Problems Related to Part 2

Single Unit, Non-Reactive Systems

1. Each year 50,000 people move into a city, 75,000 people move out, 22,000 are born, and 19,000 die. Write a balance on the population of the city.

2. One thousand kg/hr of feed mixture of benzene and toluene that contains 50% benzene by mass are separated by distillation into two fractions. The mass flow rate of benzene in the top output stream (referred to as overhead stream) is 450 kg B/hr, and that of toluene in the bottom output stream (referred to as bottoms) is 475 kg T/hr. The operation is at steady state. Write balances on benzene and toluene to calculate the unknown component flow rates in the output streams.

3. Two methanol–water mixtures are contained in separate flasks. The first mixture contains 40 wt-% methanol, and the second contains 70 wt-% methanol. If 200 g of the first mixture are combined with 150 g of the second, what are (a.) the mass, and (b.) composition of the product?

4. An experiment on the growth rate of certain organisms requires the establishment of an environment of humid air that is enriched in oxygen. Three input streams (A, B, and C) are fed into an evaporation chamber to produce an output stream with the desired composition.
   - A = Liquid water, fed at a rate of 20 cm³/min.
   - B = Air (21 mole-% oxygen, the balance N₂)
   - C = Pure oxygen, with a molar flow rate one fifth of the molar flow rate of stream B.

   The output is analyzed and found to contain 1.5 mole-% water. Draw and label a flow chart of the process, and calculate all unknown stream variables (moles/min & mole fraction).

5. An aqueous solution of sodium hydroxide contains 20 mass-% NaOH. It is desired to produce an 8 mass-% NaOH solution by diluting a stream of the 20 mass-% solution with a stream of pure water.
   (a.) Calculate the ratios (g pure water fed / g solution fed) and (g product solution/g feed solution).
   (b.) Determine the feed rates of 20 % solution and diluting water needed to produce 2310 lb/hr of the 8 % solution.

6. Water enters a 2 litre tank at a rate of 200 g/min, and is withdrawn at a rate of 5 g/s. The tank is initially half full.
   (a.) Is this process continuous, batch, or semibatch? Is it transient or steady state?
   (b.) Write a mass balance for this process. Identify the terms of the general balance equation that are present in your equation, and state the reason for omitting any terms not present.
   (c.) How long will it take the tank to drain completely?

7. One hundred pounds per minute of a mixture containing 60 % oil and 40 % water by mass are fed into a settler that operates at steady state. Two product streams emerge from the settler: The top one contains pure oil, and the bottom one is 90 mass-% water. Calculate the flow rates of the two product streams.
8. A liquid-phase chemical reaction \( A \rightarrow B \) takes place in a well-stirred tank. The concentration of \( A \) in the feed is \( C_{A0} \) (g-moles/cm\(^3\)), and that in the tank and the outlet stream is \( C_A \) (g-moles/cm\(^3\)). Neither concentration varies with time. The volume of the tank contents is \( V \) (cm\(^3\)) and the volumetric flow rate of the inlet and the outlet streams is \( Q \) (cm\(^3\)/s).

The rate at which \( A \) is consumed by the reaction in the tank is given by the expression
\[
r (\text{moles/s}) = kV C_A
\]
where \( k \) is the rate constant.
(a.) Is this process continuous, batch or semibatch? Transient or steady state?
(b.) Write a differential balance on \( A \) to derive the following relation between the inlet and outlet reactant concentrations:
\[
C_A = \frac{C_{A0}Q}{1 + kV/Q}
\]

9. A liquid mixture of benzene and toluene contains 50 mass-% benzene. A portion of the mixture is vaporized to yield a vapor containing 60 mass-% benzene and a residual liquid containing 37.5 mass-% benzene.
(a.) The process is carried out continuously and at steady state, with a mixture feed rate of 100 kg/hr. Let \( Q_v \) (kg/hr) and \( Q_l \) (kg/hr) be the flow rates of the vapor and liquid product streams. Write and solve balances to determine \( Q_v \) and \( Q_l \).
(b.) Reconsider the process, this time it is carried out in a closed container, which initially contains 100 kg of the liquid mixture. Let \( Q_v \) (kg) and \( Q_l \) (kg) be the masses of the vapor and liquid product phases. Write and solve integral balances on total mass and on benzene to determine \( Q_v \) and \( Q_l \).

10. For each of the situations described below, derive expressions for the unknown quantities indicated in terms of the given variables. The solution to (a.) is given as an example.
(a.) A flowing stream contains 40 mole-% benzene and the balance toluene. Derive expressions for the molar and mass flow rates of benzene in terms of the total molar flow rate \( Q \) (g-moles/s) of the stream.

\[\text{Solution: } q_{ben} = 0.4Q \text{ g-moles } C_6H_6/s = (0.4Q \text{ g-moles } C_6H_6/s) \times (78.1 \text{ g } C_6H_6/g \text{-mole } C_6H_6) = 31.2Q \text{ g } C_6H_6/s \]
(b.) A batch stream contains equal parts of CH\(_4\) and C\(_2\)H\(_4\) by mass. Derive an expression for the number of moles of methane in terms of the total mass \( Q \) (lb-moles) of the stream.
(c.) 100 kg/min of a stream contains substances \( A, B, \) and \( C \). Derive an expression for the mass flow rate of \( B \) in g/hr in terms of the mass fraction \( X_B \) (kg B/kg sol'n).
(d.) A continuous gas stream contains water and a gas that by itself contains 25 mole-% CO\(_2\), 5 % O\(_2\), and the balance N\(_2\). Derive expressions for the molar flow rate of CO\(_2\) and for the mole fractions of H\(_2\)O and CO\(_2\) in the gas in terms of \( Q_l \) (lb-moles H\(_2\)O/s) and \( Q_o \) lb-moles dry gas/s).
(e.) A batch stream contains NO, NO\(_2\), and N\(_2\)O\(_4\); the mole fraction of NO\(_2\) is 0.3. Derive an expression for the moles of N\(_2\)O\(_4\) in terms of \( Q \) (kg-moles total) and \( X \) (kg-mole NO/ kg-mole sol'n).
11. One hundred kilograms of a solid fuel are burned with air in a batch furnace. The products are analyzed, and the flow chart is drawn to summarize the results.
   (a.) Check the given values with a total mass balance.
   (If your test is successful it does not guarantee that the values are correct, but if it is not successful the values must be wrong.)
   (b.) Calculate the quantity (kg SO\textsubscript{2} produced)/(kg fuel fed to the furnace).

12. A distillation column operates as shown in the sketch to the right.
   (a.) How many independent material balances may be written for this system?
   (b.) How many stream flow rates must be specified before the others may be calculated?

13. Consider the flow chart below of an extraction process in which a solute (A) is transferred from one solvent (S) to another solvent (T) in which it is more soluble.
   (a.) What is the maximum number of independent material balances that can be written for this process?
   (b.) Calculate W, Q, and R, using the given feed as a basis and writing balances in an order such that you never have an equation that involves more than one unknown quantity.
   (c.) Calculate the difference between the amount of A in the feed solution and that in the 2 % A – 98 % S solution, and show that it equals the amount that leaves in the 20 % A – 80 % T solution.
   (d.) Calculate the ratio (g A in final Q solution/g A in feed solution).

14. Eggs are sorted into two sizes (large and extra large) at Cheerful Chickens, Inc. Unfortunately, business has not been good lately, and since Cheerful Chickens' 40-year-old egg sorting machine finally gave up the ghost, there have been no funds available to replace it. Instead, 80-year-old Fred Yokel, one of the firm's sharper-eyed employees, has been equipped with a “Large” rubber stamp in his right hand and an “X-large” stamp in his left, and is assigned to stamp each egg with the appropriate label as it goes by on the conveyor belt. Down the line, another employee (Loraine Quiche) puts the eggs into one of two hoppers, each egg according to its stamp. The system works reasonable well, all things considered, except that Old Fred has been working-out lately and has a heavy hand – on average he cracks 30 % of the 120 eggs that pass by him each minute. At the same time, a check of the “X-Large” stream reveals a flow rate of 70 eggs/min, of which 25 eggs/min are broken.
(a.) Draw and label a flow chart for this process.
(b.) Write and solve “total egg” and “cracked egg” balances for the sorter.
(c.) How many “large” eggs leave the Cheerful Chicken plant each minute?
(d.) What fraction of the “large” eggs are cracked?
(e.) Is Old Fred right or left handed?

15. Heavy naphtha A is mixed with heavy naphtha B.

\[ \text{Naphtha A} = 60 \text{ mass-\% C}_6 \text{ and } 40 \text{ mass-\% C}_4 \text{ hydrocarbons} \]
\[ \text{Naphtha B} = 50 \text{ mass-\% C}_6 \text{ and } 50 \text{ mass-\% C}_4 \text{ hydrocarbons} \]
If 200 kg A and 100 kg B are mixed per minute,

(a.) How many kg of product are produced per min?
(b.) What is the composition (mass-\%) of the product?

16. In #15 above, assume A and B are to be mixed to yield a product of 53 \% C_6 and 47 \% C_8 by mass. What ratio of flow rates of A and B are required?

17. One thousand kg/hr of a feed containing 50 mass-\% benzene (B) and 50 mass-\% toluene (T) are distilled. There are two output streams:

Distillate or overhead, 95 mass-\% B
Residue or bottoms, 512 kg/hr
Calculate:
(a.) Mass flowrate of B in residue.
(b.) Mass fraction of B in residue.
(c.) Mole fraction of B in residue.

18. A mixture containing 45 \% benzene (B) and 55 \% toluene (T) by mass is fed to a distillation column. An overhead stream of 95 wt-\% B is produced, and 8 \% of the benzene fed to the column leaves in the bottom stream. The feed rate is 2000 kg/hr. Determine the overhead flow rate and the mass flow rates of benzene and toluene in the bottom stream.

19. Rework #16 using a basis of 200 kg of entering A rather than 100 kg of mixture produced.

20. Rework #16 using as unknowns the amount of C_6 in A and in B rather than the total amounts of A & B.

21. A city needs a gas containing 45 mole-\% CH_4. Natural gas containing 90 mole-\% CH_4 and coal gas containing 30 mole-\% CH_4 are available for this purpose.

