Chapter 12

Recycle, Bypass, Purge, and the Industrial Application of Material Balances

12.1 Introduction

- **Recycle** is fed back from a **downstream** unit to an **upstream** unit, as shown in Figure 12.lc. The stream containing the recycled material is known as a **recycle stream**.
- Recycle system is a system that includes one or more recycle streams.
- Because of the relatively **high cost** of industrial feedstocks, when **chemical reactions** are involved in a process, **recycle** of **unused reactants** to the reactor can offer significant **economic** savings for high-volume processing systems. **Heat recovery** within a processing unit (**energy recycle**) reduces the overall energy consumption of the process.

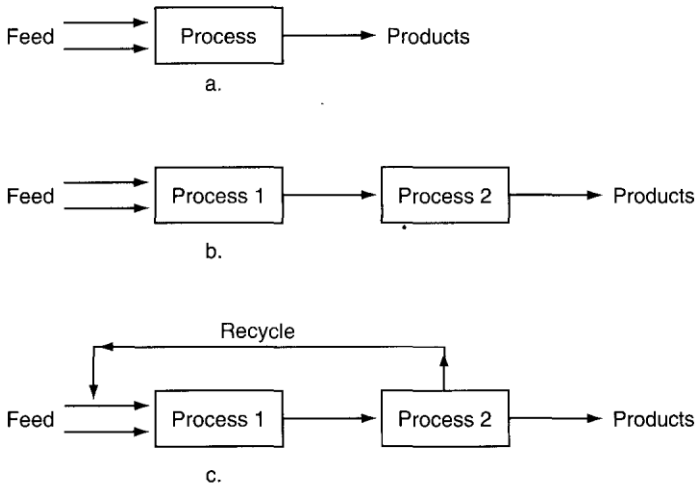


Figure 12.1: Figure 12.la shows a single unit with serial flows. Figure 12.b shows multiple units but still with serial flows. Figure 12.lc shows the addition of recycle.

12.2 Recycle without Chemical Reaction

- ❖ **Recycle** of material occurs in a variety of processes that do **not** involve chemical reaction, including **distillation**, **crystallization**, and **heating and refrigeration** systems.
- ❖ Examine Figure 12.2. You can write material balances for several different systems, **four** of which are shown by dashed lines in Figure 12.2 **(Overall balance 1, Mixer balance 2, Process balance 3 & Separator balance 4)**.
- ❖ The **fresh feed** enters the overall system and the **overall or net product** is removed.
- ❖ The **total (gross) feed** enters the process and the **gross product** is removed.

❖ In addition, you can make balances (not shown in Figure 12.2) about **combinations of subsystems**, such as the **process plus the separator** (**3 plus 4**), or the **mixing point plus the process** (**2 plus 3**).

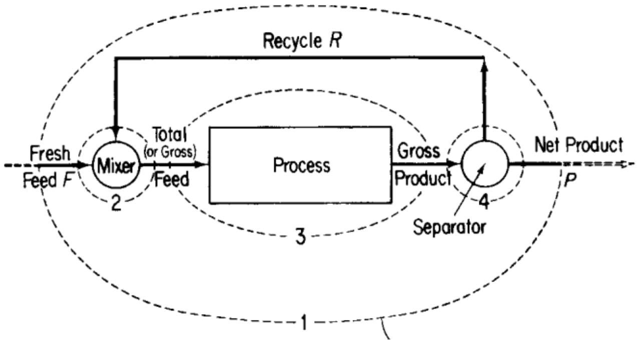


Figure 12.2 Process with recycle (the numbers designate possible system boundaries for the material balances).

Example 12.1

Figure E12.la is a schematic of a process for the production of flake NaOH, which is used in households to clear plugged drains in the plumbing (e.g., Drano).

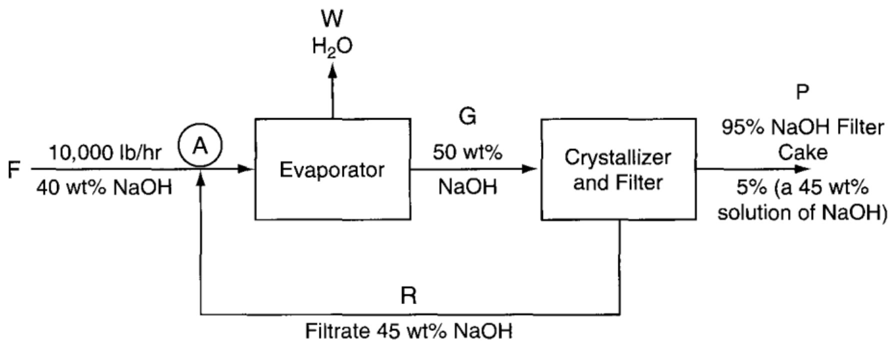


Figure E12.1a

The fresh feed to the process is 10,000 lb/hr of a 40% aqueous NaOH solution. The fresh feed is combined with the recycled filtrate from the crystallizer, and fed to the evaporator where water is removed to produce a 50% NaOH solution, which in turn is fed to the crystallizer. The crystallizer produces a filter cake that is 95% NaOH crystals and 5% solution that itself consists of 45% NaOH. The filtrate contains 45% NaOH.

a. You are asked to determine the flow rate of water removed by the evaporator, and the recycle rate for this process.
b. Assume that the same production rate of NaOH flakes occurs, but the filtrate is not recycled. What would be the total feed rate of 40% NaOH have to be then? Assume that the product solution from the evaporator still contains 50% NaOH.

Solution

Open, steady-state process.

a. Basis: 10,000 lb fresh feed (equivalent to 1 hour)

The unknowns are W, G, P, and R.

