- **45.6250**

- **TOTAL LB/HR**
- **10520.1**
- **2482.28**

- **1000 BTU/HR**
- **111.95**
- **-397.42**

- **DEGREES F**
- **126.20**
- **41.00**

- **PSIA**
- **100.00**
- **100.00**

- **DENSITY, LB/FT3**
- **38.9928**
- **38.9928**

- **MOLE FRACT VAPOR**
- **.8232**
- **.0000**

25% Recycle

(continued)
### Solutions Chapter 31

<table>
<thead>
<tr>
<th>STREAM NAME:</th>
<th>BOTM LBMOL/HR</th>
<th>FEED LBMOL/HR</th>
<th>OXID LBMOL/HR</th>
<th>PROD LBMOL/HR</th>
<th>RECY LBMOL/HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 METHANE</td>
<td>0.2109</td>
<td>3.16182</td>
<td>3.10100</td>
<td>0.1582</td>
<td>0.0952</td>
</tr>
<tr>
<td>2 ETHANE</td>
<td>1.4225</td>
<td>3.32579</td>
<td>3.21911</td>
<td>0.1068</td>
<td>0.0356</td>
</tr>
<tr>
<td>3 PROPAINE</td>
<td>2.34175</td>
<td>15.8752</td>
<td>14.1189</td>
<td>1.75631</td>
<td>0.5543</td>
</tr>
<tr>
<td>4 N-BUTANE</td>
<td>4.20569</td>
<td>15.0000</td>
<td>9.55700</td>
<td>5.44219</td>
<td>1.81406</td>
</tr>
<tr>
<td>5 ISO-BUTANE</td>
<td>8.70940</td>
<td>21.0000</td>
<td>14.4229</td>
<td>6.57705</td>
<td>2.19235</td>
</tr>
<tr>
<td>6 1,3-BUTADIENE</td>
<td>42.3184</td>
<td>95.0000</td>
<td>62.3251</td>
<td>31.7383</td>
<td>10.5796</td>
</tr>
<tr>
<td>TOTAL LBMOL/HR</td>
<td>60.8492</td>
<td>153.318</td>
<td>107.681</td>
<td>45.6369</td>
<td>15.2123</td>
</tr>
<tr>
<td>TOTAL LBM/HR</td>
<td>3310.57</td>
<td>8038.43</td>
<td>5555.92</td>
<td>2482.93</td>
<td>827.642</td>
</tr>
<tr>
<td>DEGREES F</td>
<td>-530.03</td>
<td>509.26</td>
<td>64.43</td>
<td>-397.52</td>
<td>-12.51</td>
</tr>
<tr>
<td>PSIA</td>
<td>41.00</td>
<td>185.00</td>
<td>41.00</td>
<td>41.00</td>
<td>41.00</td>
</tr>
<tr>
<td>DENSITY, LB/FT3</td>
<td>38.9928</td>
<td>83.13</td>
<td>2504.00</td>
<td>38.9928</td>
<td>38.9928</td>
</tr>
<tr>
<td>MOLE FRACTION VAPOR</td>
<td>0.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

### Solutions Chapter 31

<table>
<thead>
<tr>
<th>STREAM NAME:</th>
<th>BOTM LBMOL/HR</th>
<th>FEED LBMOL/HR</th>
<th>OXID LBMOL/HR</th>
<th>PROD LBMOL/HR</th>
<th>RECY LBMOL/HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 METHANE</td>
<td>0.01582</td>
<td>3.11682</td>
<td>3.10100</td>
<td>0.1382</td>
<td>0.0952</td>
</tr>
<tr>
<td>2 ETHANE</td>
<td>1.0668</td>
<td>3.32579</td>
<td>3.21911</td>
<td>0.1068</td>
<td>0.0356</td>
</tr>
<tr>
<td>3 PROPAINE</td>
<td>1.75631</td>
<td>15.8752</td>
<td>14.1189</td>
<td>1.75631</td>
<td>0.5543</td>
</tr>
<tr>
<td>4 N-BUTANE</td>
<td>5.44219</td>
<td>15.0000</td>
<td>9.55700</td>
<td>5.44219</td>
<td>1.81406</td>
</tr>
<tr>
<td>6 1,3-BUTADIENE</td>
<td>31.7568</td>
<td>95.0000</td>
<td>62.3251</td>
<td>31.7383</td>
<td>10.5796</td>
</tr>
<tr>
<td>TOTAL LBMOL/HR</td>
<td>45.6369</td>
<td>153.318</td>
<td>107.681</td>
<td>45.6369</td>
<td>15.2123</td>
</tr>
<tr>
<td>TOTAL LBM/HR</td>
<td>2482.93</td>
<td>8038.43</td>
<td>5555.92</td>
<td>2482.93</td>
<td>827.642</td>
</tr>
<tr>
<td>DEGREES F</td>
<td>-397.52</td>
<td>509.26</td>
<td>64.43</td>
<td>-397.52</td>
<td>-12.51</td>
</tr>
<tr>
<td>PSIA</td>
<td>41.00</td>
<td>185.00</td>
<td>41.00</td>
<td>41.00</td>
<td>41.00</td>
</tr>
<tr>
<td>DENSITY, LB/FT3</td>
<td>38.9928</td>
<td>83.13</td>
<td>2504.00</td>
<td>38.9928</td>
<td>38.9928</td>
</tr>
<tr>
<td>MOLE FRACTION VAPOR</td>
<td>0.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

### 31.14

#### STREAM COMPONENT FLOW RATES - KG MOL/S

<table>
<thead>
<tr>
<th>STREAM ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAME</td>
<td>INLET GAS</td>
<td>H2</td>
<td>N2</td>
<td>O2</td>
<td>AR</td>
<td>MIXED</td>
</tr>
<tr>
<td>1 NITROGEN</td>
<td>100.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>2 O2</td>
<td>100.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>3 METHANE</td>
<td>100.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>4 ETHANE</td>
<td>100.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>5 PROPAINE</td>
<td>100.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>6 1,3-BUTADIENE</td>
<td>100.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>7 TOTALS</td>
<td>900.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>WARNING</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

### STREAM ID

<table>
<thead>
<tr>
<th>PHASE</th>
<th>VAPOR</th>
<th>LIQUID</th>
<th>MIXED</th>
<th>VAPOR</th>
<th>LIQUID</th>
<th>VAPOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NITROGEN</td>
<td>183.5368</td>
<td>0.1279</td>
<td>179.5692</td>
<td>1.1203</td>
<td>1.3401</td>
<td></td>
</tr>
<tr>
<td>2 O2</td>
<td>198.4200</td>
<td>0.2811</td>
<td>196.3282</td>
<td>3.1980</td>
<td>3.2880</td>
<td></td>
</tr>
<tr>
<td>3 METHANE</td>
<td>242.2647</td>
<td>0.3759</td>
<td>242.2647</td>
<td>5.3642</td>
<td>5.3642</td>
<td></td>
</tr>
<tr>
<td>4 ETHANE</td>
<td>272.9193</td>
<td>0.5468</td>
<td>272.9193</td>
<td>9.0494</td>
<td>9.0494</td>
<td></td>
</tr>
<tr>
<td>5 PROPAINE</td>
<td>353.3134</td>
<td>0.8202</td>
<td>353.3134</td>
<td>16.5905</td>
<td>16.5905</td>
<td></td>
</tr>
<tr>
<td>6 1,3-BUTADIENE</td>
<td>428.6208</td>
<td>0.8202</td>
<td>428.6208</td>
<td>16.5905</td>
<td>16.5905</td>
<td></td>
</tr>
<tr>
<td>7 BUTANE</td>
<td>937.5274</td>
<td>8.5099</td>
<td>937.5274</td>
<td>41.4053</td>
<td>41.4053</td>
<td></td>
</tr>
<tr>
<td>8 ETHANE</td>
<td>1071.8543</td>
<td>8.5099</td>
<td>1071.8543</td>
<td>41.4053</td>
<td>41.4053</td>
<td></td>
</tr>
<tr>
<td>9 PROPAINE</td>
<td>332.4200</td>
<td>0.8202</td>
<td>332.4200</td>
<td>8.5099</td>
<td>8.5099</td>
<td></td>
</tr>
<tr>
<td>10 1,3-BUTADIENE</td>
<td>332.4200</td>
<td>0.8202</td>
<td>332.4200</td>
<td>8.5099</td>
<td>8.5099</td>
<td></td>
</tr>
<tr>
<td>11 TOTALS</td>
<td>458.0756</td>
<td>12.2675</td>
<td>458.0756</td>
<td>52.3775</td>
<td>52.3775</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
### Solutions Chapter 31

#### Temperature, Dec 21

<table>
<thead>
<tr>
<th>Temperature, DEC</th>
<th>-17.4 &amp; 39.2</th>
<th>-17.4 &amp; 39.2</th>
<th>-14.0 &amp; 38.0</th>
<th>-14.0 &amp; 38.0</th>
<th>-14.0 &amp; 38.0</th>
<th>-14.0 &amp; 38.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure, psig</td>
<td>125.000</td>
<td>125.000</td>
<td>125.000</td>
<td>125.000</td>
<td>125.000</td>
<td>125.000</td>
</tr>
<tr>
<td>NMM Btu/lb</td>
<td>3,877</td>
<td>-3,794</td>
<td>-4,629</td>
<td>-1,500</td>
<td>2,395</td>
<td>-3,239</td>
</tr>
<tr>
<td>Fuel Liquid</td>
<td>0.267</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Recycle Converges</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**SUMMARY OF HEAT EXCHANGE UNITS**

5 UNIT E1, GAS-GAS EX, IS A HEAT EXchanger

**OPERATING CONDITIONS**

- DUTY, MM KJ/HR: 5574.17
- WEIGHTED LMTD, DEG K: 1000.00
- FACTOR: 30.008
- MTD, DEG K: 30.008
- U * A, KJ/HR, DEG K: 18265.594

**HOT SIDE CONDITIONS**

<table>
<thead>
<tr>
<th>FEED(S)</th>
<th>MIXED PRODUCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAPOR, KG MOLS/HR</td>
<td>1215.1807</td>
</tr>
<tr>
<td>M KSg/hr</td>
<td>27.3531</td>
</tr>
<tr>
<td>CP, KJ/KG – DEG K</td>
<td>2.2837</td>
</tr>
<tr>
<td>LIQUID, KG MOLS/HR</td>
<td>0.0000</td>
</tr>
<tr>
<td>M KSg/hr</td>
<td>137.8730</td>
</tr>
<tr>
<td>CP, KJ/KG – DEG K</td>
<td>6.1539</td>
</tr>
<tr>
<td>TOTAL, KG MOLS/HR</td>
<td>1215.1807</td>
</tr>
<tr>
<td>CONDENS VAPORIZATION, KG MOLS/HR</td>
<td>1215.1807</td>
</tr>
<tr>
<td>TEMPERATURE, DEG K</td>
<td>322.039</td>
</tr>
<tr>
<td>PRESSURE, KPA</td>
<td>4155.435</td>
</tr>
<tr>
<td>COLD SIDE CONDITIONS</td>
<td></td>
</tr>
<tr>
<td>FEED(S)</td>
<td>MIXED PRODUCT</td>
</tr>
<tr>
<td>VAPOR, KG MOLS/HR</td>
<td>995.9433</td>
</tr>
<tr>
<td>M KSg/hr</td>
<td>17.3280</td>
</tr>
<tr>
<td>CP, KJ/KG – DEG K</td>
<td>2.1518</td>
</tr>
<tr>
<td>LIQUID, KG MOLS/HR</td>
<td>0.0000</td>
</tr>
<tr>
<td>M KSg/hr</td>
<td>2.1288</td>
</tr>
<tr>
<td>(continued)</td>
<td></td>
</tr>
</tbody>
</table>