(a.) How many lb-moles of natural gas are required for each 100 lb-mole of coal gas?
(b.) How many lb-moles of natural gas are required per 1000 ft^3 of city gas produced?

22. How many moles of 100 percent C_6 hydrocarbons must be blended with a liquid containing 40 mole-\% C_6 and 60 mole-\% C_8 hydrocarbons to produce 100 moles of a liquid containing 60 mole-\% C_6?
23. A particular liquid fuel should contain 35 mole-% C\textsubscript{8} and 65 mole-% C\textsubscript{11} hydrocarbons. How much light oil containing 75 mole-% C\textsubscript{8} and 25 mole-% C\textsubscript{11} must be blended with a heavy oil containing 20 mole-% C\textsubscript{9} and 80 mole-% C\textsubscript{11} to produce 100 lb-moles of the desired product?

24. Referring to problem 23, how many pounds of light oil must be blended with heavy oil to produce 100 lb\textsubscript{m} of product?

25. To meet a certain octane number specification, it is necessary to produce a gasoline containing 80 wt-% iso-octane and 20 wt-% n-heptane. How many gallons of a high-octane gasoline containing 90 wt-% iso-octane and 10 wt-% n-heptane must be blended with a straight-run gasoline containing 65 wt-% iso-octane and 35 wt-% n-heptane to obtain 10 000 gal of the desired gasoline? The density of each of the liquids is 6.7 lb\textsubscript{m}/gal.

26. The feed to a continuous still (that is, distillation column) contains 20 mole-% C\textsubscript{6} and 80 mole-% C\textsubscript{11} hydrocarbons. The composition of the overhead distillate is pure C\textsubscript{6} hydrocarbon, and the still bottoms contain 5 mole-% C\textsubscript{6} and 95 mole-% C\textsubscript{11} hydrocarbons. How many moles of distillate are produced per 100 mole of feed to the still?

27. The feed to a distillation column contains 0.4 mole fraction C\textsubscript{6} and 0.6 mole fraction C\textsubscript{10} hydrocarbons. If the composition of the distillate is 0.6 mole fraction C\textsubscript{8} and 0.4 mole fraction C\textsubscript{10} and the composition of the bottoms is 0.3 mole fraction C\textsubscript{6} and 0.7 mole fraction C\textsubscript{10}, on the basis of 100 mole of feed, how many moles of distillate and bottoms are produced?

28. To improve its octane number, a natural gasoline is to be topped in a distillation column to produce a medium-octane gasoline. If the compositions of the natural feed, the overhead distillate, and the medium-octane bottoms are as indicated in the table below, how many litres of medium-octane gasoline can be produced from 50 000 bbl of natural gasoline? The density of each of these streams is 0.8 g/cm\textsuperscript{3}.

<table>
<thead>
<tr>
<th></th>
<th>Natural gasoline</th>
<th>Medium-octane gasoline</th>
<th>Overhead distillate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{6}H\textsubscript{14}</td>
<td>25</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>C\textsubscript{7}H\textsubscript{16}</td>
<td>25</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>C\textsubscript{8}H\textsubscript{18}</td>
<td>50</td>
<td>78</td>
<td>10</td>
</tr>
</tbody>
</table>

29. A liquid stream containing kerosene and lighter hydrocarbons is fed to a stripper, which removes the light hydrocarbons from the kerosene.

(a) If the stream enters the stripper at a rate of 18 000 bbl/hr and contains 58.3 wt-% kerosene and 41.7 wt-% light hydrocarbons, how much kerosene is produced if the stripper is 100 percent efficient in separating the two components (that is, pure light hydrocarbons leave the stripper as a vapor; pure kerosene leaves the stripper as a liquid)? The specific gravity of the side stream is 32°API.
(b.) Part (a.) represents an ideal situation, which is never met in practice. A more typical case is one in which pure kerosene is produced at the bottom of the stripper, and the vapors removed at the top contain 80 wt-% light hydrocarbons and 20 percent kerosene. Under these conditions, how much kerosene is produced?

30. A feed stream (see below) is split by distillation into three product streams: an overhead fraction, a middle cut, and a residue. It is known that the overhead fraction contains 50 percent of the \( \text{C}_8 \) hydrocarbons entering the still in the feed. If the compositions of the various streams are as indicated below, on the basis of 100 moles of the feed, how many moles of each of the product streams are produced?

<table>
<thead>
<tr>
<th></th>
<th>Feed</th>
<th>Overhead</th>
<th>Middle Cut</th>
<th>Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mole-%</td>
<td></td>
<td>mole-%</td>
<td></td>
</tr>
<tr>
<td>( \text{C}_8 )</td>
<td>30</td>
<td>51.6</td>
<td>30</td>
<td>14.6</td>
</tr>
<tr>
<td>( \text{C}_{10} )</td>
<td>70</td>
<td>48.4</td>
<td>70</td>
<td>85.4</td>
</tr>
</tbody>
</table>

31. Commercial gasoline is usually a blend of several types of intermediate products: straight-run gasoline, catalytically cracked gasoline, reformed gasoline, and alkylate. All these materials contain substantial amounts of propane, butane, and pentane which, if left in the gasoline, would cause it to have a higher volatility than is desirable or necessary for safe and satisfactory performance in present-day automobiles. To adjust the composition of light hydrocarbons in gasoline the propane, butane, and pentane are removed. The composition of a particular blend of unstabilized gasoline is given below.

\[
\begin{array}{c|c|c|c|c}
\text{C}_3 & 4 \text{ mole-%} \\
\text{C}_4 & 7 \text{ mole-%} \\
\text{C}_5 & 10 \text{ mole-%} \\
\text{C}_6 & 18 \text{ mole-%} \\
\text{C}_7 & 28 \text{ mole-%} \\
\text{C}_8 & 33 \text{ mole-%} \\
\end{array}
\]

(a.) Suppose the stabilizer is operated so that all the \( \text{C}_3 \) and \( \text{C}_4 \) hydrocarbons appear in the distillate and all the \( \text{C}_6, \text{C}_7, \) and \( \text{C}_8 \) hydrocarbons in the residue, and so that half of the hydrocarbons appear in the distillate and half in the residue. What is the composition of the distillate and residue streams? On the basis of 100 mole of feed, how many moles of distillate and residue are produced?

(b.) In winter it is necessary to have 9 mole-% pentane in the stabilized gasoline for easy starting. If the feed composition and conditions with respect to the \( \text{C}_3, \text{C}_4, \text{C}_6, \text{C}_7, \) and \( \text{C}_8 \) hydrocarbons are the same as in (a.) but the pentane in the stabilized gasoline is 9 mole-%, on the basis of 100 moles of feed, how many moles of stabilized gasoline are produced?

(c.) The government specification for a particular type of airplane gasoline indicates that its composition should be

\[
\begin{array}{c|c|c|c}
\text{C}_4 & 2 \text{ mole-%} \\
\text{C}_5 & 6 \text{ mole-%} \\
\text{C}_6 & 15 \text{ mole-%} \\
\end{array}
\]

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\[C_7 \quad 31 \text{ mole-%} \]
\[C_8 \quad 46 \text{ mole-%} \]

The stabilizer is operated so that all the \(C_8\) hydrocarbons appear in the residue. If the composition of the feed is as given (a.) above, on the basis of the 100 moles of feed, how many moles of airplane fuel will be produced?

(d.) In producing the gasoline for the specification in (c.) above, it was found necessary to operate the stabilizer in such a way that the composition of \(C_8\) hydrocarbons in the distillate was 4 mole-\%. On the basis of 100 moles of feed, how much airplane gasoline was produced under these conditions?

32. You need 1250 kg of a solution containing 12 wt-% ethyl alcohol in water. Two storage tanks are available, the first of which contains 5 wt-% ethanol in water and the second of which contains 25 wt-% ethanol in water. How much of each solution should you weigh out?

33. Strawberries contain about 15 wt-% solids and 85 wt-% water. To make strawberry jam, crushed strawberries and sugar are mixed in 45:55 ratio, and the mixture is heated to evaporate water until the residue contains one third water. How many pounds of strawberries are needed to make a pound of jam?

34. A paint mixture containing 25 wt-% of a pigment and the balance water sells for $6.00/kg, and a mixture containing 10 % pigment sells for $3.50/kg. If a paint retailer produces a blend containing 15 % pigment, for how much should he sell it ($/kg) to make a 10% profit.

35. Liquid water and air flow into a humidification chamber, in which the water evaporates completely, the entering air contains 1 mole-% \(H_2O(v)\), 20.8 % \(O_2\), and the balance \(N_2\), and the humidified air contains 10.0 mole-% \(H_2O(v)\). Calculate the volumetric flow rate (ft\(^3\)/min) of liquid required to humidify 200 lb-moles/min of the entering air.

36. A gas containing equal parts (on a molar basis) of \(H_2\), \(N_2\), and \(H_2O\) is passed through a column of calcium chloride pellets, which absorb 97 % of the water and none of the other gases. The column packing was initially dry, and has a mass of 2 kg. Following six hours of continuous operation, the pellets are re-weighed and found to have a mass of 2.21 kg. Calculate the molar flow rate (moles/hr) of the feed gas and the mole fraction of water vapor in the product gas.

37. Fifty millilitres/min of a 10 molar aqueous solution of NaOH (SG = 1.37) are mixed with 4 litres/hr of a 5 molar aqueous solution of NaOH (SG = 1.18). What is the composition of the final mixture in terms of mass fractions and mole fractions?