Overall NaOH balance

$$(0.4)(10{,}000) = 0.95\ P + (0.45)\ (0.05)\ P$$
$$P = 4113\ \text{lb}$$

Overall H_2O balance

$$(0.6)\ (10{,}000) = W + [(0.55)(0.05)](4113)$$
$$W = 5887\ \text{lb}$$

(or use the overall total balance 10,000 = 4113 + W)

The total amount of NaOH exiting with P is [(0.95) + (0.45)(0.05)](4113) = 4000 lb

NaOH balance on the **crystallizer** 0.5 G = 4000 + 0.45 R

H_2O balance on the **crystallizer** 0.5 G = 113 + 0.55 R

(or use the total balance G = R + 4113)

$$R = 38{,}870\ \text{lb}$$

b. Figure E12.lb.

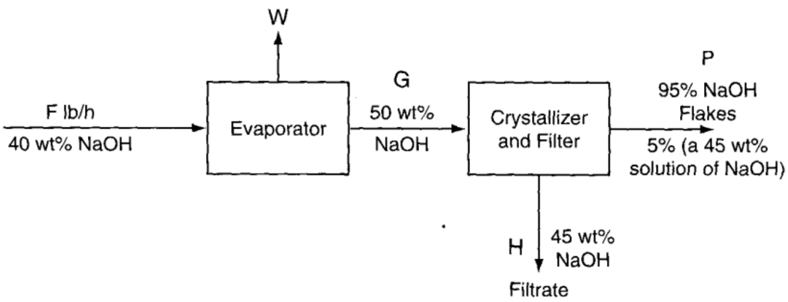


Figure E12.1b

The basis is now P = 4113 lb (the same as 1 hour)

The unknowns are now F, W, G, and H.

NaOH balance on the **crystallizer**

$$0.5\ G = [(0.95) + (0.05)\ (0.45)]\ (4113) + 0.45\ H$$

H_2O balance on the **crystallizer**

$$0.5G = [(0.05)\ (0.55)\ (4113)] + 0.55\ H$$
$$H = 38{,}870\ \text{lb}$$

Overall NaOH balance

$$0.40\ F = 0.45(38{,}870) + 4000$$
$$F = 53{,}730\ \text{lb}$$

- Note that **without recycle**, the feed rate must be **5.37 times larger** than **with recycle** to produce the same amount of product.

12.3 Recycle with Chemical Reaction

- The most common application of recycle for systems involving chemical reaction is the recycle of reactants, an application that is used to increase the overall conversion in a reactor. Figure 12.3 shows a simple example for the reaction

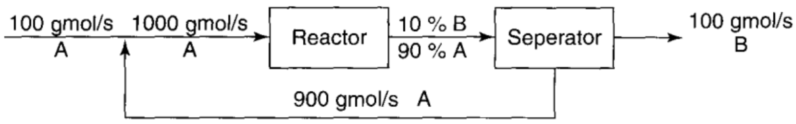


Figure 12.3 A simple recycle system with chemical reaction.

If you calculate the **extent of reaction** for the **overall process** in Figure 12.3 **based on B**

$$\xi_{\text{overall}} = \frac{100 - 0}{1} = 100 \text{ moles reacting}$$

If you use material balances to calculate the **output P** of the **reactor** (on the **basis** of **1 second**) you get A = 900 g mol B = 100 g mol

And the **extent of reaction based on B** for the **reactor** by itself as the system is

$$\xi_{\text{reactor}} = \frac{100 - 0}{1} = 100 \text{ moles reacting}$$

In general, **the extent of reaction** is the **same** regardless of whether an **overall material** balance is used or a material balance for the **reactor** is used.

- Two types of **conversion** when reactions occur:

1. **Overall fraction conversion:**

$$\frac{\text{mass (moles) of reactant in the fresh feed - mass (moles) of reactant in the output of the overall process}}{\text{mass (moles) of reactant in the fresh feed}}$$

2. **Single - pass (“once - through”) fraction conversion:**

$$\frac{\text{mass (moles) of reactant fed into the reactor - mass (moles) of reactant exiting the reactor}}{\text{mass (moles) of reactant fed into the reactor}}$$

For the simple recycle reactor in Figure 12.3, **the overall conversion** is

$$\frac{100 - 0}{100} \times 100 = 100\%$$

And the **single-pass conversion** is

$$\frac{1000 - 900}{1000} \times 100 = 10\%$$

When the **fresh feed** consists of **more than one reactant**, the **conversion** can be expressed for a **single component**, usually the **limiting reactant**, or the most important (expensive) reactant.

- The **overall conversion** and the **single-pass conversion** can be expressed in terms of the **extent of reaction**, ξ.

$$\text{Overall conversion of species A} = f_{OA} = \frac{-v_A \xi}{n_A^{\text{fresh feed}}} \qquad (12.1)$$

$$\text{Single-pass conversion} = f_{SP} = \frac{-v_A \xi}{n_A^{\text{reactor feed}}} \qquad (12.2)$$

$$\frac{f_{SP}}{f_{OA}} = \frac{n_A^{\text{fresh feed}}}{n_A^{\text{fresh feed}} + n_A^{\text{recycle}}} \qquad (12.3)$$

<u>**Example 12.2**</u>

Cyclohexane (C_6H_{12}) can be made by the reaction of benzene (Bz) (C_6H_6) with hydrogen according to the following reaction:

$$C_6H_6 + 3H_2 \rightarrow C_6H_{12}$$

For the process shown in Figure El2.2, determine the ratio of the recycle stream to the fresh feed stream if the overall conversion of benzene is 95%, and the single-pass conversion is 20%. Assume that 20% excess hydrogen is used in the fresh feed, and that the composition of the recycle stream is 22.74 mol % benzene and 77.26 mol % hydrogen.