### 31.15

**STEAM ID**

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NAME</strong></td>
<td>VAPOR</td>
<td>LIQUID</td>
<td>VAPOR</td>
<td>LIQUID</td>
<td>VAPOR</td>
</tr>
<tr>
<td><strong>FRACTION MIXED</strong></td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>THERM</strong></td>
<td>190.0745</td>
<td>211.9109</td>
<td>0.0000</td>
<td>211.9109</td>
<td>211.9109</td>
</tr>
<tr>
<td><strong>ETHANE</strong></td>
<td>150.3057</td>
<td>191.8709</td>
<td>0.0000</td>
<td>191.8709</td>
<td>191.8709</td>
</tr>
<tr>
<td><strong>PROPANE</strong></td>
<td>31.7935</td>
<td>40.2482</td>
<td>0.0000</td>
<td>40.2482</td>
<td>40.2482</td>
</tr>
<tr>
<td><strong>BUTANE</strong></td>
<td>10.0424</td>
<td>13.9756</td>
<td>0.0000</td>
<td>13.9756</td>
<td>13.9756</td>
</tr>
<tr>
<td><strong>PENTANE</strong></td>
<td>0.0560</td>
<td>0.0725</td>
<td>0.0000</td>
<td>0.0725</td>
<td>0.0725</td>
</tr>
<tr>
<td><strong>HEXANE</strong></td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>316.8726</td>
<td>215.6202</td>
<td>0.0000</td>
<td>215.6202</td>
<td>215.6202</td>
</tr>
</tbody>
</table>
### Solutions Chapter 31

<table>
<thead>
<tr>
<th>CP, KJ/KG – DEG K</th>
<th>0.0000</th>
<th>0.0000</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL, KG MOLS/HR</td>
<td>995.9431</td>
<td>995.9431</td>
</tr>
<tr>
<td>CONDENS(VAPORIZATION), KG MOLS/HR</td>
<td>0.0000</td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE, DEG K</td>
<td>160.797</td>
<td>316.483</td>
</tr>
<tr>
<td>PRESSURE, KPA</td>
<td>963.168</td>
<td>928.694</td>
</tr>
</tbody>
</table>

### HEAT EXCHANGER ZONE ANALYSIS

<table>
<thead>
<tr>
<th>DUTY ZONE</th>
<th>DEG K AT COLD INLET</th>
<th>DEG K AT COLD OUTLET</th>
<th>LMTD</th>
<th>DUTY</th>
<th>TOTAL MM KJ/HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98.72</td>
<td>80.44</td>
<td>89.27</td>
<td>1.073</td>
<td>19.26</td>
</tr>
<tr>
<td>2</td>
<td>80.44</td>
<td>61.43</td>
<td>70.51</td>
<td>1.073</td>
<td>19.26</td>
</tr>
<tr>
<td>3</td>
<td>61.43</td>
<td>42.58</td>
<td>51.43</td>
<td>1.073</td>
<td>19.26</td>
</tr>
<tr>
<td>4</td>
<td>42.58</td>
<td>24.59</td>
<td>32.77</td>
<td>1.073</td>
<td>19.26</td>
</tr>
<tr>
<td>5</td>
<td>24.59</td>
<td>7.86</td>
<td>14.67</td>
<td>1.073</td>
<td>19.26</td>
</tr>
<tr>
<td>6</td>
<td>7.86</td>
<td>5.56</td>
<td>6.64</td>
<td>0.208</td>
<td>3.72</td>
</tr>
</tbody>
</table>
32.1

\[
\frac{10 \text{ kg soln}}{\text{min}} \rightarrow 15 \text{ kg soln/min}
\]

The amount of solution decreases at a rate of \(15-10 = 5 \text{ kg/min}\). By an overall balance, the amount of solution after \(t\) min is

\[(100-5t) \text{ kg}\]

Let \(x = \text{ kg of salt per kg of solution in the tank at time } t\) min

\[x(0) = 0.60\]

Then \(\frac{dx}{dt} = \text{ rate of change of the concentration in the tank. Salt balance at any time } t\):

\[
\text{Accumulation} = \text{In} - \text{Out}
\]

\[
(100-5t) \frac{dx}{dt} = (10)(0.1) - 15x
\]

Separating variables

\[
\frac{dx}{1-15x} = \frac{dt}{100-5t}
\]

Integrating from 0 to 10 min

\[
\ln \left(\frac{1-15x}{1-9}\right) = 3 \ln \left(\frac{100-50}{100}\right)
\]

Solving: \(x = \frac{2}{15}\)

32.2

\[
\text{kg of solution after 10 min } = 100 - 50 = 50 \text{ kg}
\]

\[
\text{kg of salt in the tank } = \frac{2}{15}(50) = 6.67 \text{ kg}
\]

Assume:

1. Ideal gas law applies
2. Rate of inflow = rate of outflow

Propane balance: Accumulation = Input − Output

\[
\left[ \frac{x \text{ ft}^3 \text{ propane}}{\text{ ft}^3 \text{ mixture}} \bigg|_{t=0}^{\text{dt}} - \frac{x \text{ ft}^3 \text{ propane}}{\text{ ft}^3 \text{ mixture}} \bigg|_{t=\text{dt}} \right] (500 \text{ ft}^3)
\]

\[
\ln \left( \frac{0 \text{ ft}^3 \text{ propane}}{\text{ ft}^3 \text{ mixture}} \bigg|_0^{\Delta t \text{ min}} \right)
\]

Out

\[
\frac{x \text{ ft}^3 \text{ propane}}{\text{ ft}^3 \text{ mixture}} \bigg|_{t=\text{dt}}^{\Delta t \text{ min}}
\]

\[
1500 \int_{0}^{0.01} \frac{dx}{x} = -30 \int_{0}^{1} dt \rightarrow 1500 \ln x_{1}^{0.01} = -30 t_{1}
\]

\[
t = 230.5 \text{ min}
\]
32.3

\[
\text{2 gal/min} \quad \frac{\text{0 UO}_2}{\text{100 gal H}_2\text{O}} \quad \text{2 gal/min}
\]

\[
\text{2 lb UO}_2/\text{100 lb H}_2\text{O}
\]

Ignore volume changes as the slurry concentration changes, and assume UO\textsubscript{2} in the H\textsubscript{2}O does not change the density of the solution from that of water. The independent variable is \( t \) = time; dependent variable is \( x \) = lb UO\textsubscript{2} in tank/lb H\textsubscript{2}O in tank.

At \( t = 0 \), \( x = 0 \)

Material Balance on UO\textsubscript{2} in \( \Delta t \):

\[
\text{In} \quad \frac{2 \text{ gal}[8.33 \text{ lb H}_2\text{O}]}{\text{min}} \cdot \frac{2 \text{ lb UO}_2}{\text{100 lb H}_2\text{O}} \cdot \Delta t \text{ min} = \frac{2 \text{ gal}[8.33 \text{ lb H}_2\text{O}]}{\text{min}} \cdot \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \cdot \Delta t \text{ min}.
\]

\[
\text{Out} \quad \frac{2 \text{ gal}[8.33 \text{ lb H}_2\text{O}]}{\text{min}} \cdot \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \cdot \Delta t \text{ min} = \]

\[
\text{Accumulation} \quad \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \left[ \frac{500 \text{ lb H}_2\text{O}}{\text{lb UO}_2} \right]_{t}^{t+\Delta t} = \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \left[ \frac{500 \text{ lb H}_2\text{O}}{\text{lb UO}_2} \right]_{t}^{t}.
\]

\[
\frac{(2)(8.33)}{(500)} \int_{0}^{t} \frac{dy}{0.02 - y} = -1\ln[(0.02) - x] = x = 0.0173 \text{ lb UO}_2/\text{lb H}_2\text{O}.
\]

32.4

Assume:

1. Ideal gas law applies
2. Rate of inflow = rate of outflow

O\textsubscript{2} balance: Accumulation = Input - Output

\[
\left[ \frac{x \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \right]_{t+\Delta t} - \left[ \frac{x \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \right]_{t} = \left[ \frac{94 \text{ m}^3 \text{ free vol}}{100 \text{ m}^3 \text{ reactor vol}} \right] \left[ \frac{20 \text{ m}^3}{\text{min}} \right]
\]

\[
= \left[ \frac{0 \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \right]_{\text{min}} - \left[ \frac{x \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \right]_{\text{min}} \left[ \frac{20 \text{ m}^3}{\text{min}} \right] \text{ min}
\]

\[
188 \int_{0}^{0.001} \frac{dx}{0.210} = -20 \int_{0}^{t} dt \quad \text{ln} \quad 188 \text{ ln} 0.001 = -20 \text{ t}
\]

\( t = 50.3 \text{ min} \)

32.5

\( V_1 = \) initial volume

\( = (4/3) (\pi)^3 = (4/3) (3.14)(10)^3 = 4190 \text{ (ft)}^3 \)

\( V_2 = \) final volume

\( = (4/3) (\pi)(9.5)^3 = 3590 \text{ (ft)}^3 \)

(a) At constant pressure: (continued)
Solutions Chapter 32

\[
\frac{dV}{dt} = 5; \quad \int_{V_1}^{V} dV = 5 \int_0^t dt; \quad 5t = 4190 - 3590 \\
\therefore t = 120 \text{ min}
\]

(b) Assuming the rate of escaping is proportional to the volume and initially

\[
\frac{dV}{dt} = KV; \quad 5 = KV_1 = 4190 \quad \text{K or } K = \frac{5}{4190}
\]

\[
\frac{V_1}{V} \int_{V_1}^{V} \frac{dV}{V} = 5 \int_0^t dt \\
1 = \frac{4190}{5} \ln \left( \frac{V^2}{V_1} \right) = 858 \ln \frac{4190}{3590} = \left[ 31 \text{ min} \right]
\]

(c) Not without another piece of information as the mass balance contains two
unknowns, such as \( p \) and \( V \).

32.6

Let the moisture content be \( w \)

then, \( \frac{dw}{dt} = kw \)

\[
\int_{w_0}^{w_f} dw = k \int_0^t dt \\
\int_{w_0}^{w_f} w = k \int_0^t dt
\]

\[
\ln \frac{w}{w_0} = kt
\]

At \( t = 15 \), \( w = w_0/2 \); \( k = \frac{\ln \left( \frac{w}{w_0} \right)}{15} = -0.463 \)

\[
\ln \left( \frac{w}{w_0} \right) = -0.0463t
\]

When \( w = 0.1 w_0 \), \( t = \frac{\ln \left( \frac{0.1 w_0}{w_0} \right)}{-0.0463} = 49.7 \text{ min} \)

32.7

a. Ignore friction, non-ideality at the discharge and the orifice coefficient and use instead

0.020 \( (2 + h^2) \) \text{ m}^3/\text{min}

Vol cone = \( \frac{1}{3} \pi r^2 h \)

\[
\frac{r}{h} = \frac{3}{5}; \quad r = \frac{3}{5} h \quad \therefore \quad V = \frac{9}{75} \pi h^3
\]

\[
\frac{dV}{dt} = \frac{9}{25} \pi h^2 \frac{dh}{dt} = 1.13 \frac{h^2}{\text{min}} \frac{dh}{dt} \left( \text{m} \right)^3
\]

\[
= 0.020 (2 + h^2)
\]

(continued)
\[
\frac{66.6}{2 + h^2} \frac{dh}{dt} = -t
\]

\[
h_1 = 5 \text{ m} \quad h_2 = (3 \sqrt{0.25}) \quad h_1 = 3.15 \text{ m}^3
\]

\[
h_1 = 5m \quad h_2 = (3 \sqrt{0.25}) \quad h_1 = 3.15 \text{ m}^3
\]

\[
-56.6 (3.15 - 5) + 79.9 (\tan^{-1} 4.45 - \tan^{-1} 7.07)
\]

\[
t = 98 \text{ min}
\]

b. The rate of discharge at that time is:

\[
\frac{dV}{dt} = 0.02 (2 + h^2)
\]

\[
= 0.02 (2 + (3.15)^2) = 0.24 \text{ m}^3/\text{min}
\]

32.8

Initially

20,000 gph
0 lb organic

75,000 gal
60,000 lb organic

35,000 gph x lb organic
gal total

(1) Overall Balance:

Let \( y = \) total gal of mixture in the tank at time \( t \) (in hours)

then

\[
\frac{dy}{dt} = 20,000 - 15,000 = 5000
\]

\[
\frac{dy}{dt} = 5000 \frac{dt}{75,000}
\]

\( y = 5000 (15 + t) \)

(2) Organic Material Balance:

Let \( x = \frac{\text{lb organic}}{\text{gal of mix}} \) in the tank at time \( t \).