38. The house special at Oswald's Oasis is a mixture containing 75 mass-% \(C_2H_5OH\) and the balance water. The cost of alcohol has been increasing and Oswald has decided that perhaps a 60 mass-% blend would be just as effective. He has on hand a vat containing 300 gallons of the 75 % mixture (SG = 0.877), and can purchase any desired amount of a 40 % mixture (SG = 0.952). Determine (a) how many gallons of the 40 % mixture must he buy and (b) how much will it cost him if the 40 % mixture costs $1.00/litre?
39. A dilute aqueous solution of H$_2$SO$_4$ (solution A) is to be concentrated with a solution containing 90 mass-
% H$_2$SO$_4$ (solution B) to produce a 75 % solution (solution C). The flow rate and concentration of
solution A change periodically, so that it is necessary to adjust the flow rate of solution B to keep the
product concentration constant. Flowmeters A and B have linear calibration plots of mass flow rate ($q$)
versus meter reading ($R$), which pass through the following points:
Flow meter A: $q_a = 150$ lb/hr corresponds to a reading of $R_a = 20$
$q_a = 500$ lb/hr corresponds to a reading of $R_a = 60$
Flow meter B: $q_b = 200$ lb/hr corresponds to a reading of $R_b = 20$
$q_b = 800$ lb/hr corresponds to a reading of $R_b = 60$

The analyzer calibration is a straight line when % H$_2$SO$_4$ (assigned the symbol $\Theta$ below) is plotted
on a logarithmic scale versus meter reading ($R_o$) on a linear scale. The line passes through the points ($\Theta = 20$, $R_o = 3.0$) and ($\Theta = 100\%$, $R_o = 10.0$).
(a.) Calculate the flow rate of solution B needed to concentrate 300 lb/hr of 55 % H$_2$SO$_4$ solution (that
is, solution A), and the resulting flow rate of solution C. (The calibration data are not needed for
this part).
(b.) Derive the calibration equations for $q_A(R_A)$, $q_B(R_B)$, and $q_o(R_o)$. Calculate the value of $R_A$, $R_B$, and
$R_o$ corresponding to the flow rates and concentrations of part (a).
(c.) The process technician's job is to read flowmeter A and the analyzer periodically and then to adjust
the flow rate of solution B to its required value. Derive a formula that the technician can use for $R_o$
in terms of $R_A$ and $R_o$ and check it by substituting the values of part (b).

40. A gas (A) contains 85 mole-% CH$_4$, 10 % C$_2$H$_6$, and 5 % C$_3$H$_8$; a second gas (B) contains 89 mole-% C$_4$H$_8$
and 11 % C$_4$H$_{10}$; and a third gas (C) contains 94 mole-% C$_4$H$_{10}$ and 6 % CH$_4$. How many moles of A, B,
and C must be mixed to produce 100 moles of a blend containing equal parts of CH$_4$, C$_2$H$_6$, and C$_3$H$_8$?

41. Wet sugar that contains 20 wt-% water is sent through a dryer in which 75 % of the water is removed.
(a.) Taking a basis of 100 kg feed, calculate the mass fraction of sugar in the product that leaves the
dryer.
(b.) Calculate the ratio (kg removed/kg wet sugar leaving the dryer).
(c.) If 1000 tons/day of wet sugar are fed to the dryer; how much additional water must be removed
from the outlet sugar to dry it completely, and how much revenue can be expected if dry sugar sells
for $0.25/lb$?

42. You have an acid containing 30 mole-% H$_3$PO$_4$ in water and you wish to bring the acid strength to 75 %
H$_3$PO$_4$ by adding concentrated acid (90 % H$_3$PO$_4$, 5 % H$_2$SO$_4$, and 5 % H$_2$O). You start with 1000 kg of
the dilute acid in a large tank and add concentrated acid at a rate of 100 kg/min, how long will it take
(minutes) to bring the acid to the desired strength? What will be the final molar analysis (mole-%) and
weight (kg)?

43. A mixture of methane and air (79 mole-% N$_2$ and 21 % O$_2$) is capable of igniting spontaneously only if
the mole-% of methane is between 5 % and 15 %. A mixture containing 9 mole-% CH$_4$ in air flowing at a
rate of 700 kg/hr is to be diluted with an air stream to reduce the methane concentration to the lower
flammability limit. Calculate the required flow rate of the air stream in kg-moles/hr. (Hint: Since you are not concerned with the reaction, you can treat air as a single component).

44. A gas cylinder (cylinder A) contains 10 mole-% N$_2$ and 90 % H$_2$ and a second cylinder (cylinder B) contains 50 mole-% N$_2$ and H$_2$. Calculate the molar flow rates (lb-moles/min) of gases A and B required to produce 1000 lb$_m$/hr of a gas containing 25 mole-% N$_2$. (See hint following Problem 43).

45. Air (79 mole-% N$_2$ and 21 % O$_2$) flowing at 150 kg/min is to be enriched with pure oxygen to produce a gas to be used for oxygen therapy. The product gas must contain 40 mass-% O$_2$. Calculate:
(a.) The mass flow rate (kg/hr) of the pure O$_2$ feed.
(b.) In part (a) you should have calculated a mass flow rate for the product gas. If that corresponds to a volumetric flow rate of 2.5 m$^3$/s, what is the density (kg/m$^3$) of the product gas.

46. The feed to a combustion reactor is to contain 8 mole-% CH$_4$. To produce this feed, a natural gas containing 85 wt-% CH$_4$ and 15 % C$_2$H$_6$ is mixed with air (79 mole-% N$_2$ and 21 % O$_2$). Calculate the ratio (moles natural gas/mole air).

47. An artificial kidney or dialyzer is a device that removes water and waste metabolites from blood. In one such device, the blood flows from an artery through the insides of hollow fibers, and dialyzing fluid, which consists of water and various dissolved salts, flows on the outside of the fibers. Water and waste metabolites — principally urea, creatinine, uric acid, and phosphate ions — pass through the fiber walls into the dialyzing fluid, and the purified blood is returned to a vein. At some time during a dialyzation to the arterial and venous blood conditions are as follows:

<table>
<thead>
<tr>
<th>Arterial (Entering) Blood</th>
<th>Venous (Exiting) Blood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (ml/min)</td>
<td>150.0</td>
</tr>
<tr>
<td>Urea (H$_2$NCONH$_2$)</td>
<td>1.90</td>
</tr>
</tbody>
</table>

(a.) Calculate the rates at which urea and water are being removed from the blood.
(b.) If the dialyzing fluid enters at a rate of 1500 ml/min, calculate the concentration of urea in the exiting dialysate. (Neglect the urea volume).
(c.) Suppose we want to reduce the patient's urea level from an initial value of 2.7 mg/ml to a final value of 1.1 mg/ml. If the total blood volume is 5 litres and the average rate of urea removal is that calculated in (a.), how long must the patient be dialyzed? (Neglect the loss in total blood volume due to the removal of water in the dialyzer).

48. In a tannery, mangrove bark is extracted by treating the finely ground wood with hot water. The original bark contains 4 % moisture, 37 % tannin, and 23 % soluble non-tannin material by weight. The residue (spent bark) removed form the extraction tanks contains 62 wt-% moisture, 2.8 % tannin, and 0.9 %
soluble non-tannin material. What percentage of the tannin in the original bark remains un-extracted in the residue?

49. The liquid feed rate to a reboiler is 115 kg/hr, of which 75 % is to be vaporized. Chlorobenzene (CB) is the most volatile component of the feed, and it is anticipated that the mass fraction in the vapor product stream will be 3.5 times that in the liquid product, \( X_{CB} \). Calculate the ratio of \( X_{CB} \) to the mass fraction of CB in the feed.

50. An evaporator is fed continuously with 25 tons/hr of a solution that contains 10 % NaCl, 10 % NaOH, and 80 % \( \text{H}_2\text{O} \) by mass. During the evaporation process, water is boiled away from the solution and NaCl crystallizes and is filtered out of the remaining liquor. The concentrated liquor leaving the evaporator contains 50 % NaOH, 2 % NaCl, and 48 % water by mass. Calculate:
   (a.) the pounds of water evaporated per hour
   (b.) the pounds of salt precipitated per hour
   (c.) the pounds of concentrated liquor that leave the evaporator each hour.

51. A gas entering an absorber contains 15.0 mole-% \( \text{CS}_2 \), 17.8 % \( \text{O}_2 \), and 67.2 % \( \text{H}_2 \). Most of the \( \text{CS}_2 \) is absorbed in liquid benzene fed to the top of the tower. Some of the benzene entering as liquid evaporates and leaves the top of the column as vapor. If the gas leaving the absorber contains 2 % \( \text{CS}_2 \) and 2 % benzene, what fraction of the \( \text{CS}_2 \) is recovered?

52. Pipes through which process materials are transported in industrial plants are often several feet in diameter, making such flow-metering devices as rotameters and orifice meters difficult or impossible to use. A technique to measure flow rates in such pipes is the indicator dilution method, in which a continuous stream of an easily measured substance (the tracer) is injected into the process stream at a known rate, and the concentration of the tracer downstream of the injection point is measured. The larger flow rate of the process stream, the lower the concentration of the tracer at the measurement point.

A stream of natural gas that contains 1 mole-% \( \text{CO}_2 \) and the balance methane flows through a pipeline. Fifty kilograms of \( \text{CO}_2 \) per minute are injected into the line and a sample of gas downstream of this point is found to contain 1.7 mole-% \( \text{CO}_2 \). Calculate the molar flow rate of the natural gas.

53. A variation of the indicator dilution technique described in Problem 52 is used to measure total blood volume. A known amount of a tracer is injected into the bloodstream and disperses uniformly throughout the circulatory system. A blood sample is then withdrawn, the tracer concentration in the sample is measured, and the measured concentration (which equals (tracer injected)/(total blood volume) if no tracer is lost through blood vessel walls) is used to determine the total blood volume.

In one such experiment, 0.6 cm³ of a solution containing 5 mg/litre of a dye is injected into an artery of a man. About 10 min later, after the tracer has had time to distribute itself uniformly throughout the bloodstream, a blood sample is withdrawn and placed in the sample chamber of spectrophotometer. A beam of light passes through the chamber, and the spectrophotometer measures the intensity of the transmitted beam and displays the value of the solution absorbance (a quantity that increases with the amount of light absorbed by the sample). The value displayed is 0.18. A calibration curve of absorbance
(A) versus tracer concentration (C) (micrograms dye/litre blood) is a straight line through the origin and the point \((A = 0.9, \ C = 3 \ \text{g/litre})\). Estimate the patient's total blood volume from these data.