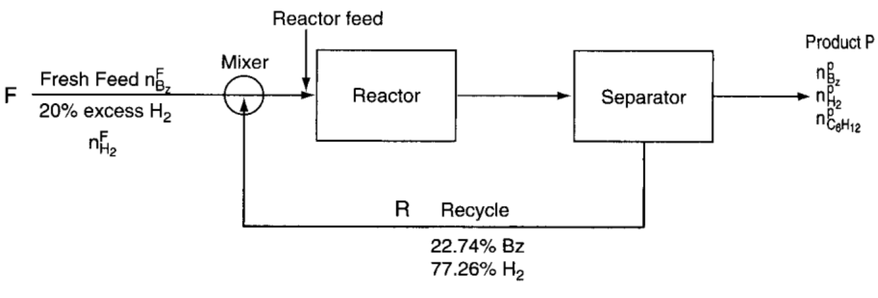


Figure E12.2 Schematic of a recycle reactor.

Solution

The process is **open** and **steady state**.

Basis = 100 mol (g mol or lb mol) of fresh benzene feed

Excess H_2 = (in – required)/ required (**for complete reaction**)

In H_2 (Feed):

$$n_{H_2}^{F} = 100(3)(1 + 0.20) = 360 \text{ mol}$$

The total fresh feed = 100 + 360 = 460 mol.

From Equation (12.1) for benzene (ν_{Bz} = - 1)

$$0.95 = \frac{-(-1)\xi}{100}$$

ξ = 95 reacting moles.

The unknowns are R, n_{Bz}^{P}, $n_{H_2}^{P}$, and $n_{C_6H_{12}}^{P}$.

The species **overall balances** are

$$n_i^{out} = n_i^{in} + \nu_i \xi_{overall}$$

$$\begin{aligned} &Bz: & n_{Bz}^{P} &= 100 + (-1)(95) &= 5 \text{ mol} \\ &H_2: & n_{H_2}^{P} &= 360 + (-3)(95) &= 75 \text{ mol} \\ &C_6H_{12} & n_{C_6H_{12}}^{P} &= 0 + (1)(95) &= \underline{95 \text{ mol}} \\ & & & & P = 175 \text{ mol} \end{aligned}$$

The amount of the **Bz** feed to the **<u>reactor</u>** is **100 + 0.2274 R**, and **ξ = 95.** Thus, for benzene

$$0.20 = \frac{-(-1)95}{100 + 0.2274R}$$

and R = 1649 mol

Finally, the ratio of **recycle** to **fresh feed** is

$$\frac{R}{F} = \frac{1649 \text{ mol}}{460 \text{ mol}} = 3.58$$

<u>Example 12.3</u>

Immobilized glucose isomerase is used as a catalyst in producing fructose from glucose in a fixed-bed reactor (water is the solvent). For the system shown in Figure El2.3a, what percent conversion of glucose results on one pass through the reactor when the ratio of the exit stream to the recycle stream in mass units is equal to 8.33? The reaction is

$$\underset{\text{Glucose}}{C_{12}H_{22}O_{11}} \rightarrow \underset{\text{Fructose}}{C_{12}H_{22}O_{11}}$$

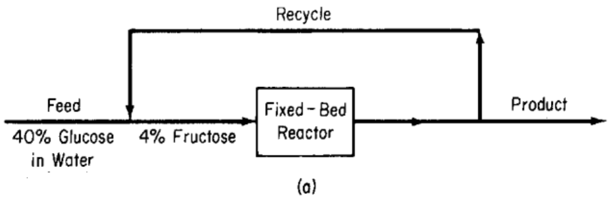


Figure E12.3a

Solution

The process is an **open**, **steady-state** process with a **reaction occurring** and a **recycle**.

- Figure E12.3b includes all the known and unknown values of the variables using appropriate notation (W stands for water, G for glucose, and F for fructose).
- **Note** that the **recycle stream** and **product stream** have the **same composition**, and consequently the same mass symbols are used in the diagram for each stream.

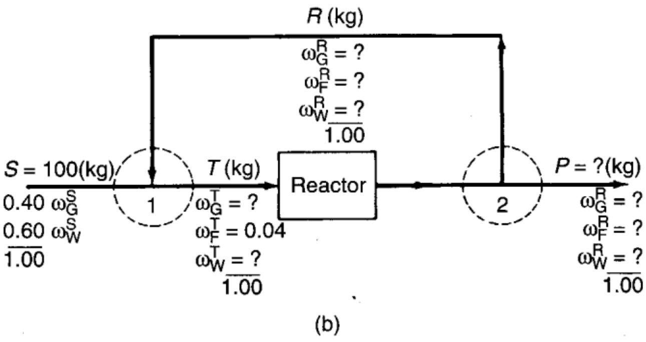


Figure E12.3b

Pick as a basis S = 100 kg

Overall balances

Total: P = S = 100 kg

Consequently,

$$R = \frac{100}{8.33} = 12.0 \text{ kg} \qquad \textbf{[P/R = 8.33]}$$

Overall no **water** is **generated** or **consumed**, hence

Water:

$$100(0.60) = P\omega_W^R = 100\omega_W^R$$

$$\omega_W^R = 0.60$$

Mixing point 1

$$\textit{Total:} \quad 100 + 12 = T = 112$$

$$\textit{Glucose:} \quad 100(0.40) + 12\omega_G^R = 112\omega_G^T$$

$$\textit{Fructose:} \quad 0 + 12\omega_F^R = 112(0.04)$$

Or $\omega_F^R = 0.373$

Also, because $\omega_F^R + \omega_G^R + \omega_W^R = 1$,

$\omega_G^R = 1 - 0.373 - 0.600 = 0.027$

$$\omega_G^T = 0.360$$

Next from the glucose balance

Reactor plus Separator 2

Total: T = 12 + 100 = 112 (a redundant equation)