Initially, \( x = \frac{60,000}{75,000} = 0.8 \)

Total amount of organic in the tank at time \( t \) is \( xy \) lbs.

Then the rate of accumulation of organic will be \( \frac{d(xy)}{dt}, \text{lb/hr.} \)

Rate Accumulation = Rate in – Rate out

\[
\frac{d(xy)}{dt} = 0 - 15,000 x
\]

\[
y \frac{dx}{dt} + x \frac{dy}{dt} = -15,000
\]

\[
\frac{dx}{dt} = \frac{-20,000x}{5000(15 + t)}
\]

\[
\frac{dx}{x} = \frac{1}{15 + t} \frac{dt}{0.8}
\]

\[
\ln x = 4 \ln \frac{15}{18}
\]

\[
x = 0.396
\]

The total wt of organic material in the tank after 3 hrs is:

\[
yx = (75,000 + (5000) (3)) (0.396) = 34,700 \text{ lbs}
\]

(continued)
Alternative Solution:

If \( x = \text{total lb of organic in the tank at any time } t \), then the concentration of organic is \( x/y \).

The balance becomes:

\[
\frac{dx}{dt} = -\frac{15,000 \text{ gal} \times x}{\text{lb y gal}}
\]

\[
\int_{60,000}^{x} \frac{dx}{x} = -\frac{1}{\int_{60,000}^{5000} \text{ (15 + t)}}
\]

\[
\ln \frac{x}{60,000} = 3 \ln \frac{18}{15}
\]

\[
X = 34,700 \text{ lb organic}
\]

32.9

20,000 gph

\[\text{Suspension Rate } = K(10-x) \text{ lb/hr}\]

(1) Overall Balance: Assuming the sludge does not affect the volume of the mixture in the tank, the overall balance will be the same as that in Prob. 7.8, i.e. \( y = 5000 \text{ (15t)} \text{ gal.} \)

(2) Organic Balance:

Let \( x = \text{lb of organic in suspension per gal of total in the tank at time } t \) in hours. 
\( z = \text{lb of sludge going into suspension at time } t \).

Rate of sludge going into suspension:

\[
\frac{dx}{dt} = K(10-x)
\]

\[
@ x = 0 \quad y = 75,000 \text{ gal}
\]

\[
\frac{dx}{dt} = \frac{0.05 \text{ lb}}{(\text{min x gal})} \frac{75,000 \text{ gal}}{60 \text{ min}} = K(10) \text{ lb/gal}
\]

Thus \( K = \frac{(0.05)(75,000)(60)}{10} = 22,500 \text{ gal/hr} \)

Rate of accumulation of organic:

\[
\frac{d(xy)}{dt} = (22,500)(10-x) - 15,000x
\]

\[
= y \frac{dx}{dt} + x \frac{dy}{dt}
\]

\[
\frac{dx}{dt} = \frac{45 - 8.5x}{15 + t}
\]

\[
\int_{5.3-x}^{5.3} \frac{dx}{15 + t} = -\ln \frac{5.3-x}{5.3 - 0.8} = 8.5 \ln \frac{18}{15}
\]

Solving, \( x = 4.345 \text{ lb/gal} \)

The total weight of organic in the tank after 3 hrs is \( (90,000)(4.345) = 391,030 \text{ lbs} \)

Alternative Solution: (continued)
Let \( x = \text{lb of organic in tank at time } t \)

\[
\text{conc. } = \frac{x}{y}, \text{ then }
\]

\[
\frac{dx}{dt} = K(0 - x/y) - 15,000(x/y)
\]

\[
\frac{dx}{dt} + \frac{37,500x}{5000(15+t)} = 225,000
\]

\[
\frac{dx}{dt} + \frac{75x}{15+t} = 225,000;
\quad \frac{d(15+t)^{3}x}{dt} = 225,000(15+t)^{3}
\]

\[
(15+t)^{7.5}x = \left( \frac{225,000}{8.5} \right) (15+t)^{8.5} + C
\]

\( x = 26,500(15+t) + C(15+t)^{-7.5} \)

when \( t = 0 \), \( x = 60,000 \), and \( C = -338,000 \) (15)^{-7.5}

when \( t = 3 \); \( x = 27,500 \) (18) − 338,000 (15/18)^{-7.5}

32.10

Let \( C, x, y \) = the number of moles of \( C, x, \) and \( y \) respectively at time \( t \).

1. \( C \) balance: \( C_{0} = 1 \), initial moles of \( C \)

\[
\frac{dC}{dt} = -kC; \quad \int_{C_{0}}^{C} \frac{dC}{C} = -k \int_{0}^{t} dt
\]

\[
\ln \frac{C}{C_{0}} = -kt; \quad C = C_{0} e^{-kt} = e^{-kt}
\]

2. \( x \) balance:

\[
\frac{dx}{dt} = kC = ke^{-kt}
\]

\[
x = \int_{0}^{t} ke^{-kt} dt
\]

\[
x = 1 - e^{-kt}
\]

\[
\ln 1/2 = -kt, \quad \text{or} \quad t = \frac{\ln 2}{k}
\]

32.11

Mass balance:

Accumulation = Input − Output

\[
d(VV) = 0 - \left[ U_{1}A_{1}dH + U_{2}A_{2}dH \right]
\]

where \( V = \pi (R^{2})H \text{ m}^{3} \), \( A_{1} = \pi (2.5)^{2} \text{ cm}^{2} \), \( A_{2} = \pi (3)^{2} \text{ cm}^{2} \)

\[
V = c \sqrt{2gh}, \quad c = 0.61, \quad g = 9.80 \text{ m/s}^{2} \quad \text{&} \quad h = \text{height of H}_{2} \text{O level from orifice}
\]

\( H = \text{height of H}_{2} \text{O level from bottom} \)

\( h_{1} = H - 1 \) \& \( h_{2} = H - 0.5 \)

Assume \( p \) is constant

Then \( dV = \)

\[
= -0.61 \times 2 \times 9.80 \left( \pi \times 10^{-4} \right) \left[ 6.25 \sqrt{H - 1} + 25 \sqrt{H - 0.5} \right] dt
\]

\[
-3.00 \times 10^{-3} \int_{0}^{5} \frac{dH}{10 6.25 \sqrt{H - 1} + 25 \sqrt{H - 0.5}}
\]

(continued)
-3.00 \times 10^{-5} \, t = \int_{10}^{5} \frac{dH}{\sqrt{H-1} + 25\sqrt{H-0.5}} \times \frac{\sqrt{H-1} - 25\sqrt{H-0.5}}{\sqrt{H-1} - 25\sqrt{H-0.5}} \\
= \int_{10}^{5} \frac{\sqrt{H-1}}{((625/2)-1)} - \frac{25\sqrt{H-0.5}}{((625/2)-1) - 625H} \, dH \\

Let \quad H-1 = x^2 \quad H - 0.5 = y^2 \\
H = x^2 + 1 \quad H = y^2 + 0.5 \\
dH = 2xdx \quad dH = 2ydy \\
(-3.00) \times 10^{-5} \, t = \int \frac{x \cdot 2x \, dx}{\frac{625}{2} - 625(x^2 + 1)} \\
\quad -25 \int \frac{y \cdot 2y \, dy}{\frac{625}{2} - 625(y^2 + 0.5)} \\
\boxed{t = 2.02 \times 10^3} \\

32.12 \\

10 \, gph \quad \xrightarrow{1} \quad \xrightarrow{10 \, gph} \quad \xrightarrow{10 \, gph} \quad \xrightarrow{10 \, gph} \\
\begin{array}{c|c|c|c}
\hline 
I & x_1 & 100 \, gal & \hline 
x_1 / 100 & \hline 
II & x_2 & 100 \, gal & x_2 / 100 \hline 
\end{array} \\

Let \, x_1, \, x_2 \, be \, the \, number \, of \, lb \, of \, A \, in \, tank \, \text{I} \, or \, \text{II} \, at \, any \, time \, t \, respectively \\

A. Balance in tank I. \\

\[
\frac{dx_1}{dt} = 0 - \frac{10}{100} \cdot x_1 = -0.1x_1 \\
\int_{10}^{x_1} \frac{dx}{x} = -0.1 \int_{10}^{t} dt \\
x_1 = 10 \cdot e^{-0.1t} \\
\]

for \, t = 3 \, hr; \quad x_1 = 10^{-0.3} = 7.41 \, lb \\

Conc. of A in tank A = 0.0741 \, lb/gal \\

A Balance in tank II \\

\[
\frac{dx_2}{dt} = 10 \left( \frac{x_1}{100} \right) - 10 \left( \frac{x_2}{100} \right) \\
\]

Since \, x_1 = 10e^{-0.1t} \\

\[
\frac{dx_2}{dt} = e^{-0.1t} - 0.1x_2 \\
\frac{dx_2}{dt} + 0.1x_2 = e^{-0.1t} \\
(D + 0.1) \, x_2 = e^{-0.1t} \text{ where } D = d/dt \\
\]

Particular integral \\

\[
P.I. = e^{-0.1t/D} + 0.1 = (e^{-0.1t})(D - 0.1 + 0.1) \\
= te^{-0.1t} \\
\]

The general solution is \\

\[
x_2 = Ce^{-0.1t} + te^{-0.1t} \\
\]
when \( t = 0 \), \( x_2 = 10 \), and \( C = 10 \)

\[
x_2 = e^{-0.3 \times (10 + 3)} = 9.64 \text{ lb}
\]

Conc. of A in tank II = \( \frac{0.0964 \text{ lb}}{\text{gal}} \)

### 32.13

Assuming \( p \) to be constant, the material balance is as follows: Accumulation = inflow − outflow

\[
\frac{dV}{dt} = Q_i - Q_o
\]

\[
= 2 - 0.01V
\]

\[
\frac{dV}{dt} \bigg|_{t=0} = 1.5 \text{ V increases}
\]

\[
\int_{50}^{100} \frac{dV}{2 - 0.01V} = \int_{50}^{100} \frac{dt}{2 - 0.01t}
\]

\[
- \frac{1}{0.01} \ln(V - 200) \bigg|_{50}^{100} = t \rightarrow \frac{100}{500} = -0.01t
\]

\[
t = -100 \ln \left( \frac{100}{150} \right) = 30.6 \text{ min}
\]

### 32.14

Let \( x \) be mg of fission product in the tank at any time \( t \); when \( t = 0 \), \( x = (10)(3.785)(10,000) = 3.785 \times 10^5 \text{ mg} \)

Rate of change = Rate in − Rate out − Rate decay

\[
\frac{dx}{dt} = (10)(3.785)(100) - 100 \left( \frac{x}{10,000} \right) - 0.01x
\]

\[
= 3785 - 0.02x
\]

\[
\frac{1}{0.02} \int_{x=306,000}^{x=310,000} \frac{dx}{3785 - 0.02x} = \int_{0}^{t} \frac{dx}{dt} = 24
\]

\[
x = 306,000 \text{ mg}
\]

conc. in the tank at the end of the first 24 hr =

\[
30.6 \text{ mg/gal} \rightarrow 8.1 \text{ mg/liter}
\]

b. \( \frac{dx}{dt} = -0.01x \)

\[
\int_{x=306,000}^{x=x} \frac{dx}{x} = -0.01 \int_{0}^{t} \frac{dx}{dt}
\]

\[
x = 30,600 e^{-0.24} = 241,000 \text{ mg}
\]