**Stoichiometry**

54. Calculate the following quantities for the reaction in which ammonia \((\text{NH}_3)\) is formed from its atomic constituents:
   (a.) The stoichiometric coefficients of the reactants and products.
   (b.) The stoichiometric ratio of \(\text{N}_2\) to \(\text{H}_2\)
   (c.) \((\text{moles NH}_3 \ \text{produced})/(\text{mole H}_2 \ \text{reacted})\).
   (d.) \((\text{lb H}_2 \ \text{reacted})/(\text{lb-mole NH}_3 \ \text{produced})\)
   (e.) The kg-moles of \(\text{N}_2\) and \(\text{H}_2\) that must react to form 150 kg-moles of \(\text{NH}_3\).
   (f.) The \(\text{lb}_m\) \(\text{NH}_3\) produced if 20.00 \(\text{lb}_m\) of \(\text{H}_2\) react completely.
   (g.) The \(\text{lb}_m\) \(\text{NH}_3\) produced if 20.00 \(\text{lb}_m\) of \(\text{N}_2\) is completely consumed.

55. Acetylene can be manufactured in the reaction between calcium carbide and water.

\[
\text{CaC}_2 + 2\text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{C}_2\text{H}_2
\]

State the following quantities:
   (a.) The stoichiometric coefficients of all reactants and products.
   (b.) \((\text{lb-moles H}_2\text{O consumed})/(\text{lb-mole C}_2\text{H}_2 \ \text{produced})\).
   (c.) The moles \(\text{CaC}_2\) and \(\text{H}_2\text{O}\) required to produce 100 moles of \(\text{C}_2\text{H}_2\).
   (d.) The consumption rate of \(\text{H}_2\text{O}\) (kg/hr) corresponding to a production rate of 20 000 kg \(\text{C}_2\text{H}_2/\text{day}\).

56. CO is reacted with \(\text{O}_2\) to form \(\text{CO}_2\). 100 lb-moles of each are fed.
   (a.) Determine which is the limiting reactant?
   (b.) Calculate %-excess of the other.

57. Benzene reacts with chlorine to form chlorobenzene and hydrogen chloride in a batch reactor: 120 kg of benzene and 20% excess chlorine are present initially, and 30 kg benzene remain when the reaction is quenched.
   (a.) How many kg of chlorine are present initially?
   (b.) What is the fractional conversion of benzene?
   (c.) What is the molar composition of the product?

58. Ethane may be dehydrogenated to form acetylene in the reaction

\[
\text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_2 + 2\text{H}_2
\]

If 100 lb-moles of ethane are charged to a batch reactor, and a fractional conversion of 75% is achieved, calculate the following properties of the final product gas.
   (a.) Total moles.
   (b.) Mole ratio of acetylene to hydrogen.
   (c.) Average molecular weight.
   (d.) Mass fraction of acetylene.
59. Acetylene can be converted to acetaldehyde by the hydrogen reaction

\[ \text{CH}=\text{CH} + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{CHO} \]

If 10 lb\textsubscript{m} of acetylene and 30 lb\textsubscript{m} of water are fed to a reactor
(a.) Which reactant is the limiting reactant?
(b.) What is the percent excess of the other?

60. 5 kg of methanol and 3 kg of ammonia are reacted to form ethylamine by the reaction

\[ \text{CH}_3\text{OH} + \text{NH}_3 \rightarrow \text{CH}_2\text{NH}_2 + \text{H}_2\text{O} \]

(a.) Which reactant is the limiting reactant?
(b.) What is the percent excess of the other?
(c.) Answer (a.) and (b.) above when dimethylamine is formed by the reaction

\[ 2\text{CH}_3\text{OH} + \text{NH}_3 \rightarrow (\text{CH}_3)_2\text{NH} + 2\text{H}_2\text{O} \]

61. Determine which of the reactants is the limiting reactant and their percent excess of the other in the following situations:
(a.) 50 tons of Fe\textsubscript{2}O\textsubscript{3} and 10\textsuperscript{6} ft\textsuperscript{3} of CO to form Fe\textsubscript{3}O\textsubscript{4} & CO\textsubscript{2}.
(b.) Same reactants as in (a.) above, but to form FeO & CO\textsubscript{2}.
(c.) 80 kg of TiCl\textsubscript{4} and 10 kg of Mg to form Ti & MgCl\textsubscript{2}.
(d.) 100 lb\textsubscript{m} C\textsubscript{6}H\textsubscript{5}Cl, 60 lb\textsubscript{m} H\textsubscript{2}O, and 200 lb\textsubscript{m} Na\textsubscript{2}CO\textsubscript{3} to form C\textsubscript{6}H\textsubscript{5}OH & NaCl & CO\textsubscript{2}.

62. Acrylonitrile is produced by the reaction of propylene, ammonia, and oxygen.

\[ 2\text{C}_2\text{H}_4 + 2\text{NH}_3 + 3\text{O}_2 \rightarrow 2\text{C}_2\text{H}_3\text{N} + 6\text{H}_2\text{O} \]

The feed contains 10 mole-% propylene, 12 % ammonia, and 78 % air.
(a.) Which reactant is limiting?
(b.) By what percentage are the others in excess?
(c.) Calculate the kg-moles of C\textsubscript{2}H\textsubscript{3}N produced per kg-mole of NH\textsubscript{3} fed for a 30% conversion of the limiting reactant.

63. The reactions \text{C}_2\text{H}_4 \rightarrow \text{C}_2\text{H}_6 + \text{H}_2 \quad \& \quad \text{C}_2\text{H}_6 + \text{H}_2 \rightarrow 2\text{CH}_4 \quad \text{take place in a continuous reactor at steady state.} \quad \text{The molar flow rate of the feed stream is 100 kg-moles/hr and that of the product stream is 140 kg-moles/hr. The compositions of these gases are given below:}

<table>
<thead>
<tr>
<th>Feed</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{C}_2\text{H}_6</td>
<td>85.0</td>
</tr>
<tr>
<td>Inerts</td>
<td>15.0</td>
</tr>
<tr>
<td>\text{H}_2</td>
<td>26.8</td>
</tr>
<tr>
<td>\text{Inerts}</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Calculate the fractional conversion of ethane, the yield of the desired product C\textsubscript{2}H\textsubscript{4}, and the efficiency.

\textbf{Combustion}
64. A gas has the mass-% composition shown below. Calculate the molar composition on a wet basis and on a dry-basis.

<table>
<thead>
<tr>
<th>Gas</th>
<th>CH₄</th>
<th>C₂H₄</th>
<th>CO₂</th>
<th>N₂</th>
<th>H₂O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass-%</td>
<td>5</td>
<td>2</td>
<td>10</td>
<td>65</td>
<td>18</td>
<td>100</td>
</tr>
</tbody>
</table>

65. Three litres of n-hexane (C₆H₁₄) and 4 litres of n-heptane (C₇H₁₆) are burned with 60% excess air. How many moles of air are fed to the reactor?

66. One hundred moles per hour of butane (C₄H₁₀) and 5000 moles per hour of air are fed into a combustion reactor. Calculate the percent excess air.

67. 120 lb-moles of C₂H₆ are fed to a combustion furnace along with 4284 lb-moles of air. Calculate the percent excess air supplied.

68. A natural gas contains 85 mole-% methane and the balance ethane. If 100 kg-moles/hr of this fuel are to be burned with 125% excess air, what is required air feed rate?

**Single Unit, Reactive Systems**

69. Methane is burned with oxygen to yield carbon dioxide with water. 150 kg-moles/hr of a feed stream consisting of 20 mole-% CH₄, 60 % O₂, and 20 % CO₂ are fed into a reactor, in which a conversion of 90% of the limiting reactant is obtained. Calculate the molar composition (mole-%) of the product stream.

70. In a cat-cracker, many unknown reactions reduce long chain hydrocarbons to short chain hydrocarbons. Feed (F) and product (P) compositions are those given below. Use an H balance to calculate the number of moles of P per 100 moles of F.

<table>
<thead>
<tr>
<th></th>
<th>mole-% in F</th>
<th>mole-% in P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₄H₁₀</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>C₅H₁₄</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>C₆H₁₆</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>C₇H₂₄</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>C₈H₁₈</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>C₉H₂₆</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>C₁₀H₄₀</td>
<td>35</td>
<td>15</td>
</tr>
</tbody>
</table>


72. Rework #70 using a basis of 100 moles of product rather than 100 moles of feed.

73. Ethane is chlorinated
\[ \text{C}_2\text{H}_6 + \text{Cl}_2 \rightarrow \text{C}_2\text{H}_5\text{Cl} + \text{HCl} \]

Some of the desired product, mono-chloroethane, is further chlorinated to produce the undesired \( \text{C}_2\text{H}_4\text{Cl}_2 \):

\[ \text{C}_2\text{H}_4\text{Cl} + \text{Cl}_2 \rightarrow \text{C}_2\text{H}_4\text{Cl}_2 + \text{HCl} \]

All \( \text{Cl}_2 \) fed is consumed. Conversion of ethane is 13%. Ratio of \( P_{\text{in}} / P_{\text{out}} = 93/7 \). Calculate moles of all species in the product per 100 moles of \( \text{C}_2\text{H}_5\text{Cl} \) output and % excess ethane.

74. The reaction \( \text{C}_2\text{H}_4 + \text{HBr} \rightarrow \text{C}_2\text{H}_4\text{Br} \) is carried out in a continuous reactor. The product stream is analyzed, and is found to contain 50 mole-% \( \text{C}_2\text{H}_4\text{Br} \), 16.7 mole-% \( \text{C}_2\text{H}_4 \), and 33.3 mole-% \( \text{HBr} \). The feed to the reactor contains only \( \text{C}_2\text{H}_4 \) and \( \text{HBr} \). Calculate the conversion of the limiting reactant and the percentage by which the other reactant is in excess.

75. In the Deacon process for the manufacture of chlorine, \( \text{HCl} \) and \( \text{O}_2 \) react to form \( \text{Cl}_2 \) and \( \text{H}_2\text{O} \). Sufficient air is fed to the reactor to provide 20 % excess oxygen, and the conversion of \( \text{HCl} \) is 70%. Calculate:
   (a.) The molar composition of the product stream.
   (b.) The mole fraction of \( \text{Cl}_2 \) in the gas that would remain if all of the water in the product was condensed.

76. An industrial plant carries out the reaction between methanol and oxygen to form formaldehyde and water. It produces five million kilograms of formaldehyde per year, operating 350 days per year, 24 hours per day. The oxygen fed to the reactor is 25% in excess of the amount theoretically required to react with the methanol feed, and the overall conversion of methanol is 95%. Calculate the required feed rate of oxygen in kg/hr.