$$\text{Glucose:} \quad \omega_G^T T - (R + P)(\omega_G^R) = (f)(\omega_G^T T)$$

$$(0.360)(112) - (112)(0.027) = f(0.360)(112)$$

$$40.3 - 3.02 = f(40.32)$$

$$f = 0.93$$

Check by using Equation 12.2 and the **extent of reaction**

$$\xi = \frac{3.02 - 40}{-1} = 37 \quad f = \frac{-(-1)(37)}{40} = 0.93$$

Example 12.4

Reactors that involve biological materials (bioreactors) use living organisms to produce a variety of products. Bioreactors are used for producing ethanol, antibiotics, and proteins for dietary supplements and medical diagnosis. Figure E12.4 shows a recycle bioreactor in which the overall conversion of the proprietary component in the fresh feed to product is 100%. The conversion of the proprietary component to product **per pass** in the reactor is 40%. Determine the amount of recycle and the mass percent of component in the recycle stream if the product stream contains 90% product, and the feed to the reactor contains 3 wt % of the component.

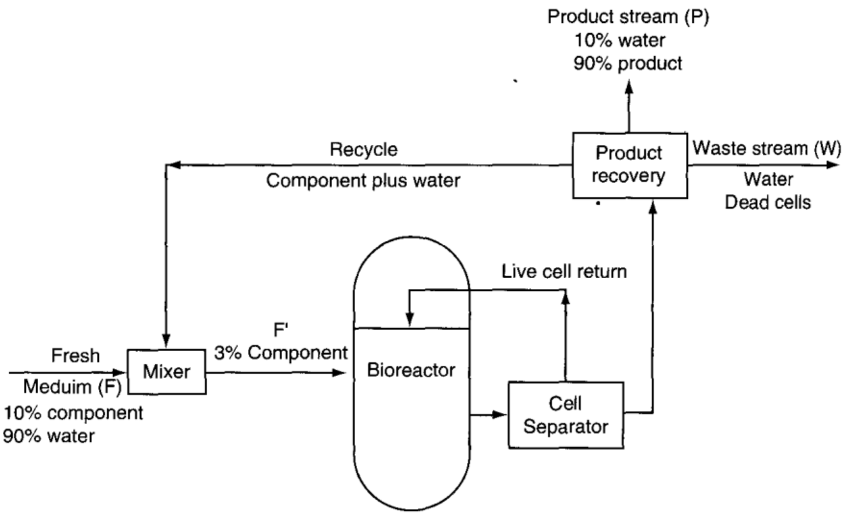


Figure E12.4

Assume that the component and the product have essentially the same molecular weight, and that the waste contains only water and dead cells.

Solution

Basis = 100 kg of fresh feed (F).

Overall balances

Total balance: 100 = P + W

Component balance: 0.10 (100) = 0.90 P

P = 11.1 kg W = 88.9 kg

The reactor plus the product recovery unit balance

$$\begin{array}{ccccc} \textit{Accumulation} & \textit{Input} & \textit{Output} & \textit{Generation} & \textit{Consumption} \\ 0 & = [100\,(0.10) + R\omega] & -\,R\omega & +\quad 0 & -0.40\,[100\,(0.10) + R\omega] \end{array}$$

$$R\omega = 15 \text{ kg of component in the recycle stream}$$

Mixer balance

Component balance: 100 (0.10) + 15 = 0.03 F′ ⟶ F′ = 833 kg

Total balance: R + 100 = F′ ⟶ R = 833 – 100 = 733 kg

$$\omega = \frac{15}{733} = 0.0205$$

12.4 Bypass and Purge

a. A **bypass** stream—a stream that skips one or more stages of the process an **goes directly** to another downstream stage (Figure 12.4).

   A **bypass** stream can be used to control the composition of a final exit stream from a unit by mixing the bypass stream and the unit exit stream in suitable proportions to obtain the desired final composition.

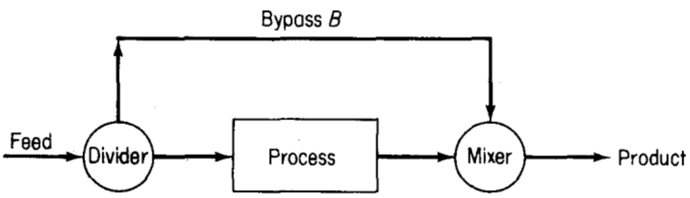


Figure 12.4 A process with a bypass stream.

b. A **purge** stream—a stream bled off from the process to remove an accumulation of inert or unwanted material that might otherwise build up in the recycle stream (Figure 12.5).

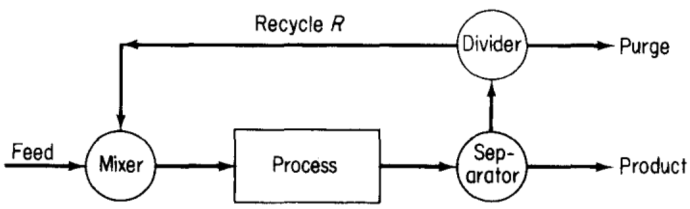


Figure 12.5 A process with a recycle stream with purge.

Example 12.5

In the feedstock preparation section of a plant manufacturing natural gasoline, isopentane is removed from butane-free gasoline. Assume for purposes of simplification that the process and components are as shown in Figure E12.5. What fraction of the butane-free gasoline is passed through the isopentane tower? The process is in the steady state and no reaction occurs.