Conc. = \[
\frac{241,000}{(10,000)(3.785)} = 6.4 \text{ mg/liter}
\]

c. The maximum conc. in the tank is \( 10 \text{ mg/liter} \)
32.15

Basis: 1 day of operation 1440 min

Sr\textsuperscript{92} balance:

Let \( x = \text{kg Sr}\textsuperscript{92} \) in tank per kg H\textsubscript{2}O at time \( t \)

Accumulation = In - Out - Decay

\[
x_{t+\Delta t} - x_t = \frac{1.5 \times 10^{-3}}{\text{min}} \times \frac{1.0 \times 10^4}{\text{m}^3} \times 1500 \frac{\text{kg Sr}\textsuperscript{92}}{10^8 \text{ kg H}_2\text{O}} \Delta t
\]

\[
- \frac{1.5 \times 10^{-3}}{\text{min}} \times \frac{1.0 \times 10^3}{\text{m}^3} \times \frac{\text{kg Sr}\textsuperscript{92}}{\text{kg H}_2\text{O}} \frac{\text{kg Sr}\textsuperscript{92}}{\Delta t}
\]

\[
- \frac{0.693}{2.7} \times \frac{1}{\text{hr}} \times \frac{\text{kg Sr}\textsuperscript{92}}{\text{kg H}_2\text{O}} \frac{\text{kg Sr}\textsuperscript{92}}{t}
\]

\[
\frac{dx}{dt} = (2.25) \times 10^{-3} - 1.5(x) - 4.28 \times 10^{-3}(x)
\]

Integrating between \( t = 0 \) and \( t = 1440 \) min,

\[
x = 1.5 \times 10^4 \times \frac{\text{kg Sr}\textsuperscript{92}}{\text{kg H}_2\text{O}}
\]

Y\textsuperscript{92} balance:

Let \( y = \text{lb Y}\textsuperscript{92} \) in tank per lb H\textsubscript{2}O at time \( t \)

\[
\frac{dy}{dt} = (4.28) \times 10^{-3}(x) - 1.5(y) - \frac{0.693y}{(3.5)(60)}
\]

from which

\[
y = 4.28 \times 10^3 \frac{\text{kg Y}\textsuperscript{92}}{\text{kg H}_2\text{O}}
\]

Zr\textsuperscript{92} balance:

Let \( z = \text{lb Zr}\textsuperscript{92} \) in tank per lb H\textsubscript{2}O at time \( t \)

\[
\frac{dz}{dt} = \frac{0.693}{(3.5)(60)} - 1.5 z
\]

from which

\[
z = 9.39 \times 10^3 \frac{\text{kg Zr}\textsuperscript{92}}{\text{kg H}_2\text{O}}
\]

32.16

Assume isothermal process

Let \( x = (\text{m}^3) \) in the tank at time \( t \)

\[
V = (\text{m}^3) / \text{min entering and leaving the tank}
\]

Material balance on O\textsubscript{2} in terms of (m\textsuperscript{3}) at T, 1 atm

\[
\frac{\text{In}}{(\text{m}^3) \text{ air}} = \frac{\text{Out}}{(3 \text{m}^3) \text{ gas}}
\]

Accumulation

\[
= x_{t+\Delta t} \Delta t - x_t \Delta t
\]

\[
\int_0^1 \frac{dx}{(0.21 - x/3)} = \int_0^9 V \text{dt} = 9 \text{ (m}^3\text{)}
\]

\[
-3 \ln \frac{(0.21 - x/3)}{0.21 - 1} = 9
\]

(continued)
x = 0.75 (m³)

Concentration = \[
\frac{9.75 \text{ (m}^3\text{)}}{3 \text{ (m}^3\text{)}} = 0.25
\]

or concentration = 25%

32.17

Basis: 1 mol C₆H₁₂

\[
\frac{d(C₆H₁₂)}{dt} = K(C₆H₁₂) \quad C₆H₁₂ = 1 - C₄H₈
\]

\[
C₆H₁₂ = 1 - C₂H₄
\]

\[
\frac{d(C₄H₈)}{dt} = K(C₆H₁₂) \quad \frac{d(C₆H₁₂)}{dt} = K(C₄H₈)
\]

\[
C₄H₈ = e^{-Kt}
\]

32.18

Let \( p_1, n_1 \) = pressure and number of moles of N₂ in the large tank at any time \( t \)

\( p_2, n_2 \) = the corresponding values in the small tank.

Then, \( \frac{dn_2}{dt} = K(p_1 - p_2) \)

Initially \( p_1 = 700, p_2 = 0; \frac{dn_2}{dt} = 0.2 \text{ kg mol/hr} \)

\( 0.2 = K \text{ (700 - 0)} \) or \( K = 2.857 \times 10^{-4} \text{ kg mol/hr/(KPa)} \)

Initially, no. of moles is

\[
n_1^0 = \frac{30 \text{ m}^3}{22.4 \text{ m}^3/\text{mol KPa}} 700 \text{ kPa} 273 \text{ K} = 8.62 \text{ kg mol}
\]

Assume ideal gas law holds.

\( pV = nRT \)

\[
p_i = \frac{8.31 \text{ (kPa)(m}^3\text{)}}{\text{(K)(kg mol)} \left[30 \text{ m}^3\right]} n_i = 81.2 \text{ n}_i
\]

\[
p_i = \frac{8.31 \text{ (kPa)(m}^3\text{)}}{\text{(K)(kg mol)} \left[15 \text{ m}^3\right]} n_i = 162.3 \text{ n}_i
\]

\( n_1 + n_2 = 8.62 \)

\[
\frac{dn_2}{dt} = 2.857 \times 10^{-4} (700 - 81.2) n_2
\]

Final moles in tank 2 will be \((15/30+15)(8.62) = 2.87\) hence

\(1/2 (2.87) = 1.44\).

\[
r^{1/44} \frac{dn_2}{dt} = 2.857 \times 10^{-4} \int_0^t \text{dt}
\]

\( t = 27.5 \text{ hr} \)
Applying this general procedure to the integration of Eq. (5), we find that the integrating factor is $e^{\int k_1 \, dt}$. The constant of integration is found to be $-k_1 C_{AO} / (k_2 - k_1)$ from the initial condition $C_{BO} = 0$ at $t = 0$, and the final expression for the variation in concentration of $B$ is

$$C_B = C_{AO} k_1 \left( \frac{e^{-k_1 t}}{k_2 - k_1} + \frac{e^{-k_2 t}}{k_1 - k_2} \right)$$

If $k_1$ is much larger than $k_2$, then

$$C_B = C_{AO} e^{-k_1 t}$$

In other words, the concentration of $B$ is determined by $k_2$. Noting that for the constant-volume system there is no net change in total number of moles, we find the material balance at any time to be

$$C_{AO} = C_A + C_B + C_C$$

which with Eqs. (4) and (5) gives

$$C_C = C_{AO} \left( 1 + \frac{k_2}{k_1 - k_2} e^{-k_1 t} - \frac{k_1}{k_2 - k_1} e^{-k_2 t} \right)$$
\[ \frac{dC_A}{dt} = -k_2 C_A + k_1 C_B - k_3 C_A = -(k_2 + k_3) C_A + k_1 C_B \]  
\[ \frac{dC_B}{dt} = k_2 C_A - k_1 C_B \]  
\[ \frac{dC_C}{dt} = k_3 C_A \]  

(1)

(2)

(3)

Initial conditions: at \( t = 0 \), \( C_A = C_{AO} \) and \( C_B = C_C = 0 \).

To solve Eqs. (1) - (3) use matrix operations

\[ Q = \begin{bmatrix} -(k_2 + k_3) & k_2 \\ k_1 & -k_1 \end{bmatrix} \]

\[ C^T = [C_A, C_B] \]

\[ C(0)^T = [C_{AO}, 0] \]

To find the eigenvalues of \( Q \) we set

\[ |Q - \lambda I| = \begin{vmatrix} -(k_2 + k_3) - \lambda & k_2 \\ k_1 & -k_1 - \lambda \end{vmatrix} = (k_2 + k_3 + \lambda)(k_1 + \lambda) - k_2 k_1 = 0 \]

The roots are

\[ \lambda_1 = \frac{-a + \sqrt{a^2 - 4k_2 k_3}}{2} \]

\[ \lambda_2 = \frac{-a - \sqrt{a^2 - 4k_2 k_3}}{2} \]

where: \( a = (k_1 + k_2 + k_3) \). Consequently the solution to the set of Eqs. (1) and (2) is:
Solutions Chapter 32

32.21

**Tank A:**

1. \( FC_C - FC_A = V \frac{dC_A}{dt} \)
2. \( FC_A - FC_B = V \frac{dC_B}{dt} \)
3. \( FC_B - FC_C = V \frac{dC_C}{dt} \)

\[ P = \frac{1 \text{ gal}}{\text{min}} = 50 \]

\[ V = 1000 \text{ gal} \]

\[ C = \frac{\text{lb}}{\text{gal}} \]

\[ \Delta = \begin{bmatrix} -50 & 50 & 0 \\ 50 & -50 & 50 \\ 50 & 0 & -50 \end{bmatrix} \]

\( Y^T = [C_A, C_B, C_C] \)

\[ \chi^T(0) = [3, 0, 3] \]

\[ \Delta - \lambda I = \begin{bmatrix} -50 - \lambda & 50 & 0 \\ 0 & -50 - \lambda & 50 \\ 50 & 0 & -50 - \lambda \end{bmatrix} = 0 \]

\[ 0 = -(50 + \lambda)^3 + (50)^3 \]

\[ 0 = (50)^3 - 3(50)^2 \lambda - 150\lambda^2 - \lambda^3 + (50)^3 \]

roots:

\[ \lambda_1 = 0 \]

\[ \lambda_{2,3} = \frac{-150 \pm \sqrt{22,500 - 30,000}}{2} \]

when \( t = 0, C_A V = 3000 \text{ lb}, C_C V = 3000, C_B V = 0 \)

\( t_A = ?, C_A V = 2100 \text{ lb}, t_C = ?, C_C V = 2100 \text{ lb}, t_B = ?, C_B V = 1900 \text{ lb} \)

Solve the equations to get \( t_A = 22.8 \text{ min}, t_C = [28.2 \text{ min}], t_B = 24.4 \text{ min} \)

32.22

Energy balance around the tank:

\[ \frac{dU}{dt} = -\Delta (\frac{\Delta h}{m}) \tag{1} \]

Energy balance around the heat exchangers:

\[ 0 = \frac{dU}{dt} = \frac{dU}{dt} - \Delta (\frac{\Delta h}{m}) = Q \tag{2} \]

We have assumed that the residence time of the liquid in the heat exchanger is very small and that kinetic and potential energy contributions are negligible. From Eqs. 1 and 2 we obtain

\[ \frac{dU}{dt} = -Q \tag{3} \]
Subscripts T and H refer to the tank and the heat exchanger, respectively. Because the liquid is approximately incompressible, \( C_p \equiv C_v \). Then, \( dU_T = mC_p dT = mC_p dT \). Furthermore, the rate of heat addition to the liquid \( Q \) is given by \( Q = U_0 A_0 (T - 180^\circ) \). The notation used here is the same as the one introduced in Problem 7.24. Hence, Eq. 3 becomes

\[
mC_p \frac{dT}{dt} = -U_0 A_0 (T - 180) \quad (4)
\]

\[
\frac{dT}{dt} + \frac{U_0 A_0}{mC_p} T = 180 \frac{U_0 A_0}{mC_p} \quad (5)
\]

Eq. 5 is a first-order linear differential equation. Its solution is

\[
T = \exp \left( \frac{U_0 A_0}{mC_p} \right) T = 180 \frac{U_0 A_0}{mC_p} \quad (6)
\]