77. Ethanol (the desired product) is produced commercially by the hydration of ethylene:

\[ \text{C}_2\text{H}_4 + \text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_5\text{OH} \]

Some of the product is converted to the undesired product diethyl ether by the side reaction

\[ \text{C}_2\text{H}_5\text{OH} \rightarrow (\text{C}_2\text{H}_5)_2\text{O} + \text{H}_2\text{O} \]

The feed to a reactor contains 53.7 mole-% \( \text{C}_2\text{H}_4 \), 36.7 % \( \text{H}_2\text{O} \), and the balance is non-reactive inert gases. These intert gases do not react as they pass through the reactor. An ethylene conversion of 5% and an efficiency as defined in your class notes of 90% are achieved. Balance the chemical reactions and calculate the molar composition (mole-%) of the reactor output stream, and the selectivity.

78. In the presence of hydrogen and a special platinum catalyst it is possible to crack high-molecular-weight saturated hydrocarbons to low-molecular-weight saturated products. The input and output compositions of hydrocarbons from a certain hydrogen cracker are:

<table>
<thead>
<tr>
<th></th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{C}<em>4\text{H}</em>{12} )</td>
<td>—</td>
<td>10 mole-%</td>
</tr>
<tr>
<td>( \text{C}<em>6\text{H}</em>{14} )</td>
<td>—</td>
<td>40 mole-%</td>
</tr>
<tr>
<td>( \text{C}<em>7\text{H}</em>{16} )</td>
<td>—</td>
<td>20 mole-%</td>
</tr>
<tr>
<td>( \text{C}<em>{12}\text{H}</em>{26} )</td>
<td>100 mole-%</td>
<td>30 mole-%</td>
</tr>
</tbody>
</table>

(a.) How many kg-mole of product are produced per 100 kg-mole of hydrocarbon fed?
(b.) How many kg-mole of hydrogen are consumed per 100 kg-mole of hydrocarbon fed?
(c.) If the specific gravity of the hydrocarbon feed is 0.9 and that of the product is 0.8, how many litres of hydrocarbon feed will be required to produce 10,000 litres of product.

79. Natural gas, which is essentially pure methane, is being used to fire a tube-still furnace. An analysis of the flue gas indicates the following composition of a dry basis:

\[ 86.6 \text{ mole-% } N_2, 3.8 \text{ mole-% } O_2, 9.6 \text{ mole-% } CO_2 \]

(a.) Calculate the molar ratio of natural gas to air fed to the furnace.
(b.) Suppose that the only information available for this problem was that the oxygen content of the flue gas is 6.2 percent on a dry basis and that there is no CH₄ in the stack gas. Under these conditions what is the molar ratio of natural gas to air fed to the furnace.

80. Acetylene can be produced by cracking hydrocarbons such as methane or butane. A recent patent for the production of acetylene by cracking butane, C₄H₁₀, at 1300°C gives the following composition of gases leaving the reactor:

\[ 29 \text{ mole-% } CH_4, 22 \text{ mole-% } C_2H_4, 12 \text{ mole-% } C_2H_2 \]

If hydrogen makes up the balance of the reaction products, does the analysis as indicated in the patent seem reasonable?

81. In the Fischer-Tropsch process carbon monoxide and hydrogen are reacted over an iron–chromium catalyst to form synthetic hydrocarbons. How much carbon monoxide and hydrogen are required to produce 1 gal of an equimolar mixture of heptane (C₇H₁₆) and octane (C₈H₁₈)? The density of the mixture if 6.6 lb/gal. Assume all CO & H₂ are converted. Water is a by-product.

82. Coal can be converted into a liquid hydrocarbon by treatment with hydrogen at high pressure in the presence of an iron oxide–chromium oxide catalyst. The elemental analysis of a certain lot of coal is 80 wt-% carbon, 5.5 wt-% hydrogen, 7 wt-% oxygen, 5.5 wt-% ash, and 2 wt-% sulfur. How many kilograms of this coal and how many standard cubic metres of hydrogen are required to produce 10 million bbl of C₃₋₅H₂₆? The specific gravity of this hydrocarbon is 0.94. Assume that sulfur appears in the output as hydrogen sulfide and oxygen as water.

83. When ethane is cracked to form ethylene, side reactions take place that produce methane, free carbon, and hydrogen. Pure ethane was fed to a converter, and the product was found to be 0.33 mole fraction CH₄, C₂H₄, and C₂H₆. No analytic technique was available for determination of the free carbon produced or the amount of hydrogen in the gas mixture. On the basis of 100 moles of ethane entering the reactor, how many moles of ethylene were produced?

84. An alkylation process depends on the fact that the branched carbon atom of an iso-paraffin is particularly reactive and, in the presence of certain acid-type catalysts, compounds such as isobutane undergo an addition reaction with olefins such as propylene, butylene, or amylene to form saturated, branched-chain hydrocarbons in the range C₈ to C₁₀. These products are of particular importance to the petroleum industry, as they can be blended with various types of gasoline to increase the octane number.
During the testing of a certain alkylation unit, samples were taken from the iso-butane input stream, the olefin input stream, and the product stream of the reactor. These samples were analyzed in a gas chromatograph, and the following results obtained:

<table>
<thead>
<tr>
<th>Stream</th>
<th>C₂H₁₀</th>
<th>mole-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isobutane</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>Olefin Stream</td>
<td>35.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>Product Stream</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂H₆</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>C₂H₈</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>C₂H₁₀</td>
<td>80.9</td>
<td></td>
</tr>
<tr>
<td>C₂H₁₂</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>C₂H₁₆</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>C₂H₁₈</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>C₂H₂₀</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

Based on these data, what were the relative amounts of the three streams?

85. Sulfur is one of the most undesirable impurities in hydrocarbon products. It is usually present as organic sulfur compounds called mercaptans (compounds which contain the functional group SH; such as, propyl mercaptan, CH₃–CH₂–CH₂–SH). These mercaptans may be eliminated by reacting them with hydrogen in the presence of cobalt–molybdenum catalyst at temperature of 700°F and a pressure of 450 psia. A typical example of such a reaction is

\[
\text{C}_\text{11}\text{H}_\text{2}_{3}\text{SH} + \text{H}_2 \rightarrow \text{C}_\text{11}\text{H}_{2_{4}} + \text{H}_2\text{S} \tag{1}
\]

The conditions of the reaction such that any unsaturated hydrocarbons present will also be hydrogenated by reactions such as

\[
\text{C}_{10}\text{H}_{2_{0}}=\text{CH}_2 + \text{H}_2 \rightarrow \text{C}_{11}\text{H}_{2_{4}} \tag{2}
\]

A flowsheet of a fuel oil desulfurization process is shown.

The flow rate of fuel oil (23°API) to the reactor is 1000 bbl/hr, and the flow rate of hydrogen is 380 000 ft³/hr measured at 1 atm and 60°F. Further, the composition of the fuel oil entering and leaving the reactor is

<table>
<thead>
<tr>
<th>Compound</th>
<th>Fuel Oil feed</th>
<th>Desulfurized fuel oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁₁H₂₃SH</td>
<td>5 mole-%</td>
<td>0.1 mole-%</td>
</tr>
<tr>
<td>C₁₁H₂₄</td>
<td>70 mole-%</td>
<td>96.8 mole-%</td>
</tr>
<tr>
<td>C₁₀H₂₀=CH₂</td>
<td>25 mole-%</td>
<td>3.1 mole-%</td>
</tr>
</tbody>
</table>

(a.) What is the composition of the gas leaving the separator?
(b.) What percent of the hydrogen entering the reactor is consumed by chemical reactions [that is, by reactions (1) and (2) combined]?
(c.) What percent of the hydrogen entering the reactor is consumed by the desulfurization reaction [that is, by reaction (1) alone]?

86. *Cracking* is a process in which high-molecular-weight hydrocarbons are broken down into lower-molecular-weight products by the effect of high temperature in the presence of an aluminum–silica catalyst. In fluid-bed catalytic cracking, the catalyst is present as a bed of fine particles that are agitated by the vaporized hydrocarbons as they pass through the bed. The catalyst mass behaves much like a liquid, and it is this condition that gives rise to the name *fluidized bed*. The composition of the combined feed (cracking stock and recycle oil) at point A and the composition of the products leaving the reactor at point B are as follows:

<table>
<thead>
<tr>
<th>Combined Feed at A</th>
<th>Reactor Product at B</th>
</tr>
</thead>
<tbody>
<tr>
<td>mole-%</td>
<td>mole-%</td>
</tr>
<tr>
<td>C₆H₁₄</td>
<td>0</td>
</tr>
<tr>
<td>C₇H₁₄</td>
<td>0</td>
</tr>
<tr>
<td>C₈H₁₈</td>
<td>3.1</td>
</tr>
<tr>
<td>C₁₁H₂₄</td>
<td>7.4</td>
</tr>
<tr>
<td>C₁₂H₂₄</td>
<td>15.7</td>
</tr>
<tr>
<td>C₁₅H₃₂</td>
<td>36.8</td>
</tr>
<tr>
<td>C₁₈H₃₆</td>
<td>36.8</td>
</tr>
</tbody>
</table>

(a.) Calculate the ratio of the number of moles of products leaving the reactor to the number of moles of combined feed entering the reactor.

(b.) If the reactor is operated with a combined feed rate of 2920 bbl/hr at 25°API gravity oil, how many moles of product will be produced?

(c.) If the *fractionator* produces three streams (as shown above) of the compositions given below, what amount of each of these is produced based on the feed rate given in (b)?