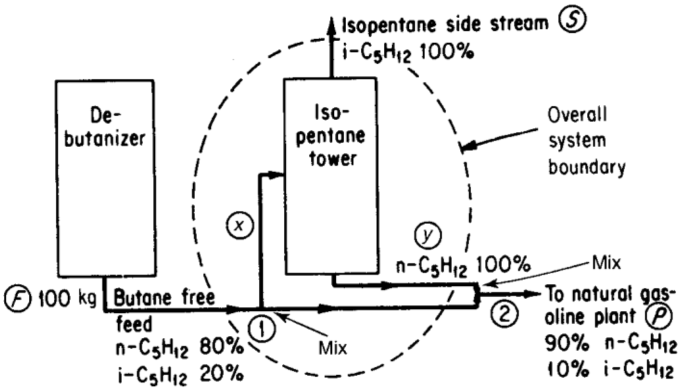


Figure E12.5

Solution

Basis: 100 kg feed

Overall balances

Total material balance:

$$\frac{In}{100} = \frac{Out}{S + P} \qquad \text{(a)}$$

Component balance for n-C_5 (tie component)

$$\frac{In}{100(0.80)} = \frac{Out}{S(0) + P(0.90)} \qquad \text{(b)}$$

Consequently,

$$P = 100\left(\frac{0.80}{0.90}\right) = 88.9 \text{ kg}$$

$$S = 100 - 88.9 = 11.1 \text{ kg}$$

Balance around isopentane tower:

Let **x** be the kg of butane-free gas going to the isopentane tower, and **y** be the kg of the n-C_5H_{12} stream leaving the isopentane tower.

Total material balance:

$$\frac{In}{x} = \frac{Out}{11.1 + y} \qquad \text{(c)}$$

Component balance for n-C_5 $\quad x\,(0.80) = y \quad$ (d)

Consequently, combining (c) and (d) yields **x = 55.5 kg**, or the desired fraction is 0.55.

Another approach to this problem is to make a balance at **mixing points 1** and **2**.

Balance around mixing point 2:

Material into junction = Material out

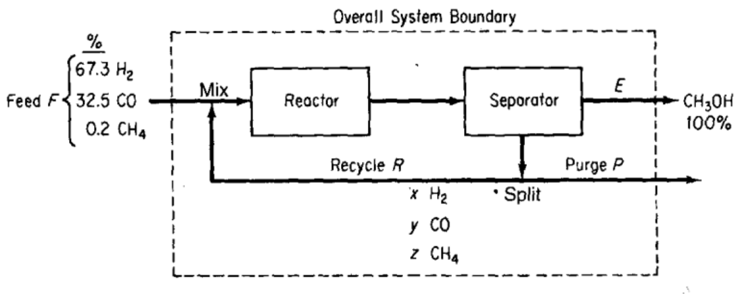
Total material: (100 – x) + y = 88.9 (e)

Component (iso-C_5): (100 –x)(0.20) + 0 = 88.9(0.10) (f)

Solving yields **x = 55.5 kg as before**

Example 12.6

Figure E12.6 illustrates a steady-state process for the production of methanol. All of the compositions are in mole fractions or percent. The stream flows are in moles.



$$CO + 2H_2 \rightarrow CH_3OH$$

Figure E12.6

Note in Figure E12.6 that some CH_4 enters the process, but does not participate in the reaction. A purge stream is used to maintain the CH_4 concentration in the exit from the separator at no more than 3.2 mol%, and prevent hydrogen buildup as well. The **once-through conversion** of the CO in the reactor is 18%.

Compute the moles of recycle, CH_3OH, and purge per mole of feed, and also compute the purge gas composition.

Solution

The mole fraction of the components in the purge stream have been designated as x, y, and z for H_2, CO, and CH_4, respectively.

Basis: F = 100 mol

The variables whose values are unknown are x, y, z, E, P, and R.

$$z = 0.032 \quad \text{(a)}$$

The implicit mole fraction balance in the recycle stream $x + y + z = 1$ (b)

The **overall element balances** are (in moles):

$$2H:\quad 67.3 + 0.2(2) = E\,(2) + P\,(x + 2z) \qquad (c)$$
$$C:\quad 32.5 + 0.2 = E\,(1) + P\,(y + z) \qquad (d)$$
$$O:\quad 32.5 = E\,(1) + P\,(y) \qquad (e)$$

Reactor plus the Separator

$$CO:\quad \underset{[32.5 + Ry]}{\underline{In}} - \underset{[y(R + P)]}{\underline{Out}} = \underset{(32.5 + Ry)(0.18)}{\underline{Consumed}} \qquad (f)$$

Equation (a) can be substituted into Equations (b) through (f), and the resulting five equations solved by successive substitution or by using a computer program. The resulting values obtained are (in moles)

E	CH_3OH	31.25
P	purge	6.25
R	recycle	705
x	H_2	0.768
y	CO	0.200
z	CH_4	0.032

Problems

1. How many recycle streams occur in Figure SAT12.1PI?

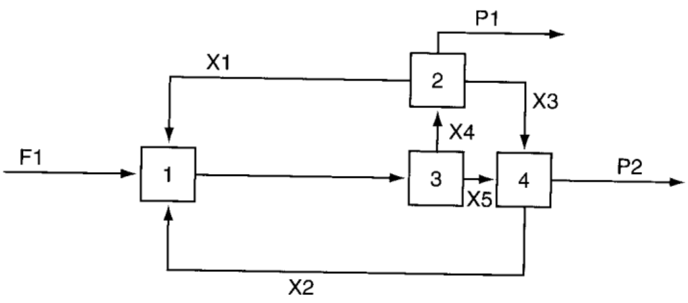


Figure SAT12.1P1

2. The Hooker Chemical Corporation operates a process in Michigan for the purification of HCl. Figure SATI2.1P2 shows the flow sheet for the Hooker process. The streams from the bottoms of the five towers are liquid. The streams from the tops of the towers are gases. HCl is insoluble in the HCB (hexachlorobutadiens). The various stream compositions are shown in Figure SAT12.1P2.

   How many recycle streams are there in the Hooker process?