From the initial condition, \( T = 60^\circ F \) at \( t = 0 \), the value of the constant is this:

\[
\text{constant} = -120^\circ F \quad (7)
\]

For the expression for \( t \) is

\[
t = \frac{mC_p}{U_0 A_0} \ln \left( \frac{120}{180 - 120} \right) = 0.578 \text{ hr} \quad (7)
\]

For the data given,

\[
t = \frac{10,000 \times 0.0 \times \ln \left( \frac{120}{180 - 120} \right)}{40 \times 300} = 0.578 \text{ hr}
\]

32.23

a. We shall make the following assumptions:

1. Steam temperature remains constant in coil.

2. Heat capacity of suspension does not change very much with change in temperature.

3. Agitator maintains uniform temperature throughout.

4. Heat-transfer coefficient is independent of position and time.

5. The walls of the tank are adiabatic.

The unsteady-state macroscopic energy balance

\[
\frac{d}{dt} U_{in} = -Q \quad (1)
\]

because the kinetic and potential energy in the accumulation term and the work term \( W \) as well as the kinetic and potential energy terms may be neglected.

\[
\Delta U_{in} = wC_p(T - T_s) \quad (2)
\]

Furthermore, the rate of heat addition to the system \( Q \) is given by \( Q = \dot{U}A(T_s - T) \). Hence Eq. (1) becomes

\[
\frac{d}{dt} U_{in} = \dot{U}A(T_s - T) - mC_p(T - T_s) \quad (2)
\]

Multiplying through by \( \frac{1}{mC_p(T_s - T_s)} \), Eq. (2) becomes

\[
\frac{wC_p}{mC_p(T_s - T_s)} \frac{d(T - T_s)}{dt} = \frac{\dot{U}A}{mC_p(T_s - T_s)} (T_s - T) - \frac{T - T_s}{T_s - T_s} \quad (2)
\]

(continued)
\[
\frac{w}{m} \frac{d}{dt} \left( \frac{T - T_a}{T_s - T_a} \right) = \frac{UA}{mC_p} \left( \frac{T - T_a}{T_s - T_a} - \frac{T - T_f}{T_f - T_a} \right) \tag{3}
\]

Introducing the dimensionless variables

\[
\Phi = \frac{T - T_a}{T_s - T_a}, \quad n = \frac{m}{w}, \quad B = \frac{UA}{mC_p}
\]

Eq. (3) becomes,

\[
\frac{d\Phi}{dn} = B(1 - \Phi) - \Phi, \text{ or}
\]

\[
\frac{d\Phi}{dn} + \Phi(1 + B) = B
\]

which is a first-order linear differential equation of the form

\[
\frac{dy}{dx} + Py = Q
\]

The solution to this equation is

\[
ye^{\int Pdx} = Qe^{\int Pdx} + \text{constant}
\]

Applying this principle to Eq. (4), we find that the integrating factor is \(e^{(1+B)n}\). The constant of integration is found to be \(-\frac{B}{(1+B)}\) from the boundary condition \(n = 0, \Phi = 0\). The final expression for \(\Phi\), the reduced temperature is

\[
\Phi e^{(1+B)n} = \left(\frac{B}{1+B}\right) \left(e^{(1+B)n} - 1\right)
\]

the expression for \(n\) as a function of \(B\) and \(\Phi\) is,

\[
n = \left(\frac{1}{1+B}\right) \ln \left[ \frac{B}{B - \Phi(1+B)} \right]
\]
5. Heat-transfer coefficient is independent of position and time.

6. The walls of the tank are adiabatic.

We choose the fluid within the tank as our system. Kinetic and potential energy may be neglected in this position. Since the work term is zero and there is no outlet stream, \( m_2 = 0 \). Hence, for this system the energy balance reduces to

\[
\frac{d}{dt} U_{\text{int}} = mH_1 + Q
\]  

which states that the internal energy of the system is increasing because of the addition of fluid with enthalpy \( H_1 \) and because of the addition of heat \( Q \) through the steam coil.

In view of the fact that \( U_{\text{int}} \) and \( H_1 \) cannot be given absolutely, we now select the inlet temperature \( T_s \) as the thermal datum plane. Then \( H_1 = 0 \) and \( U_{\text{int}} = \rho C_p V(T - T_s) \equiv \rho C_p V(T - T_s) \). Furthermore, the rate of heat addition to the system \( Q \) is given by \( Q = \dot{U}A(T_s - T) \). Hence Eq. 1 becomes

\[
\rho C_p \frac{d}{dt} V(T - T_s) = \dot{U}A(T_s - T)
\]  

Now the instantaneous area and volume are simply related to the total available area and volume according to the relations

\[
V(t) = \frac{mt}{\rho}, \quad A(t) = \frac{mt}{\rho V_o} A_o
\]

where \( \rho V_o / m = t_0 \) is the time required to fill the tank. Substitution of these expressions in Eq. 2 gives

\[
mC_p \frac{d(T - T_s)}{dt} + \dot{C}_p m(T - T_s) = \dot{U}A_o \frac{mt}{\rho V_o} (T_s - T)
\]

which is to be solved with the initial condition that at \( t = 0, T = T_s \).
where the constant of integration has been determined from the initial condition (11). Finally, the temperature of the liquid in the tank, when it has been filled, is given by Eq. 12 when \( n = 1 \) (or \( \alpha = B \)), in terms of the original variables, this result is

\[
\frac{T_r - T_s}{T_i - T_s} = 1 - \frac{1 - \exp \left( -\frac{UA_s}{mC_p} \right)}{\left( \frac{UA_s}{mC_p} \right)} \tag{13}
\]

For the data given in the problem,

\[
B = \frac{100 \times 32.9}{1200 \times 1.0} = 2.74.
\]

For this value, Eq. (13) gives \( \left( T_r - T_s \right) / \left( T_i - T_s \right) = 0.659 \), whence \( T_r = 155.5^\circ F \)

When the tank is half full, \( n = 1/2 \), \( \alpha = \alpha / 2 \). Thus

\[
\phi = 1 - \frac{1 - \exp \left( -\frac{\alpha}{2} \right)}{\left( \frac{\alpha}{2} \right)} = \frac{1 - 0.254}{1.37} = 0.455, \text{ whence}
\]

\[
T_r = 129.0^\circ F
\]

32.25

a. If heat losses from the top and the bottom of the tank are neglected, the resulting energy balance is

\[
\rho VC_p \frac{dT}{dt} = \tilde{U}A(T_i - T) \tag{1}
\]

or

\[
\int \frac{dT}{T_i - T} = \frac{\tilde{U}A}{\rho VC_p} \tag{2}
\]

Numerical Calculations:

\[
\frac{\tilde{U}A}{\rho C_p V} = \frac{(40 \times 25\pi)}{(62.4 \times 1.0 \times 125 \pi / 4)} = 0.513 \text{ hr}^{-1}. \text{ Since}
\]

\[
T_s = 230^\circ F, T = 170^\circ F, \text{ and } T_e = 70^\circ F, \text{ the time necessary to raise the temperature of the tank contents to } 170^\circ F \text{ is given by Eq. 3. Thus,}
\]

\[
t = 1.91 \text{ hr}
\]

b. If the heat losses from the top and the bottom of the tank are taken into account, the energy balance for the system is,

\[
\rho VC_p \frac{dT}{dt} = \tilde{U}A(T_i - T) + \tilde{U}_sA_s(T_w - T) \tag{4}
\]

where \( \tilde{U}_s \) = overall heat transfer coefficient for both the top and the bottom of the tank.

If we let \( a = UA + UA_s \) and \( K = UAT_s + U_sA_sT_s \), Eq. 4 becomes

\[
\rho VC_p \frac{dT}{dt} = \frac{K}{a} - T \tag{5}
\]

and when integrated we obtain the following equation:

\[
\int \frac{K - aT}{K - aT_s} = \frac{a}{\rho VC_p} - t \tag{6}
\]

For the data given in this problem,

\[
a = (40 \times 25\pi / 2) = 3540 \text{ Btu} / (\text{hr} \cdot ^\circ F)
\]

\[
K = (40 \times 25\pi \times 230) + (10 \times 25\pi / 2 \times 70) = 7.50 \times 10^4 \text{ Btu/hr}.
\]

Thus, \( t = 2.10 \text{ hr} \).
SOLUTIONS TO THOUGHT PROBLEMS

Section 1.1

1. This is a fuzzy problem because many volume units called barrel exist:
   
   British dry = 36 gal
   Cranberry = 5826 in³
   Oil = 42 gal
   US dry = 105 quarts
   US liquid = 31.5 gal

Section 1.3

1a. Gravity is not a force, it is an acceleration. Weight is a force.

1b. In SI a person has mass in kg but weight in Newton's even though common usage may use kg for weight.

1c. Use of such a conversion factor implies that a relation exists between g and °C, which does not exist. It is ok to write: 1.00 g water/1.00 cm³ water, because a relation between water and cm³ water does exist.

2. Not really, because kg is not a unit of force; kg is commonly used nevertheless.

Section 1.4

1. No. You can only determine that the equation has consistent terms.

2. The units are wrong.

Section 1.5

1a. Yes; (b) Not if measured with an error of 1/8 inch, but ok if 6 5/8 is exact.

1b. No, because it is an exact number. The answer is good to three significant figures.

1c. You know that 100mL can be measured easily to 3 or 4 significant figures.

Section 2.1

1. If the question refers to mass, the answer is yes. If the answer refers to any other measure, such as moles, the answer is no.

2. The question is: are the holes entities? The answer is yes.

Section 2.2

1. Would not sink because the overall density of the ship including the oil is less than that of sea water.

2. The density of hot water is less than that of cold water hence the container might not hold a gallon of hot water whereas it would hold a gallon of cold water or milk.

3. The density of gasoline is 0.81 and that of pentane 0.69. On more than one occasion tanks have overflowed because the contents were replaced by a liquid of lower specific gravity. The operators did not realize that the level indicator measured weight, not volume.

Section 2.3

1. Most organic bromides or iodides can be dissolved in a suitable organic solvent and a solution with the proper specific gravity to discriminate between the jade and arbsite, serpentine, and other imitations of jade. For example, methylene iodide (sp. gr. = 5.7) is a liquid at room temperature and can be blended with ethanol to give a harm- less liquid of the desired specific gravity.

Chapter 3

1. Follow the regulations of the U.S. Department of Agriculture which has proposed a strict permit system that, through tamper-proof computerized controls, assures that elevator operators adhere to Agriculture Department standards. Alternatively, grain could be priced at its dry weight on an industry wide basis (which is not currently done).
Chapter 4

1. The temperature probably is just a conversion from 2700°F, hence the answer is 2.

2. Examine Figure 4.2 for suggestions.

3. The thermocouple well was set only one inch into a 48 inch pipeline. When it rained, the exterior of the pipeline, and the thermocouple, would cool, causing a furnace to heat the residual going into the pipeline, excessively as it turned out.

Section 5.1

1. What counts is pressure, not force. On a floor the contact area with your body is small, so the pressure at the contact points is larger than experienced on a sofa.

2. When the water rushes through the tube its inertia is sufficient to carry it above bend B and start the siphon working.

Section 5.2

1. The essential point is that the covering paper can bulge out a bit so that the air pressure inside the glass is lowered. The pressure difference keeps the water in place. The water in the glass is compressed by the air. A glass plate on top of the completely filled glass is acted upon by the external air pressure and an equally large force from the compressed water on the other side. Thus, there is no pressure difference to support the weight of the water in the glass.

2. The tank, like most such tanks, was designed for a vacuum of 2 ½ inches water gauge only (0.1 psi or 0.6 kPa), and would collapse at a vacuum of about 6 inches water gauge (0.2 psi or 1.5 kPa).