<table>
<thead>
<tr>
<th>Gasoline Stream</th>
<th>Oil Stream</th>
<th>Recycle Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>mole-%</td>
<td>mole-%</td>
<td>mole-%</td>
</tr>
<tr>
<td>C₆H₁₄</td>
<td>19.7</td>
<td>0.2</td>
</tr>
<tr>
<td>C₇H₁₄</td>
<td>40.0</td>
<td>11.8</td>
</tr>
<tr>
<td>C₈H₁₈</td>
<td>20.0</td>
<td>35.4</td>
</tr>
<tr>
<td>C₁₁H₂₄</td>
<td>20.0</td>
<td>35.0</td>
</tr>
<tr>
<td>C₁₂H₂₄</td>
<td>0</td>
<td>11.6</td>
</tr>
<tr>
<td>C₁₅H₃₂</td>
<td>0</td>
<td>4.7</td>
</tr>
<tr>
<td>C₁₈H₃₆</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

87. During the oxidation of naphthalene using air to form phthalic anhydride, it is found that the waste gas stream has an analysis of 12.6 mole-% O₂, 83.2 % N₂, and 4.2 % CO₂ on a dry basis. (Although any water produced during the oxidation would undoubtedly be present in the waste gas stream as water vapor, most
gas analysis techniques do not include water vapor). Assuming the oxidation of the naphthalene is 100 percent complete, what is the ratio of input air to naphthalene?

88. A mixture of hydrogen and methane is completely burned to its final products of combustion in a boiler using air. The analysis of the stack gas on a dry basis is 83.4 mole-% N₂, 11.3 % O₂, and 5.3 % CO₂
   (a.) What is the ratio of H₂ to CH₄ in the fuel?
   (b.) What is the ratio of fuel (H₂ + CH₄) to air?

89. If 1 mole of CH₄ is burned completely with 20 moles of air, what is the composition of the stack gas?

90. The mole-% analysis of the waste gas from a burner fueled with natural gas (essentially pure CH₄) is as follows: 75 % N₂, 10 % O₂, 5 % CO₂, 10 % H₂O. What is the ratio of moles air to moles of natural gas fed to the burner?

91. A mixture of H₂ and CH₄ is burned with air. The following is the analysis for the waste gas on a dry basis: 86.9 mole-% N₂, 4.35 mole-% O, 8.7 mole-% CO₂.
   (a.) What is the composition (mole-%) of the fuel mixture of H₂ and CH₄?
   (b.) What is the ratio of the fuel mixture to air?

92. One method for producing chlorobenzene is to react benzene, HCl, and air; the following reaction takes place:

   \[ C₆H₆ + HCl + \frac{1}{2} O₂ \rightarrow C₆H₅Cl + H₂O \]

After the waste gas from such a process has been scrubbed to remove any unreacted and benzene, and all the products, its composition is 88.8 mole-% N₂ and 11.2 mole-% O₂. Determine the number of moles of chlorobenzene produced per mole of air to the process.

93. By optimizing the composition of the catalyst for phthalic anhydride production, it is possible to eliminate the production of maleic anhydride in fluidized-bed operations of the Sherwin–Williams Badger type. In this type of process naphthalene is either converted to phthalic anhydride or consumed by complete combustion.

   During a test of such a process a sample is taken of the waste gas leaving the switch condensers. The analysis of this gas on a dry basis is as follows: 80.9 mole-% N₂, 15.7 % O₂, 3.4 % CO₂.

   What fraction of the naphthalene feed is converted to phthalic anhydride and what fraction is lost by complete combustion?

94. During a test of BASF phthalic anhydride process it was only possible to analyze the gases leaving the switch condensers, and the amount of water present was not determined. The composition of the waste gas was found to be 0.0089 mole fraction CO₂, 0.1352 mole fraction O₂, and 0.8559 mole fraction N₂.
   (a.) If pure o-xylene and air were fed to the process, and if it is assumed that the only two reactions taking place were the formation of phthalic anhydride and the formation of maleic anhydride, how much of each was produced?
   (b.) What was the o-xylene/air ratio in the feed to the reactor?
(c.) In a later test, the naphthalene flow meter was found to be broken. Fortunately, the engineer conducting the test took the precaution of determining the concentration of water vapor in the waste gases. The data from this test were as follows:

Air flow rate = 34 000 ft³/min (at 60°F)

<table>
<thead>
<tr>
<th>Waste gas analysis</th>
<th>mole fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.037</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.029</td>
</tr>
<tr>
<td>O₂</td>
<td>0.141</td>
</tr>
<tr>
<td>N₂</td>
<td>0.793</td>
</tr>
</tbody>
</table>

Determine (a) flow rate (lbₘ / hr) naphthalene feed, and (b) the fraction converted to phthalic anhydride.

95. In an effort to improve the yield of phthalic anhydride per kilogram of naphthalene feed, the management bought a more active catalyst for the reactor. This allowed the reaction to take place at a lower temperature, 650 K, and it was hoped that this in turn would reduce the amount of naphthalene lost by complete oxidation to carbon dioxide and water.

During a test to evaluate the new catalyst, the air flow meter broke, and there was a strong suspicion that air leaked into the gas sampling bottle used to collect the waste gas sample. Furthermore, it was noticed that water droplets formed in the waste gas sampling line, indicating that the moisture analysis in the waste gas was in error. In desperation the engineer in charge of the test sent a technician back to the plant to obtain a sample of the crude product, and an analysis of this product was made. In all, the following data were available:

Naphthalene flow rate: 8500 kg/hr
Air flow rate: Not available
Waste gas mole-% analysis: CO = 2.87; HO = 1.6; O = 15.7; N = 79.8

Product analysis:
- Phthalic anhydride: 91.4 wt-%
- Maleic anhydride: 5.7 wt-%
- Undetermined: 2.9 wt-%

(a.) Despite the experimental difficulties, the board of directors will meet in 2 days and would like to know whether the new catalyst has improved the yield of phthalic anhydride from naphthalene compared to your old process, which yields 0.95 kg phthalic anhydride/kg naphthalene.

(b.) The plant superintendent would like to know the production of phthalic anhydride.

96. Pure methane is burned with 25 % excess air. The conversion of methane is 87 % and no CO is formed. If the feed rate of CH₄ is 5000 kg/hr, what is the molar flowrate of the total stack gas?

97. 250 moles of liquified petroleum gas (LPG) contains 65 mass-% propane, 25 % propylene, and 10 % n-butane. The LPG is burned with 45 % excess air. The butane, propylene, and 90 % of the propane are consumed. No CO is formed.

(a.) How many moles of each feed component are fed to the furnace?

(b.) Calculate the ratio (moles water/mole dry stack gas).
98. Ethane is burned with 50% excess air. The percentage conversion of the ethane is 90%; of the ethane burned, 25% reacts to form CO and the remainder goes to form CO₂. Calculate the composition of the flue gas and the ratio of water to dry flue gas.

99. A gas of unknown composition is burned with air. Analysis of the product gas yields the following:
   Ratio of moles H₂O/mole wet gas = 0.130
   Orsat analysis (mole-%) of flue gas: 1.5 CO; 6.0% CO₂; 8.2% O₂; 84.3% N₂
   Calculate the ratio of hydrogen to carbon in the feed gas, and speculate on what the gas might be.

100. The flow chart to the right depicts a combustion process in which propane and butane are burned with air.
   (a.) What basis of calculation was assumed in labeling this figure?
   (b.) In terms of labeled variables, write expressions for the theoretical O₂ requirement, percent excess air, and mole fraction of CO₂ in the stack gas on a wet basis.
   (c.) Identify the balances you would write to determine n₁, n₂, n₃, and n₄ and the easiest order in which to solve them. Be sure to distinguish the species and type (atomic, moles, mass) balances. (Your solution should read “First solve _______ _______ balance for variable _______; Second solve ...; etc. Indicate if any equations need to be solved simultaneously).

101. Butane is burned with air. Determine the molar composition of the product gas if no CO is formed, assuming:
   (a.) Theoretical air is supplied, 100% conversion of the fuel.
   (b.) 20% excess air, 100% conversions.
   (c.) 20% excess air, 90% conversion. Calculate the composition of the flue gas on a dry basis.

102. Hexane is burned with excess air. An analysis of the product gas yields the following dry-basis mole-% composition: 83.0% N₂, 9.1% CO₂, 7.6% O₂, 0.268% C₆H₁₄. Calculate the percent excess air fed to the reactor and the conversion of hexane.

103. Liquid methanol is fed to a space heater at a rate of 10 litres/hr, and is burned with excess air. The product gas is analyzed, and the following dry-basis mole-% are determined: CH₃OH = 0.84%, CO₂ = 7.1%, CO = 2.4%.
   (a.) Calculate the fractional conversion of methanol.
   (b.) Calculate the flow rate of water (mole/hr) in the product gas.

104. A mixture of 70 mole-% butane and 30 mole-% hydrogen is burned with 25% excess air. Conversions of 80% of the butane and 99% of the hydrogen are achieved; of the butane that reacts, 90% goes to form CO₂ and 10% goes to form CO. Calculate the mole fraction of water in the product gas.
105. The analysis of coal indicates 70 wt-% C, 20 % H, 2 % S, and the balance non-combustible ash. The coal is burned at a rate of 5000 lbₘ/hr, and the feed rate of air to the furnace is 50 lb-moles/min. All of the ash and 6 % of the carbon in the fuel leave the furnace as a solid slag; the remainder of the carbon leaves in the stack gas as CO and CO₂; the hydrogen in the coal is oxidized to water, and the sulfur emerges as SO₂. The molar ratio of CO₂ to CO is 10:1. All of the H goes to H₂O. Calculate the mole fractions of the gaseous pollutants — CO and SO₂ — in the stack gas, and the emission rates of these substances in lbₘ/hr.

Multiple Units

106. Consider the labeled flow chart shown to the right for a continuous, steady state two-unit distillation process. Each stream contains A and B as indicated. S indicates solution. Three streams of unknown composition and flow rate are labeled as 1, 2, and 3. Calculate the unknown flow rates and compositions.

107. Consider the flow chart on the right showing a steady-state two-unit process. The boundaries are shown to denote subsystems for which balances can be taken. The compositions of each stream are indicated (note: the blue dashed lines are not flow streams, they are just arrows indicating the location of the Q₁ and Q₂ streams). State the maximum number of balances that can be taken for each subsystem and the order in which you would do balances to determine the unknown process variables.

108. An evaporator is a device in which a solution is contracted with steam; the steam heats the solution and boils off a portion of the solvent, leaving the solution more concentrated. A multiple effect evaporator is a connected series of evaporators (called effects) through which a solution passes, becoming more concentrated in each unit. A triple-effect evaporator is used to produce fresh water from sea water, which contains 3.5 wt-% salt. (The salt may be assumed to be all NaCl in this problem). Thirty thousand pounds per hour of sea water are fed to the first effect of the evaporator. A simplified diagram of the process is given below.