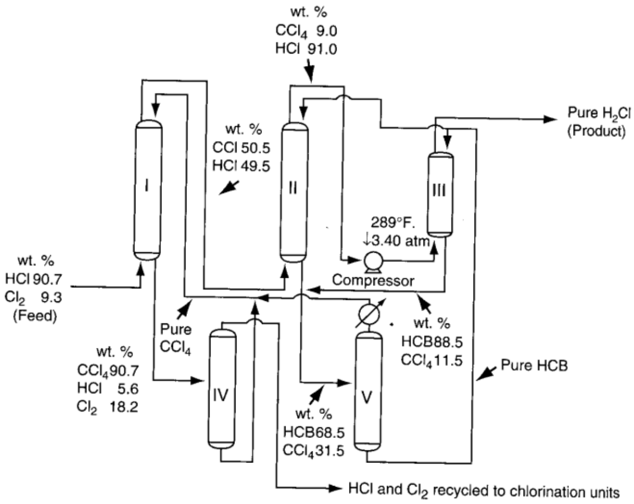


Figure SAT12.1P2

3. A ball mill grinds plastic to make a very fine powder. Look at Figure SAT12.2P1.

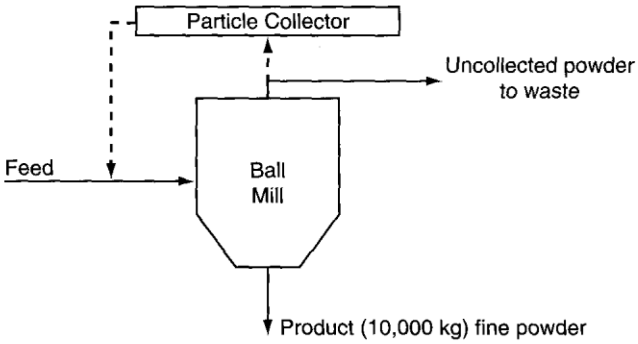


Figure SAT12.2P1

At the present time 10,000 kg of powder are produced per day. You observe that the process (shown by the solid lines) is inefficient because 20% of the feed is not recovered as powder—it goes to waste.

You make a proposal (designated by the dashed lines) to recycle the uncollected material back to the feed so that it can be remilled. You plan to recycle 75% of the 200 kg of uncollected material back to the feed stream. If the feed costs $1.20/kg, how much money would you save per day while producing 10,000 kg of fine powder?

4. Sea water is to be desalinized by reverse osmosis using the scheme indicated in Figure SATI2.2P2. Use the data given in the figure to determine: (a) the rate of waste brine removal (B); (b) the rate of desalinized water (called potable water) production (P); (c) the fraction of the brine leaving the reverse osmosis cell (which acts in essence as a separator) that is recycled.

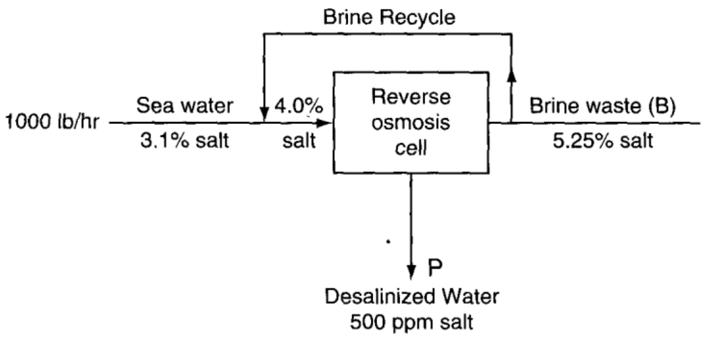


Figure SAT12.2P2

5. A material containing 75% water and 25% solid is fed to a granulator at a rate of 4000 kg/hr. The feed is premixed in the granulator with recycled product from a dryer, which follows the granulator (to reduce the water concentration of the overall material fed into the granulator to 50% water, 50% solid). The product that leaves the dryer is 16.7% water. In the dryer, air is passed over the solid being dried. The air entering the dryer contains 3% water by weight (mass), and the air leaving the dryer contains 6% water by weight (mass).
    a. What is the ratio of the recycle to the feed entering the granulator?
    b. What is the rate of air flow to the dryer on a dry basis?
6. Benzene, toluene, and other aromatic compounds can be recovered by solvent extraction with sulfur dioxide (SO_2). Figure SAT12.2P4 is the process schematic. As an example, a catalytic reformate stream containing 70% benzene and 30% nonbenzene material is passed through the countercurrent extractive recovery scheme shown in Figure SAT12.2P4. 1000 lb of reformate and 3000 lb of SO_2 are fed to the system per hour. The benzene product stream contains 0.15 lb of SO_2 per lb of benzene. The raffinate stream contains all the initially charged nonbenzene material as well as 0.25 lb of benzene per lb of nonbenzene material. The remaining component in the raffinate stream is SO_2. How many lb of benzene are extracted in the product stream on an hourly basis? How many lb of raffinate are produced per hour?

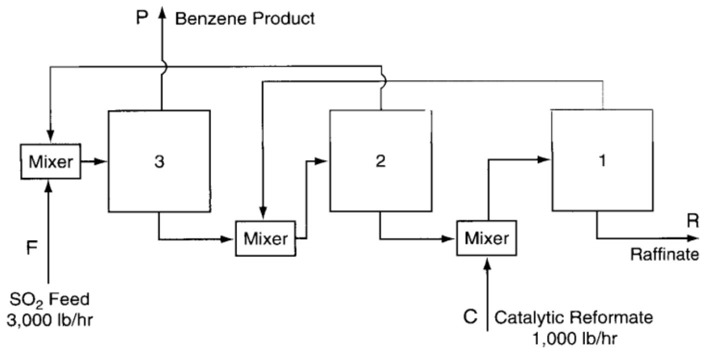


Figure SAT12.2P4

7. A catalytic dehydrogenation process shown in Figure SAT12.3Pl, produces 1, 3 butadiene (C_4H_6) from pure normal butane (C_4H_{10}). The product stream contains 75 mol/hr of H_2 and 13 mol/hr of C_4H_{10} as well as C_4H_6. The recycle stream is 30% (mol) C_4H_{10} and 70% (mol) C_4H_6, and the flow is 24 mol/hr.