If the tank had been filled instead of emptied it might have burst because it was designed to withstand a pressure of only 8 inches water gauge (0.3 psi or 2 kPa) and would burst at about three times this pressure. Whether it burst or not would have depended on the depth of water above the end of the hose.

3. The answer surprisingly is yes! Such pressures exist all around us—the pressure of sap in trees often gets as low as -2 MPa. Pressures as low as -20 MPa have been obtained in water in the laboratory.

When discussing pressure in gases, we often define the pressure as “the sum of impulses transferred to the wall of a container per unit time and area”. By this definition, pressures lower than a vacuum could not be produced. For pressures to be lower than a vacuum, our molecular interpretation would have to include attractive forces between the molecules of the fluid and the walls of the container. Such forces are typical of liquids but not of gases.

Attractive and repulsive forces between molecules correspond well to the macroscopic concepts of tension and compression. If we consider material with normal stresses lower than the pressure of a vacuum to be under tension and compression. If we consider material with normal stresses lower than the pressure of a vacuum to be under tension and material with normal stresses higher than the pressure of a vacuum to be under compression, then one way to distinguish liquids from gases is that liquids are fluids that can sustain compression or tension and gases are fluids that can sustain only compression. A lucid description of osmotic pressure is presented by Hammel and Scholander (H.T. Hammel and P.F. Scholander, *Osmosis and Tensile Solvent* (Springer Verlag, Berlin, 1967), pp. 1-73.)

4. During the fall, the force on the water exerted by gravity drops to zero.

Section 6.1

1. Energy, linear momentum, angular momentum, electric charge are some.

2. No. The totals of the withdrawals are valid outputs but the totals of the amount left are meaningless.

Section 6.3

1. By the conservation of mass in the closed system, the answer is d.

2. A pipe connected to system at the desired level (to retain some liquid) connected to an orifice operating in parallel with the controller will allow liquid to pass if the controller ceases to separate.

Section 6.4

1. The frozen orange juice was not completely removed from the tank truck on discharge, and this residual was dumped into the lake on cleaning the tank on return to Florida.
Section 7.2

1. The material balances are:

\[
\begin{align*}
(1) & \quad 0.10(10) + 0.30(6) = 0.175(16) \quad \text{checks, and does not contain unknowns} \\
(2) & \quad 0.90(10) + 0.50(6) = w'_{16} \quad \text{is uncoupled} \\
(3) & \quad 0.0(10) + 0.20(6) = w'_{16} \quad \text{is uncoupled} \\
(4) & \quad 1 = 0.175 + a'_{1} + a'_{2}
\end{align*}
\]

Only two unknowns exist if you introduce equation (4) into (1) - (3). The rank of the coefficient matrix of (2), (3), and (4) is 2, hence the problem has a unique solution.

Chapter 8

1. You can detect counterfeit gold or silver by weighing and measuring a coin or bar against the issuing mint's specifications. Modern counterfeiters may have mastered the appearance of their fakes but the principle of density—the ratio of mass to volume—has not changed. Gold has a greater density than the common metals such as lead, brass, copper and steel. This means that it is impossible to make a common metal fake identical to a genuine coin in both weight and size from these metals.

<table>
<thead>
<tr>
<th>References</th>
<th>gold</th>
<th>silver</th>
<th>copper</th>
<th>lead</th>
<th>iron</th>
<th>nickel</th>
<th>zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perry</td>
<td>19.30</td>
<td>10.49</td>
<td>8.93</td>
<td>11.33</td>
<td>7.86</td>
<td>8.90</td>
<td>7.135</td>
</tr>
<tr>
<td>CRC</td>
<td>18.88</td>
<td>10.50</td>
<td>8.96</td>
<td>11.35</td>
<td>7.87</td>
<td>8.90</td>
<td>7.133</td>
</tr>
<tr>
<td>S &amp; E of materials (Askeland)</td>
<td>19.30</td>
<td>10.49</td>
<td>8.93</td>
<td>11.36</td>
<td>7.87</td>
<td>8.90</td>
<td>7.133</td>
</tr>
<tr>
<td>Himmelblau</td>
<td>--</td>
<td>--</td>
<td>8.92</td>
<td>11.34</td>
<td>7.70</td>
<td>8.90</td>
<td>7.140</td>
</tr>
</tbody>
</table>

Silver can be imitated, but if made of a lead/tin alloy it would be too soft. Use 79.1% Pb, 20.9% Sn.

2. If the ash in the sludge is identical to the ash in the residual ash, then on the basis of 100 kg of sludge:

\[
\frac{67 \text{ lb ash}}{100 \text{ kg ash}} \quad \frac{100 \text{ kg residual ash}}{100 \text{ kg ash}} \quad \frac{184 \text{ mg of Cd}}{100 \text{ kg ash}} \quad \frac{142 \text{ mg}}{1 \text{ kg residual ash}}
\]

This number can be compared with 169 kg in the sludge so that 169 - 142 = 27 mg. (16%) is lost up the stack if the assumptions made hold.

Similarly for Pb, compare 307 mg with 412 mg in the sludge, and for Zn compare 1496 mg with 1554 mg. Not all of the heavy metals end up in the residual ash.

Section 9.1

1. The residual material on the metal surface reacted with oxygen and reduced the oxygen content of the residual air.

2. One gallon of crude oil at room temperature is about 3000g or 6 to 30 g mol of oil that requires for complete combustion 3 to 15 g mol O₂. The seawater with 10 ppm O₂ contains in 3x10^3 gal about 35g mol O₂ which agrees roughly with the statement in the article.

3. Calculation shows the statement to be wrong. If the average car gets 25 miles per gallon, 26,000 miles corresponds to an output of about 11 tons of carbon dioxide. It has been estimated that a young apple tree produces about 44 lb of sugar per growing season, which is equivalent to an uptake of about 66 lb of carbon dioxide. Thus even 100 young apple trees would not remove the carbon dioxide produced annually by an average car until the trees had grown to more than twice their size when planted.

Section 9.2

1. A gas was in the black cylinder and reacted with the material in the facepiece.

Section 10.3

1. A service engineer from the manufacturer was called to test the combustion controls and found that the flue gas contained no excess oxygen and approximately 4% combustible gas. The ratio of combustion air to fuel was increased until the flue gas contained zero percent combustible gas and then the steam flow increased to the full 120,000 lb per hour capacity. In determining the cause of the combustion control malfunction, it was found that moisture from the products of combustion had condensed in the piping to the combustion air flow controller causing erroneous action. To eliminate this problem, an oxygen and combustible recorder was installed and a regular maintenance contract was
set up with the combustion control manufacturer. The installed cost of the new control equipment was $95,000 vs. a loss of $54,900 in fuel in the two months.

2. Fossil fuels contain more carbon than hydrogen. This is especially so for coal (over 95% of our fossil-fuel supply).

We prefer gaseous and liquid rather than solid fuels. So, there has been much effort to develop processes that convert coal, or waste materials, to gaseous and liquid forms as supplements to natural gas and petroleum. In all these processes, the main technical consideration has been to lower the carbon-to-hydrogen ration, by adding hydrogen.

Superficially, it might seem that this increase in the relative amount of hydrogen in the fuel would lessen CO$_2$ emissions. But that is not the case, because the production of the hydrogen itself inevitably consumes more energy (derived from carbon-containing fuel) than is subsequently regained when the hydrogen in the synthesized fuel is burned. In short, there is a net addition of carbon dioxide to the atmosphere.

Gases from coal, cellulose, and other waste materials via most of the known processes contribute 10 to 20 percent more carbon dioxide than would pure carbon for the same heat availability. The story is analogous with respect to ethanol as an alternative automotive fuel: In the absence of free ethanol, any process to manufacture alcohol would give off at least twice as much CO$_2$ as would the use of gasoline, instead of ethanol, in the vehicle. It is true that using ethanol in automobiles gives off less carbon monoxide, but this is perhaps overshadowed by the danger posed by CO$_2$.

Another point should be made. Analysis shows that all of the synthetic fuels are intrinsically less efficient (based on actual heating value vs. that theoretically obtainable from the fuel’s constituents in elemental form) than the fuel forms as they occur in nature.

Chapter 11

1. (1) Select a system with the smallest number of unknowns. (2) Select a system for which the data is the most accurate (3) select a system at the beginning of a sequence (or at the end).

Section 12.2

1. To protect the pump, a minimum-flow line (line with an orifice) normally is created leading from the pump’s main discharge line back to the suction tank.

Section 13.1

1. The loss of free oxygen is more or less compensated for by reaction products such as CO and CO$_2$ (and also H$_2$O which, however, condenses). The important observation is that the water level inside the glass does not rise gradually. As the gas inside the glass is heated by the candle, the gas pressure increases and gas leaks out. (Some hot air is also caught in the glass as it is lowered towards the candle.) When the candle goes out, the gas cools off rapidly, its pressure decreases, so that water is forced into the glass.

2. In fact, this statement is wrong, and is wrong regardless of how one interprets the word “empty”. If empty means evacuated or containing helium at one atmosphere pressure, then it is obviously untrue. One the other hand, if empty means containing air at one atmosphere then it is still untrue, although only slightly. The can has a volume of about 43 cubic inches and when full is said to contain 0.21 cubic feet of helium, the air inside would still weigh a bit less than the compressed helium.

Two possibilities for this error suggest themselves. One, the author of the statement neglected to carry out the computation, and just guessed (wrongly) that the compressed helium would have a mass less than the same can full of air at atmospheric pressure. Another explanation possible is that the author misunderstood the nature of buoyancy, and fell into the trap of thinking that since “helium rises,” it will exert an upward (buoyant) force from inside the can and cause it to feel lighter than if the can contained air or even a vacuum.

3. Either p, V, n, or T would have to be rescaled, and the rescaled variables would not be compatible with the underlying definitions of the variables as used in other calculations. For example, T could be rescaled as $T^* = 8.314T$ if the usual $R = 8.314 J/(g mol) (K)$ was revised to a value of $R$ equal 1 $J/(g mol) (K)$.

4. No. The change in buoyancy caused by the decrease in volume has to be taken into account. The small values displaces less air, and this volume is equivalent to the volume of escaped air. No weight loss should be observed.
Chapter 14

1. Rust had jammed the valve so that it could not be fully closed. Cl₂ at high pressure leaked through the valve when the regulator was removed. Apparently the regulator was defective and did not show the Cl₂ pressure.

2. Yes. The initial pressure is 1 atm. If the liquid expands by 1%, the gas volume is composed to 0.04L. The pressure rise of the gas bubble (assuming ideal gas) is 100 atm. Something on a normal piping system will blow.

3. Yes.

4. At the bottom of the well the pressure is 1400 psig (9600 kPa) and the temperature reaches 530°F (277°C). Oxidation takes place without boiling which would make it very difficult to clarify the effluent after oxidation. Also, the oxygen concentration in the water is much higher at 1400 psia.

Chapter 15

1. The main reason for the higher temperature is that Venus is closer to the sun than the earth. Venus receives more energy per unit area per unit time. The cause of the high pressure is not understood. The high temperature might cause an increase about 2.5 in the pressure, and the CO₂ vs. air might be another factor of 1.5. However, the gravity of Venus is about 0.8 that of earth. The net effect of the three factors would be only 2.5 x 1.5 x 0.8 = 3. The actual state on Venus requires a molar specific volume of about 1L/g mol vs. 30L/g mol on earth.

2. The advantage is that the proteins are not exposed to organic solvents, heat, or oxygen, and retain their biological activity. Also, inasmuch as the process is supercritical, the solubility of the proteins in, say CO₂, is good, and the disposal of the solvent is easy.

Section 16.1

1. At 144°C the liquid butadiene would have expanded to fill the tank, but tests showed that the tank would expand enough so that it would not rupture at 160°C. Further tests showed that a dimerization of butadiene to vinyl cyclohexene (an exothermic reaction initiated at 100°C) would produce a rapid rise in temperature to over 500°C, hence the pressure exceeded the bursting pressure of the tank.