The composition of the solution leaving the third effect is measured with an electrical conductivity probe, calibrated to provide a reading of the mole fraction of NaCl in the solution. The probe indicates the stream has a concentration of 0.01593 mole fraction NaCl. The same quantity of water is boiled off in each effect. Calculate the evaporation rate in each effect and the wt-% of NaCl in the solution leaving the second effect.
109. Coffee beans contain some components that are soluble in water and others are not. Instant coffee is produced by dissolving the soluble portion in boiling water (i.e.; by making coffee) in large percolators, then feeding the coffee to a spray dryer in which water is evaporated, leaving the soluble coffee as dry powder. The insoluble portion of the coffee beans (the spent grounds) passes through several drying operations, and the dried grounds are either burned or used as landfill. The solution removed from the grounds in the first stage of the drying operation is fed to the spray dryer to join the effluent from the percolators. A flow chart of this process is shown. The symbols S and I denote the soluble and insoluble components of the coffee beans, W is water, and C is a solution containing 35 % S and 65 % W by mass.

(a.) Calculate the flow rates (kg/hr) of each of streams ① to ⑧.
(b.) If the liquid effluent from the press (stream ⑤) could be fed to the spray dryer without affecting the taste of the product, by what percentage would the production rate of instant coffee be increased?

Recycle and Bypass

110. The flow chart of a process to recover crystalline potassium chromate (K₂₇CrO₄) from an aqueous solution of this salt is shown to the right. Forty-five hundred kilograms per hour of a feed solution that is 33.3 mass-% K₂₇CrO₄ is joined by a recycle stream containing 36.36 % K₂₇CrO₄, and the combined stream is fed into an evaporator. The concentrated stream that leaves the evaporator contains 49.4 % K₂₇CrO₄; this stream is fed into a crystallizer in which it is cooled (causing crystals of K₂₇CrO₄ to come out of solution) and then filtered. The filter cake consists of K₂₇CrO₄ crystals and a solution that contains 36.36 % K₂₇CrO₄ by mass; the crystals account for 95 % of the total mass of the filter cake. The solution that passes through the filter, also 36.36 % K₂₇CrO₄ is the recycle stream.

Calculate the kg/hr of water removed in the evaporator, the rate of production of crystalline K₂₇CrO₄ in kg/hr, the ratio (kg recycle)/(kg fresh feed), and the feed rates that the evaporator and crystallizer must be designed to handle in kg/hr.

111. Propane is dehydrogenated to form propylene in a catalytic reactor: C₃H₈ → C₃H₆ + H₂

The process is to be designed for a 95% overall conversion of propane. The reactor products (RP) are sent to a separator, which separates RP into two streams: (i) the first product stream (P), which contains...
all of the H₂, some of the C₃H₆, and 0.555 % of the propane, (ii) the RC stream, which contains the balance of the unreacted propane and an amount of the propylene equal to 5% of the C₃H₆ in the P stream. Calculate (a) the moles of each component in the P stream, (b) the ratio (moles recycled)/(moles fresh feed), and (c) the single pass conversion.

112. A distillation column is to be designed to separate a mixture containing 50 mass-% hexane (H) and 50 % pentane (P). The top product stream is to contain 95 mass-% P and the bottoms should be 96 mass-% H. The steam leaving the top of the column is to be condensed; a portion of the condensed stream is returned to the column as reflux, and the balance is drawn off as a distillate (product). The reflux ratio [(mass of reflux)/(mass of distillate product)] equals 0.6 Calculate:
(a.) kg distillate & kg bottoms per kg Fresh Feed
(b.) kg fed to condenser/kg FF
(c.) mass flow rate of each stream if FF is 100 kg-moles/hr.

113. Fresh orange juice contains 12 % solids and the balance water, and concentrated orange juice contains 42 % solids. Initially a single evaporation process was used for the concentration, but volatile constituents of the juice escaped with water, leaving the concentrate with a flat taste. The present process overcomes this problem by bypassing the evaporator with a fraction of the fresh juice; the juice that enters the evaporator is concentrated to 58 % solids, and the product is mixed with the bypassed fresh juice to achieve the desired final concentration of solids.
(a.) Calculate the amount of concentrated juice produced per 100 kg fresh juice fed to the process, and the fraction of the feed that bypasses the evaporator.
(b.) The volatile ingredients that provide the taste are contained in the fresh juice that bypasses the evaporator. You could get more of these ingredients in the final product by evaporating to 90 % solids instead of 58 %; you could then bypass a greater fraction of the fresh juice, and you would thereby obtain an even better tasting product. Can you think of any possible drawbacks of this proposal?

114. An evaporation–crystallization process is used to obtain solid potassium sulfate from an aqueous solution of this salt. The fresh feed to the process contains 18.6 wt-% K₂SO₄. The wet filter cake consists of solid K₂SO₄ crystals and a 40 wt-% K₂SO₄ solution, in a ratio (10 lbₘ crystals)/(1 lbₘ solution). The filtrate, also a 40 % solution, is recycled to join the fresh feed; 42.66 % of the water entering the evaporator is evaporated. The evaporator has a maximum capacity of 100 lbₘ evaporated/min.
(a.) Calculate the maximum production rate of solid K₂SO₄, the rate at which fresh feed must be supplied to achieve this production rate, and the ratio (lbₘ recycle/lbₘ fresh feed).
(b.) Calculate the composition and feed rate of the stream entering the crystallizer if the process is scaled to 75 % of its maximum capacity.
115. Methanol is produced by reacting carbon monoxide and hydrogen. A portion of the methanol leaving the reactor is condensed, and the unconsumed CO and H₂ and uncondensed CH₃OH are recycled back to the reactor. The reactor effluent flows at a rate of 275 moles/min, and contains 10.6 wt-% H₂, 64.0 wt-% CO, and 25.4 wt-% CH₃OH. The mole fraction of methanol in the recycle stream is 0.004. Calculate the molar flow rates of CO and H₂ in the fresh feed, and the production rate (moles/min) of liquid methanol leaving the process.

116. Methane reacts with chlorine to produce methyl chloride and hydrogen chloride.

\[
\text{CH}_4 + \text{Cl}_2 \rightarrow \text{CH}_3\text{Cl} + \text{HCl}
\]

Once formed, the methyl chloride may undergo further chlorination to form methylene chloride (CH₂Cl₂), chloroform (CHCl₃), and carbon tetrachloride (CCl₄).

In a methyl chloride production process, methane and chlorine are fed to a reactor in a mole ratio of 5:1. (The ratio is kept high to minimize polysubstitution). A single-pass chlorine conversion of 100 % may be assumed. The mole ratio of CH₂Cl₂ to CH₃Cl in the product is 4:1, and negligible amounts of CHCl₃ and CCl₄ are produced. The product gases are cooled, condensing the CH₂Cl₂ and CH₃Cl, which are then separated in a distillation column. The gas leaving the condenser goes to a scrubber, in which the HCl is absorbed. The gas leaving the scrubber, which may be considered pure methane, is recycled back to the reactor.

For the production rate of 1000 kg CH₃Cl/hr calculate:
(a.) The flow rate and molar composition of the fresh feed.
(b.) The rate at which HCl must be removed in the scrubber.
(c.) The molar flow rate of the recycle stream.

117. Benzene (C₆H₆) is converted to cyclohexane (C₆H₁₂) by direct addition of H₂. The plant produces 100 lb-moles cyclohexane per hour. Ninety-nine percent of the benzene fed to the overall process reacts to form cyclohexane. The composition of the stream entering the reactor is 80 mole-% H₂ and 20 % C₆H₆. The product stream contains H₂ dissolved in liquid C₆H₁₂ plus C₆H₆. The concentration of H₂ in the product stream is 3 mole-%. The recycle stream is pure H₂.

Calculate:
(a.) The composition of the product stream.
(b.) The feed rates of H₂ and C₆H₆ (lb-moles/hr)
(c.) The recycle rate of H₂ (lb-moles/hr)

118. Ammonia (NH₃) is produced by reacting nitrogen with hydrogen. The reactor product stream is sent to a separator where the ammonia is condensed and removed from the system as a pure ammonia product stream; gases are recycled. The flow chart appears as shown (the symbol / denotes all inert gases). The fresh feed to the process contains a small fraction of non-reactive gas material (such as argon). These
inert gases are not condensed in the separator and thus are recycled with the unconsumed nitrogen and hydrogen. Since the inert materials enter the process but are not consumed and do not leave in the product stream, we need to do something to prevent a buildup of inerts in the system, which would eventually shut the process down. To avoid this occurrence, a *purge stream* is taken off from the recycle line. The following data are given for this process:

- Molar composition of fresh feed: 24.75% N₂; 74.25% H₂; 1.00% Inerts.
- Single pass conversion of N₂ = 25%.
- Mole-% of inerts in the recycle stream = 12.5%
- The product stream is pure NH₃.
- The recycle stream contains no NH₃.

Using a basis of 100 moles FF/min, calculate:
(a.) the overall conversion of N₂
(b.) the moles/min product, recycle, purge, mixed feed
(c.) the moles/min each component in the RP stream
(d.) the mole fraction of N₂ in the recycle stream.

119. Iso-octane is to be produced by the catalytic alkylation of butylene with iso-butane according to the reaction

\[ \text{C}_8\text{H}_{18} + \text{C}_4\text{H}_8 \rightarrow \text{C}_{12}\text{H}_{26} \]

The reaction is carried out by emulsifying the liquid hydrocarbons in strong sulfuric acid. The process specifications are as follows:
(a.) The fresh feed consists of 40,000 lbₘ of liquid hydrocarbon having the following molar composition:
- iso-butane 25.00% 
- butylene 25.00% 
- n-butane 50.00% 
(b.) The fresh feed is mixed with iso-butane recycled from the still so the combined feed contains 5.0 moles iso-butane per mole butylene.
(c.) There is sufficient recycle from the product stream so that at the entrance to the reactor there are 200 mole iso-butane per mole butylene.
(d.) The reaction is to proceed to completion in the reactor.
(e.) There is 2 lbₘ of 91 wt-% sulfuric acid per lbₘ of hydrocarbon entering the reactor.
(f.) The still is operated so that no iso-butane appears in the plant product.