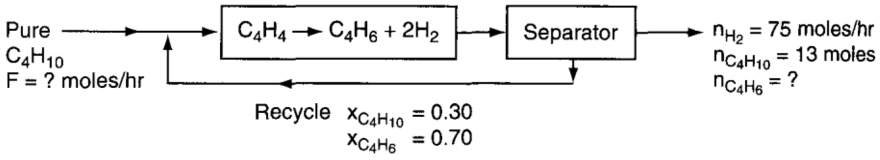


Figure SAT12.3P1

(a) What are the feed rate, F, and the product flow rate of C_4H_6 leaving the process?

(b) What is the single-pass conversion of butane in the process?

8. Pure propane (C_3H_8) from El Paso is dehydrogenated catalytically in a continuous process to obtain propylene (C_3H_6). All of the hydrogen formed is separated from the reactor exit gas with no loss of hydrocarbon. The hydrocarbon mixture is then fractionated to give a product stream containing 88 mole % propylene and 12 mole % propane. The other stream, which is 70 mole % propane and 30 mole % propylene, is recycled. The one-pass conversion in the reactor is 25%, and 1000 kg of fresh propane are fed per hour. Find (a) the kg of product stream per hour, and (b) the kg of recycle stream per hour.

9. Ethyl ether is made by the dehydration of ethyl alcohol in the presence of sulfuric acid at 140°C:

$$2C_2H_5OH \rightarrow C_2H_5OC_2H_5 + H_2O$$

Figure SAT12.3P3 is a simplified process diagram. If 87% conversion of the alcohol fed to the reactor occurs per pass in the reactor, calculate: (a) kilograms per hour of fresh feed, and (b) kilograms per hour of recycle.

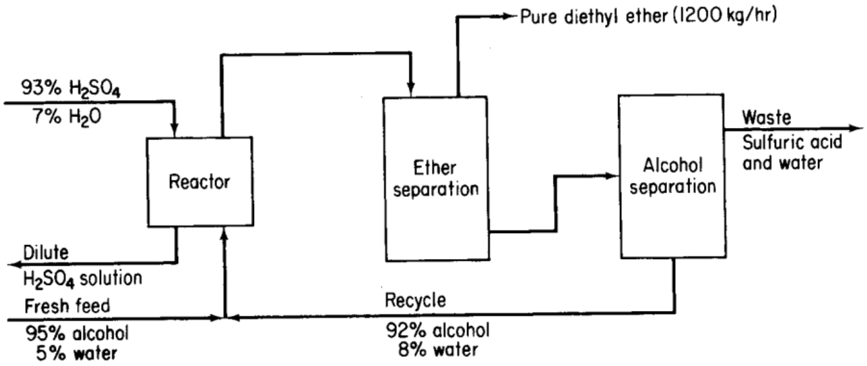


Figure SAT12.3P3

10. In the famous Haber process (Figure SAT12.4P1) to manufacture ammonia, the reaction is carried out at pressures of 800 to 1000 atm and at 500 to 600°C using a suitable catalyst.

Only a small fraction of the material entering the reactor reacts on one pass, so recycle is needed. Also, because the nitrogen is obtained from the air, it contains almost 1% rare gases (chiefly argon) that do not react. The rare gases would continue to build up in the recycle until their effect on the reaction equilibrium would become adverse. Therefore, a small purge stream is used.

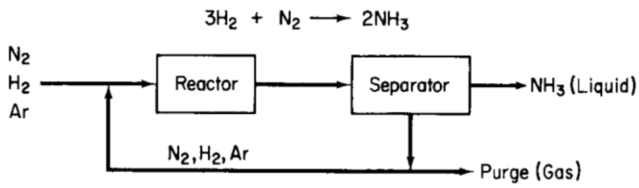


Figure SAT12.4P1

The fresh feed of gas composed of 75.16% H_2, 24.57% N_2, and 0.27% Ar is mixed with the recycled gas and enters the reactor with a composition of 79.52% H_2. The gas stream leaving the ammonia separator contains 80.0 1% H_2 and no ammonia. The product ammonia contains no dissolved gases. Per 100 moles of fresh feed:

a. How many moles are recycled and purged?

b. What is the percent conversion of hydrogen per pass?

11. Figure SAT12.4P2 shows a simplified process to make ethylene dichloride ($C_2H_4C1_2$). The feed data have been placed on the figure. Ninety percent conversion of the C_2H_4 occurs on each pass through the reactor. The overhead stream from the separator contains 98% of the Cl_2 entering the separator, 92% of the entering C_2H_4, and 0.1% of the entering $C_2H_4C1_2$. Five percent of the overhead from the separator is purged. Calculate (a) the flow rate and (b) the composition of the purge stream.