2. Vaporize the liquid through a valve. Look at the CO₂ chart in Appendix J. Proceed downward from saturated liquid at 60°F (and high pressure) to 1 atm. A mixture of solid and vapor exists at low temperature.

3. The process is technically feasible (but not economically reasonable) by compressing the vapor above the critical point of water, producing a fluid, and then reducing the pressure. Refer to the SI diagram for water in the foldout in the back of the book.

Section 17.1

1. In combustion calculations we estimate the quantity of dry air required to burn a given amount of fuel. In reality, the atmospheric air is never dry; it consists of some moisture, depending on the relative humidity and dry bulb temperature. To compute the partial pressure of water vapor in the flue gas, which is required for calculating nonluminous heat transfer, we need to know the total quantity of water vapor in flue gases, a part of which comes from the combustion air. Also, when atmospheric air is compressed, the saturation vapor pressure of water increases, and if the air is cooled below the corresponding water dew point, water can condense. The amount of moisture in the air or gas fixes the water dew point, so it is important to know the amount of water vapor in the air or flue gas.

Section 17.2

1. The probe can work well in a dilution range from 2 to 1 to 20 to 1. The effect of fluctuations of the stack pressure can be less than 0%. A glass wool plug should be used to filter out particulates. Because of error involved in the dilution, the error in gas analysis is magnified.

Section 17.3

1. The gasoline dissolved in the water in the tank to its equilibrium concentration, but the equilibrium concentration with water is quite different—much lower—than in water, hence when in the sewer, gasoline left the water as a vapor and a spark started a fire.

2. The cold liquid condensed the steam in the tank, and the pressure in the tank was lowered so rapidly that the air flow through the vent was not enough to prevent a partial vacuum from forming in the tank sufficient to collapse it.
Section 18.1

1. Possible causes are:
   1. Diffusion and convection of air (oxygen) could take place through the open manhole during lunch.
   2. Some of the CS₂ vapor might condense allowing air to pass into the tank.
   3. N₂ and CS₂ might cool and allow air to flow in.

2. The National Transportation Safety Board determined that the probable cause of the initial and subsequent explosions was the ignition of benzene vapors which were present both within the open cargo tanks and on the main deck of the tanker ship. The investigative record in this case does not contain sufficient information to determine the ignition source of the initial explosion. The probable source of ignition of the subsequent explosion was the heat produced from the preceding explosions.

As benzene cargo was discharged from the V. A. FOGG at the Phillips Petroleum Company and Dow Chemical Company terminals, air replaced the liquid benzene. The evaporation of the benzene residue which remained on the walls and bottom of the cargo tanks ensured a mixture of benzene vapor and air in the tanks. The lower and upper explosive limits of benzene vapor in air are 1.4 and 8.0 percent by volume, respectively.

Using the estimated air and water temperatures which affected the V. A. FOGG on February 1, it was determined that the benzene vapor concentration in the cargo tanks probably ranged between 5.7 and 8.0 percent.

Section 18.2

1. If the water is continually condensed from the air by the coils in the refrigerator, there is good air circulation, and the water and vapor are in equilibrium on the coils, the air can be close to being saturated if the coils are not at a sufficiently low temperature (and may not be satisfactory generation). 100% saturation could result in water condensation on surfaces and food in the refrigerator.

2. The answer to the question is satisfactory.

3. Density = mass/volume = \(\frac{\text{m} \times \text{MW}}{\text{V}}\)

Density of air \(n_0\{\text{H}_2\text{O}\text{MW}_{\text{H}_2\text{O}} + (1 - \text{Y}_{\text{H}_2\text{O}})\text{MW}_\text{Air}\}\)

On day 1, \(\text{Y}_{\text{H}_2\text{O}} > \text{Y}_{\text{H}_2\text{O}}\) on day 2.

On a humid day the air is less dense. The "heavy" or "muggy" feeling of the air occurs because of reduction of evaporation from the surface of the skin.

Section 19.2

1. The tanks were not blanketed with nitrogen and there was an explosive mixture of naphtha vapor and air above the liquid in the tanks. The source of ignition was static electricity. The pumping rate was rather high so that the naphtha flowing through the pump and lines acquired a charge. A spark passed between the liquid in the tank and the roof or walls of the tank, igniting the vapor-air mixture.

There are several ways to preventing similar explosions:

1. Use nitrogen blanketing or floating roof tanks
2. Use anti-static additives; they increase the conductivity of the liquid so that charges can drain away rapidly to earth (provided equipment is grounded). However, make sure that the additives do not deposit on catalysts or interfere with chemical operations in other ways.
3. Minimize the formation of static electricity by keeping pumping rates low (less than 3 m/s for pure liquids but less than 1 m/s if water is present) and avoiding splash filling. Filters and other restrictions should be followed by a long length of straight line to allow charges to decay.

2. This dry ice jet contains solid and gaseous components. Two categories of cleaning exist, one for removing solid particles and one for hydrocarbons. In the former, particles are sloughed and removed by a combination of the gas aerodynamic drag force and collisions between the solid CO₂ snow and the surface particles. Collisions between the snow and surface particles are believed to be responsible for the snow removing particles of all sizes, micron and submicron.

In the case of hydrocarbons adhered to the surface, liquid carbon dioxide forms by the pressure increase when the snow impacts the surface. Fortunately, the triplet point of CO₂ is only at four atmospheres pressure, and hydrocarbons are known to be soluble in the liquid.

3. (a) The vapor pressure of a gasoline is 14.7 psia at 130°F.
(b) The vapor pressure of a particular mixture of water and furfural is 760 mm at 99.9 °C.
4. If the vapor of the fluid being loaded dries all of the air out of the tank, the only vapor left is the vapor of the liquid, and its vapor pressure may be less than the atmospheric pressure outside the tank. Coast Guard regulations require that pressure sensors be installed near the hose connection at the dock, and systems (vacuum breakers) be installed to inject inerting or diluting, or enriched, gas into the vapor space.

Chapter 20

1. a. Improved separation.
   b. More economic separation (less energy used); less operating and/or capital costs for the process.
   c. Safety.

2. a. Application of heat
   b. Change in pressure
   c. Replace with a different fluid or gas.

Section 21.1

1. The data gives 151,000 gal/(mi)^3. Assume land used for crops is 738 x 10^3 mi^2. 10.7% would be used for ethanol production.

2. About 3 x 10^9 bbl oil/yr are used; 10% is 3 x 10^8 bbl. 3 x 10^8/3.26 = 9 x 10^11 tons coal. If 6.5 x 10^8 tons of coal are mined each year, the fraction is 14%.

3. A 10 ft diameter windmill in a 20 mph wind will generate about 1/4 hp (0.5 kW) and cost about $6000 including a 30 ft tower. The cost of the interest at 10% and the repayment of the $6000, and maintenance is about $3000 per year over 5 years. You have to determine the hours of operation and use of the electricity, i.e. pumping water that can be stored vs. operation of lights. Most likely your father will have to connect to the utility.

Section 21.2-1


2. The power transmitted by the drive shaft of the car can be measured when torque is applied and the shaft rotations per unit time counted: \( W = 2\pi nT \), where \( W \) is the power, \( n \) is the number of rotations/min, and \( T \) is the torque \((\text{F}) \times (\text{r})\). It is easy to read from the car instruments, but \( T \) requires a special instrument.

Section 21.2-2

1. The feeling of the 'degree' of heat or cold when our bodies touch some object is determined by the amount of heat which is given out, or is received by our bodies in unit time. The thermal conductivity of metal is greater than that of wood. If the metal and the wood are heated to the same temperature, higher than the temperature of our bodies, the metal will transmit to our bodies, on contact with them, more heat in unit time than will the wood. And if the metal is colder than our bodies, it will take from our bodies in unit time more heat than wood at the same temperature will. Therefore in the first case metal will seem hotter than wood, and in the second case it will seem colder. Plainly, it is when the metal and the wood are both at the same temperature as our bodies, and when there is no transference of heat, that they will seem equally heated to our touch.

2. (a) As an example, ice melts at 0°C only if the necessary amount of heat be imparted to it — about 330J to every gram of ice — while water will only freeze if the same amount of heat is taken from it. Therefore if the vessel is not heated or cooled from outside, the water will not freeze and the ice will not melt. A mixture of water and ice at 0°C will be in physical equilibrium.

   (b) Fire walking illustrates the difference between temperature and heat. A temperature can be extremely high (900 to 1000 K perhaps for embers), but little heat is transferred to the feet because the heat capacity and conductivity of the embers are low, the time spent in contact with the embers is short, and after a time the temperature of the coals can drop considerably.

3. After the water in the jar and the water in the pot reach equilibrium at 1 atm and 100°C, heat transfer from the stove burner occurs only to the water in the pot, hence the water in the jar remains at 100°C without boiling. (A little vaporization does occur so that a small amount of heat is transferred from the water in the pot).

Section 21.2-4

1. The potential energy is converted to kinetic energy (and a little angular energy), hence no violation occurs.
Section 21.3-5

1. Some processes are unsteady-state batch, and the internal energy term in the energy balance then is involved.

   Section 23.1

1. Steps to take:

   (1) insulate tank (but see (7) below) but it may aid corrosion, hinder inspection
   (2) cover tanks with earth (same problems as (1))
   (3) emergency depressurize systems and pipe (expensive)
   (4) liquid withdrawal/transfer system (only if very rapid — makes tank more vulnerable)
   (5) keep tank full so \( \int C_a dT \) absorbs heat transfer
   (6) admit water into tank to replace vapor/liquid losses (can over pressurize, extensive venting)
   (7) apply water spray (must be where needed)

2. Steam condensate had collected on the surface of the first batch of tar, and when the hot tar was pumped in on top of it, the water vaporized forming a large volume of steam that ejected the tar out of the tank.

Section 23.2

1. Before they reach the ice temperature they will transfer heat to the ice at different rates, but after they reach the ice temperature, heat transfer will stop and the ice will no longer melt.

2. You can write

\[
\begin{align*}
\frac{dH - dU}{dV} &= p \frac{dV}{dV} + V \frac{dp}{dV} \\
\end{align*}
\]

and show

\[
C_p - C_v = \left( \frac{\partial H}{\partial T} \right)_v - \left( \frac{\partial U}{\partial T} \right)_v = \left( \frac{\partial U}{\partial V} \right)_v \left( \frac{\partial V}{\partial T} \right)_v + p \left( \frac{\partial V}{\partial T} \right)_v
\]

The term on the right hand side is not zero. \( (\partial V/\partial T)_p \) can be evaluated from the coefficient of thermal expansion \( (1/V) (\partial V/\partial T)_p \); the internal pressure, is hard to find but can be calculated from the coefficient of thermal expansion; \( (\partial V/\partial T)_p \) is the compressibility. Examples of such calculations give the following errors for \( ((C_p - C_v)/C_v) \): 100: Hg, 12.7%; CH₃OH, 22%; C₆H₆, 30%; Ag, 4%.

3. Refer to the answer to TP22.2-2.

4. If the gas is ideal, \( \Delta H = Q \) is a function of temperature only so that there will be no difference. But if the gas is not ideal, the terms in the expression for the enthalpy \( \Delta H_{\text{ex}} = \Delta H_0^T (1 \text{ atm}) + \Delta H_0^T (T_f) + \Delta H_{\text{ex}}^T (T_f) \) must be evaluated for the particular gas.

Section 24.1

1. The side in the shade in the afternoon when the demand on the air conditioning system is the greatest, because the air intake will be cooler than on the sunny side.