Determine the amounts (lb-moles) of each component of the product stream and the three recycle streams.

120. Consider the simple recycle operation shown to the right.

Ethylene oxide is produced by the reaction \( 2\text{CH}_2=\text{CH}_2 + \text{O}_2 \rightarrow 2\text{CH}_2\text{CH}_2\text{O} \). Assume the separator is **perfect; that is, it separates all unreacted ethylene and oxygen from the product ethylene oxide**. The once-through or single-pass conversion is 50%. The reactants in the fresh feed (FF) stream are in a 2:1 ratio. All unreacted reactants are recycled.
in the RC stream to join with the FF stream and form the mixed feed (MF) stream. Under these conditions, what is the recycle ratio? Recycle ratio is defined as total moles of recycle (RC) per mole of P.

121. Reconsider Problem 120 but this time assume the separator has been taken out of service; that is, the reactor product (RP) stream is simply split so that some of it is recycled (RC) and some of it is collected as product stream (P). Under these conditions, what recycle ratio (see Problem 120 for definition) is required to achieve an overall conversion of 75 percent?

122. Consider a more realistic process for the production of ethylene oxide. In this case air rather than pure oxygen is mixed with the ethylene gas to form the FF stream. The ethylene/oxygen ratio that results is not the stoichiometric 2:1. The separator (an absorber) is used as shown to the right. The separator product stream (SP) is split: some of it becomes the RC stream and some of it becomes the waste stream (W). The ethylene oxide product is removed from the bottom of the absorber as the P stream. Assume the separator is ideal as in Problem 120.

In this example the ethylene/air ratio being fed to the process is 1:10. The conversion of ethylene to ethylene oxide on a once-through basis is 55 %. What will be the overall conversion if 65 % of the gases leaving the absorber as SP are recycled?

123. Reconsider Problem 122 from another point of view. Assume the separator is ideal as in Problem 120. In this case, we analyze the W stream and find that it is 81.5 mole-% N₂, 16.5 % O₂, and 2 % ethylene. We know that the recycle ratio RC/W is 3.0 in this problem. Calculate (a.) the ethylene/air ratio in the FF stream, and (b.) the conversion on a once-through basis.

124. FF mixture of 5 mole-% ethylene and 95 mole-% air is fed to a system in which the reactor converts 25 percent of the ethylene on a once-through basis. There is no competing side reaction.
(a.) If, after removing all the ethylene oxide from the reactor products, 60 percent of the remaining gases are recycled to the junction point and mixed with fresh feed, what will be the composition of the reactor feed stream and the reactor product stream?
(b.) What increase in yield of ethylene oxide from ethylene is realized by providing the recycle in (a) above?
(c.) What fraction of the gases leaving the product separator would have to be recycled in order to obtain a yield of 80 percent ethylene oxide from ethylene by this process?
(d.) How many once-through reactors would have to be placed in series to obtain the same yield as in (c) above?

125. The following analysis was obtained for the gases leaving the product separator of an ethylene oxide plant in which ethylene and air were fed as fresh feed. See the figure in Problem 122.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Mole-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>72.86</td>
</tr>
<tr>
<td>O₂</td>
<td>15.30</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>11.83</td>
</tr>
</tbody>
</table>
If the ratio of recycled gas to waste gas is 3:1.

(a.) What is the air/ethylene ratio in the fresh feed?
(b.) What increase in yield of ethylene oxide from ethylene is realized by providing the recycle in (a) above?
(c.) What is the overall conversion of ethylene to ethylene oxide for the process?

126. You are in charge of a reactor producing ethylene oxide. In your reactor, two reactions are occurring:

\[
2 \text{C}_2\text{H}_4 + \text{O}_2 \rightarrow 2 \text{C}_2\text{H}_6\text{O} \quad \text{and} \quad \text{C}_2\text{H}_4 + 3 \text{O}_2 \rightarrow 2 \text{CO}_2 + 2 \text{H}_2\text{O}
\]

The efficiency is 65 percent and the conversion of ethylene per pass is 35 percent. The composition of the gases entering the reactor (that is, the mixed feed) is as follows

- N\textsubscript{2} 80.0 mole-%
- O\textsubscript{2} 7.0 mole-%
- C\textsubscript{2}H\textsubscript{4} 4.5 mole-%
- CO\textsubscript{2} 8.5 mole-%

What is the composition (mole-% to one decimal place accuracy) of the gases leaving the reactor?

127. The feed to an ethylene reactor is

- N\textsubscript{2} 83.3 mole-%
- O\textsubscript{2} 6.0 mole-%
- CH\textsubscript{2}=CH\textsubscript{2} 3.1 mole-%
- CO\textsubscript{2} 7.6 mole-%

The two reactions occurring are given in Problem 126. The reactor is operated at 285°C, and the exit gas has the following composition on a dry basis

- N\textsubscript{2} 86.1 mole-%
- O\textsubscript{2} 2.2 mole-%
- CO\textsubscript{2} 9.7 mole-%
- CH\textsubscript{2}=CH\textsubscript{2} 0.7 mole-%
- C\textsubscript{2}H\textsubscript{6}O 1.3 mole-%

Determine the efficiency, conversion, and yield for the reactor.

128. Ethylene oxide is produced by the catalytic oxidation of ethylene

\[
\text{C}_2\text{H}_4 + \frac{1}{2}\text{O}_2 \leftrightarrow \text{C}_2\text{H}_6\text{O}
\]

An undesired competing reaction is the combustion of ethylene

\[
\text{C}_2\text{H}_4 + 3\text{O}_2 \leftrightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}
\]

The feed to the reactor (not the fresh feed to the process) contains 3 moles of C\textsubscript{2}H\textsubscript{4} per mole of oxygen. The conversion of ethylene in the reactor is 20 %, and the efficiency is 80 %. A multiple-unit process is used to separate the products: C\textsubscript{2}H\textsubscript{4} and O\textsubscript{2} are recycled back to the reactor, C\textsubscript{2}H\textsubscript{6}O is sold as a product, and CO\textsubscript{2} and H\textsubscript{2}O are discarded. Calculate the molar flow rates of O\textsubscript{2} and C\textsubscript{2}H\textsubscript{4} and the fresh feed needed to produce 1500 kg C\textsubscript{2}H\textsubscript{6}O/hr. Also, calculate the overall conversion, and the overall yield based on ethylene fed.
129. The following analysis (on a dry basis) of the gases leaving an ethylene oxide reactor was obtained during a test of the process (the remainder is inert ash):

\[
\begin{align*}
\text{CH}_2=\text{CH}_2 & : 3.2 \text{ mole-\%} \\
\text{N}_2 & : 79.6 \text{ mole-\%} \\
\text{O}_2 & : 10.8 \text{ mole-\%} \\
\text{C}_2\text{H}_4\text{O} & : 0.824 \text{ mole-\%} \\
\text{CO}_2 & : 5.5 \text{ mole-\%}
\end{align*}
\]

The process is shown in Problem 122 and the two reactions occurring are given in Problem 126. Calculate (a.) the efficiency and conversion on a once-through basis, (b.) the ratio of recycle to waste, and (c.) the ethylene/air ratio in the fresh feed.

130. Consider the system of two reactors in series as shown to the right. The temperature of the first reactor is adjusted so that on a once-through basis the efficiency is 70 percent, the conversion 30 percent, and the yield 21 percent. The temperature in the second reactor is chosen so that the efficiency is 55 percent, the conversion 76 percent, and the yield 42 percent. The two reactions occurring are given in Problem 126. Assuming that the ethylene/air ratio in the fresh feed is 1:10, make a plot of the overall yield of the process as a function of the ratio of recycled gas to the FF2 gas. Note: FF2 is also referred to as the purge gas.

131. Reconsider the process described in Problem 130 but substitute a mixture of 1 part ethylene to 2.1 parts pure oxygen for the fresh feed.

(a.) Again determine the effect of recycle on the overall conversion by making a plot of overall conversion versus the ratio of recycle gas to purge gas (see Problem 130 for a definition of purge gas).

(b.) For the same overall rate of production of ethylene oxide, compare the volumetric flow rate of gases through the primary reactor in the air process described in Problem 130 to the volumetric flow rate of gases in the pure oxygen process described in this problem.

132. In the pure oxygen process described in Problem 131 it should be possible to recycle all the product gases back to the process and eliminate the second half of the figure shown in Problem 130 by passing the recycle gases through a CO\textsubscript{2} scrubber. If for the reactor the efficiency is 65 percent and the conversion on a once-through basis is 35 percent:

(a.) What should the ethylene/oxygen ratio in the fresh feed be if the scrubber removes 100 percent of the CO\textsubscript{2}?

(b.) If the scrubber removes 80 percent of the CO\textsubscript{2}, how many moles of recycle are there per mole of fresh feed when the process is operating at 100 percent recycle?

(c.) What is the overall yield of ethylene oxide from ethylene under the conditions in (b) above?

(d.) Is it possible to determine the amount of oxygen in the recycle stream? Explain carefully.
133. Consider the air oxidation process for ethylene oxide described in Problem 130.
   (a.) Assuming that the fresh feed and recycle enter the reactor at 25°C, determine the amount of heat
   that must be withdrawn from the primary reactor per pound mole of fresh feed to maintain the
   reactor at 270°C. Clearly, the amount of heat to be withdrawn will depend on the amount of gas
   recycled; therefore consider at least three recycle ratios (1, 10, and 100 are convenient choices).
   (b.) It should be apparent from (a) that there is a recycle ratio above which heat must be added to the
   reactor. Determine this ratio.

134. Because of considerations of overall yield it is desirable to operate an air process for the production of
   ethylene oxide at a recycle gas/purge gas ratio of 10:1 (see Problem 130 for a definition of purge gas).
   (a.) If the efficiency, conversion, and ethylene/air feed ratio are the same as in Problem 130, to what
   temperature must the combined recycle and feed be preheated in order for the reaction mixture to
   reach 270°C as it leaves the reactor?
   (b.) If the product gases from the reactor are used to preheat the feed to the temperature calculated in
   (a) above, to what extent will the product gases be cooled?

135. Considering the pure oxygen process with 100 percent recycle described in Problem 132, how much heat
   must be withdrawn from the reactor per 100 mole of ethylene oxide product?