2. a. No

   b. No. Oversudging consumes more energy.

   c. No. Warm room air is pulled up the chimney.

   d. Yes. The room will need to be cooled down when you return, but you'll still save energy.

   e. Yes, but be sure the gas is off, too, and that the pilot light is relit before you turn the furnace back on.

   f. No. An average shower saves about 5 gallons of hot water compared with a bath, or (if daily) almost 2,000 gallons of hot water a year.

   g. No. Long-life bulbs are not energy-savers.

   h. Yes. A 40-watt fluorescent gives off 80 lumens per watt, while a 60-watt incandescent yields only 14.7 lumens per watt.

   i. No. The range will heat the refrigerator.
j. Yes. Driving 55 saves about 20 percent.

k. No. These accessories all consume energy.

Section 24.4

1. Liquid is sometimes transferred from one tank to another by gravity. Overflowing has occurred when liquid flows from a tall tank to a short one. Overflow can occur when liquid is transferred from one tank to another of the same height several hundred yards away because a slight slope in the ground is sufficient to cause the lower tank to overflow.

2. Aside from possible practical difficulties (such as the height of the tower) questions are:
   
   1. Will the system run as described?
   
   2. If so, does it constitute perpetual motion; or, if not, from what source does the energy come?
   
   3. If it would not run, point out any fallacy in the reasoning above.

   The answer to the perpetual motion problem is that the work needed to expand the hydrogen and oxygen is at least equal to the energy developed by the turbine; the fact that the water is electrolyzed does not significantly change the problem from one in which two pistons are moved away from one another inside a cylinder, creating a vacuum between them. In both cases a pressure is exerted through a volume. The machine will not run. Assuming that the water is of negligible volume, that W pounds of water are being used, that the air is of constant density \( p \), and that the air stops at the top of the column whose height is \( H \), then the energy developed by the turbine is given by \( WH \), and the weight of air which must be displaced must equal the weight of the water \( W \). If the volume is air is \( V \).

   \[
   V = W, \text{ or } V = W/p
   \]

   The work done in expanding the air is the volume through which the air is expanded times the pressure: Work = \( WpH \), \( H = WH \).

   This is the same as the work developed by the turbine. Actually, of course, the assumptions about the characteristics of the air are not strictly correct, but the same result could be obtained (with considerable more work) by finding \( \int_{b}^{a} p\,dV \).

3. Turn off the fuel burners and let the furnace cool to 1600°F (energy used = 0 MBtu). Reheat from 1600°F to 2200°F in 2.6 hours (energy used = 70 MBtu). Hold at 2200°F for 0.5 hours (energy used = 5.1 MBtu). Total energy used = 75.1 MBtu vs (10.2) \( \approx 81.6 \) MBtu by holding at 2200°F.

Section 25.1

1. \( \Delta H^\circ \) is negative for the A1 reaction and positive for the Cu reaction, hence heat has to be provided for the latter to occur.

2. The stoichiometric ratio of the air to the fuel is so low that the mixture delivered to an engine designed for gasoline will not fire. In addition, much more heat transfer is required to vaporize the fuel. Also, the fuel injection system would have to be redesigned to use straight alcohol.

Section 25.2

1. The energy balance is

   \[
   m_g(4000 \text{ J/g}) = m_o \cdot C_p(T_f - T_i) = m_w \Delta H_{\text{vap}}
   \]

   \( m_w/m_o \) is about 1/4.

2. To produce the \( H_2 \) via current technology, \( CO_2 \) is released. Production of \( H_2 \) by electrolytic decomposition of water requires 3000 Btu of fossil fuel to generate the necessary electricity to deliver 1000 Btu of energy via combustion of \( H_2 \) in a fuel cell. Steam reforming of natural gas requires 1500 Btu of fuel to do ditto. In each case \( CO_2 \) emissions occur greater than the direct use of the fuel for heat.

Section 25.3

1. Dimethyle ether added to gasoline would not be safe. The vapor pressure of dimethyl ether at 20°C is 5 atm whereas the vapor pressure of octane is about 10 mm Hg. Its practical use is nil. Problems occur in automobiles (corrosion, vaporization, etc.). On the other hand, miles per gallon of a fuel is the important consideration and it is not proportional to calorific value. The Bank of America recorded millions of miles driven by its fleet of hundreds of cars, and showed that methanol blends increase mileage, as
would be expected from the much greater efficiency of methanol in an engine that, however, was designed to use gasoline. Performance in terms of miles per million Btu in the blends is better than gasoline.

Section 25.4

1. The improper design, operation, or use of thermal combustion systems may pose a threat to public health through emissions of potentially hazardous components of the wastes or their combustion byproducts. Incinerators can remove 99.99% of the hazardous waste occurring at concentrations > 1000 ppm in the feed, but incomplete combustion products indicate decomposition is not complete, and some of the intermediate products of combustion are also hazardous. The handling of the feed requires care as inadequate atomization and overfeeding leads to CO, unburned hydrocarbon, and difficulty to detect hazardous species. A good reference is Science, vol. 206, p. 781-795 (1979); there are immemorable others. Gasohol is about at the break even point. Whatever assumptions are made about the use of crop residues, substitution of coal or oil in the processing, etc. affect the conclusions.

2. The diluent acts as an "energy absorber" so that for a fixed amount of heat transfer, the temperature of the exit products will be lower. Think of N₂ in the air.

3. None. The standard heat of reaction is defined for one mole at 25°C that reacts completely.

4. Gas turbine exhaust gases typically contain 14 to 16% oxygen, hence there is no need for additional oxygen to fuel such gas. However, if the amount of fuel (gas, oil, coal) is very large relative to the turbine exhaust, then additional oxygen may be needed.

Section 26.2

1. If efficiency is defined as Q/\Delta H^\text{rev}, each of the quantities Q and \Delta H^\text{rev} should be based on comparable amounts of fuel (or perhaps costs of fuel would be best?), such as unit mass or mole, be at the same standard state, and refer to the same ambient conditions. Whether the amount of excess air can be the same is uncertain, but if it is not or even if it is, the gaseous product composition will differ in each case, e.g., using CH₄ vs. CH₃OH fuels. The overall heat capacities will only slightly differ, but the water vapor content may differ per mole of CO₂ produced. To avoid condensing the water vapor, the natural gas products cannot be cooled as much as fuel oil combustion products.

2. Acetone has a much higher vapor pressure than gasoline so that adding acetone to gasoline, or pure acetone, would cause internal combustion engine to malfunction. Also, seals, tubing, etc. would be damaged.

3. Efficiency drops more for values of the theoretical air-fuel less than 1 vs. greater than 1, and CO is produced in the former mode. Air pressure has little effect. Preheating the air, if possible at a cheap cost, helps some. Preheating the feed water also helps a bit. A high flue gas temperature results in a much more substantial loss in efficiency. A fuel that has a higher H to C ratio reduces efficiency for high H to C ratios. Fouled heat transfer surfaces reduce efficiency a bit.

4. The heat transfer is different because for a closed system Q = \Delta U = \Delta H - p(\Delta V), and for an open system Q = \Delta H.

5. Oxygen, because the N₂ in the product of combustion with air uses up some of the available energy pool.

5. Combustion of H₂ in air gives a theoretical flame temperature of 4060°F but the actual temperature allowing for equilibrium is more like 3800°F. Preheating the fuel and air which might occur would raise both of these values.

Section 27.1

1. The magazine said that when water was poured into the funnel it would flow for up to 12 hours. When the author was asked about the apparatus, he admitted that the best he could do was have it run for a minute. The air in the spherical vessels was compressed when water was poured into the funnel; dissipation and friction caused the flow to stop.

Section 27.2

1. 20 hp is much less than 68 kW, insufficient even at 100% efficiency.

2. Comparisons are heavily dependent on the assumptions one makes relating to the performance and capacity of the electric versus the internal combustion engine (ICE) vehicle. Since no current electrically powered vehicle matches the cruising speed, acceleration, and range characteristics of competitive gasoline-powered cars, this type of comparison is always clouded by whatever is assumed as the minimum acceptable performance for the electric. If the electric car must have the power/energy capability to drive repetitively 54 miles between battery charges, a considerably heavier electric
vehicle than 2800 lb is needed (more like 4000 lb is needed). A 50-mpg road load power requirement is not a valid basis on which to size a power plant to propel highway vehicles.

Efficiencies are different from the table. Reasonable values are 36% thermal efficiency for the power generation facility, 91% electrical transmission efficiency, 10% refinery energy penalty charged to gasoline manufacturing, and 46% battery efficiency (assuming overnight recharge). The latter figure is considerably lower than the 70% figure in the table.

On this basis, the energy consumption for a currently feasible electric car used under city-suburban commuting conditions comes out to about 8300 Btu/mile versus 6000 Btu/mile for the Pinto-class gasoline powered car.

Section 27.3

1. The ball levitates because as the air reaches the expansion section of the funnel, it slows down to fill the larger cross section, and since the air is faster above the ball than below it, the pressure is higher below the ball than above it.

2. Figures b and c (which are not to scale). With tubes the equation to use is called Poiseuille’s equation. With holes, the equation is called Torricelli’s equation. With Poiseuille’s equation, the velocity is proportional to the pressure head. Torricelli’s equation states that the velocity is proportional to the square root of the pressure head, and indicates the maximum range for the liquid comes from a hole 1/3 of the way up the cylinder whereas Poiseuille’s equation designates a tube 1/3 of the way up the cylinder.

Section 28.1

1. The heat of mixing of the compounds was exothermic and caused excess vapor to form and over-pressurize the storage tank.

2. Evolution of heat of mixing vaporized water, and drove some of the solution out of the tank.

Section 28.2

1. The accident is an example of the heat of mixing. The tank contained water condensate.

2. The concentrated NaOH and the weaker NaOH solutions mixed on breaking of the crust, releasing energy.

Section 29.1

1. Advertisers and even some heating engineers appear to overlook latent heat of vaporization. The evaporation of 10 gallons of water a day (modest for the humidification of most houses) requires more than 80,000 Btu equivalent to the consumption of about 80 cubic feet of natural gas per day. This is approximately 10 percent of the natural gas needed to heat a modest home on an average winter day. It makes no difference if humidification is accomplished merely by placing pans of water on radiators. Unless condensation of water vapor releases energy to the house, it doesn’t appear as if you could save energy overall by turning down the thermostat 4°F.

Section 29.3

1. Evaporative cooling is an excellent technology for low-cost cooling and works best in desert areas. In a swamp, the humidity is so high that little water evaporates, and, in addition, the humidity of the exit air is so high that conditions are uncomfortable for people.

2. (a) Salt build up in the circulating water; (b) scaling on the slats; (c) carry-out of salty vapor onto surrounding surfaces by the wind (drift)

Chapter 30

1. No. The solution method will have to be different than for continuous variables.

2. Variables associated with any other properties such as charge (changes have to be balanced), electrical and magnetic properties, etc.
Chapter 32

1. The equations for the time to drain each tank are:

   **Vertical cylinder**
   \[ t = \frac{2b^2 \sqrt{g}}{6CA_0 \sqrt{g}} \]
   **Cone**
   \[ t = \frac{2b^2 \theta h}{5CA_0 \sqrt{g}} \]

   **Horizontal cylinder**
   \[ t = \frac{5L(D^2 - (D - h)^2)^{3/2}}{3CA_0 \sqrt{g}} \]
   **Sphere**
   \[ t = \frac{5h\sqrt{h(D - 2h)}}{3CA_0 \sqrt{g}} \]

   where:
   - \( A_o \) = orifice area, \( \text{ft}^2 \)
   - \( g \) = 32.2 \( \text{ft/s}^2 \)
   - \( C_d = 0.61 \) for sharp-edged orifice
   - \( C_d = 0.80 \) for short, flush-mounted tube
   - \( C_d = 0.96 \) for rounded orifice
   - \( \theta \) = time to empty, \( \text{s} \)

   Assume the orifice coefficient is constant. Pick an orifice area, \( D, \theta, h, L, \) and \( C_d \) so that tanks are compatible (let \( h \) and \( D \) be the same). Then calculate \( t \).

2. Refer to Problem No. 11 (p. 21) of the cited publication for the detailed information for instructors and the solution.