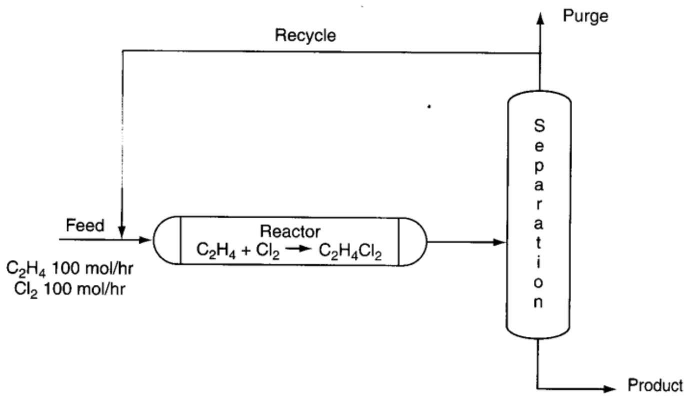


Figure SAT12.4P2

Answers:

1. 2
2. 5
3. $2250
4. (a) 591 lb/hr; (b) 409 lb/hr; (c) 0.55
5. (a) ratio = 3000 kg of recycle/hr and feed = 7000 kg/hr; (b) air = 85,100 kg/hr
6. (a) benzene extracted: P = 625 lb/hr; (b) raffinate produced: R = 3,281 lb/hr
7. (a) mol/hr C_4H_6 = 37.5 and F = 50.5 mol/hr; (b) 0.65
8. (a) 960 kg/hr; (b) 3659 kg/hr
9. (a) 1570 kg/hr; (b) 243 kg/hr
10. (a) 890 recycled and 3.2 purged; (b) 9.2% conversion (errors can be caused by loss of significant figures)
11. (a) 1.49 mol/hr; (b) Cl_2: 0.658; C_2H_4: 0.338; $C_2H_4C1_2$: 0.0033

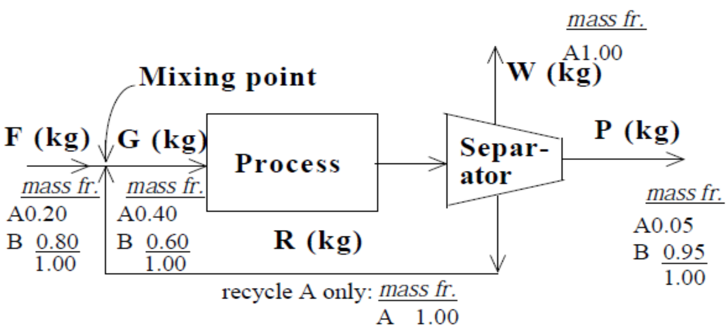
Supplementary Problems (Chapter Twelve):

Problem 1

Based on the process drawn in the diagram, what is the kg recycle / kg feed if the amount of W waste is 100 kg ? The known compositions are inserted on the process diagram.

Solution

This is a steady state problem without reaction comprised of three subsystems, the process, the separator, and the mixing point.



Basis : W = 100 kg

The unknowns are F, R, P and G

Overall balances

Total	$F = P + 100$		(1)
A	$0.20\ F = 0.05\ P + 1.00\ (100)$		(2)
B	$0.80\ F = 0.95\ P$		(3)

Mixing point

Total	$F + R = G$		(4)
A	$0.20\ F + (1.00)\ R = 0.40\ G$		(5)
B	$0.80\ F = 0.60\ G$		(6)

Process + Separator

Total	$G = P + W + R$		(7)
A	$0.40\ G = 0.05\ P + (1.00)100 + (1.00)R$		(8)
B	$0.60\ G = 0.95\ P$		(9)

Substitute (1) in (2) $0.20\ (P + 100) = 0.05\ P + 100$ $\quad P = 533$ kg; $\quad F = 633$ kg

Equation (6) $0.80\ (633) = 0.60\ G$ $\quad G = 844$ kg

Equation (4) $633 + R = 844$
$R = 211$ kg

$$\frac{R}{F} = \frac{211\ \text{kg}}{633\ \text{kg}} = \mathbf{0.33}\ \frac{\textbf{kg R}}{\textbf{kg F}}$$

Check Equations (7) and (8) can be used to verify the results.

Equation (7)

$G = P + W + R$
$844 = 533 + 100 + 211$
$844\ \text{kg} = 844\ \text{kg}$

Equation (8)

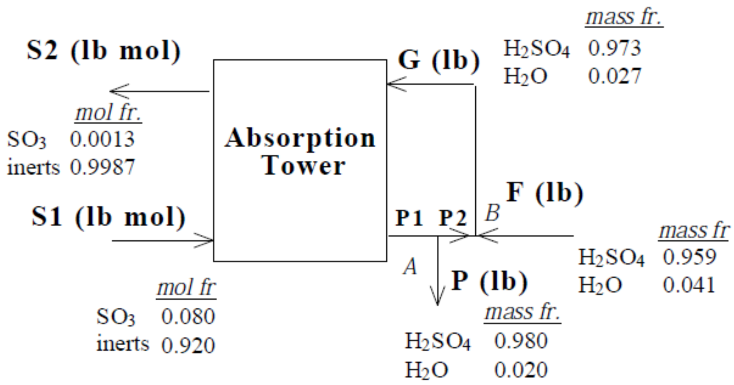
$0.40\ G = 0.05\ P + W + R$
$0.40\ (844) = 0.05\ (533) + 100 + 211$
$338\ \text{kg} = 338\ \text{kg}$

<u>Problem 2</u>

A contact sulfuric acid plant produces 98.0 % sulfuric acid, by absorbing SO_3 into a 97.3 % sulfuric acid solution. A gas containing 8.00 % SO_3 (remainder inerts) enters the SO_3 absorption tower at the rate of 28 lb mol per hour. 98.5 % of the SO_3 is absorbed in this tower. 97.3 % sulfuric acid is introduced into the top of the tower and 95.9 % sulfuric acid from another part of the process is used as make - up acid. The flow sheet is given in the figure with all of the known data on it.

Calculate the

a. Tons/day of 95.9 % H_2SO_4 make-up acid solution required.
b. Tons/day of 97.3 % H_2SO_4 solution introduced into the top of the tower.
c. Tons/day of 98 % H_2SO_4 solution produced.



Solution

This is a steady state process.

$$H_2O + SO_3 \text{ -----> } H_2SO_4$$

Calculate the SO_3 absorbed in the tower and the composition of S2.

Basis : 100 mol S1

$$\frac{0.08\ \text{mol } SO_3}{1\ \text{mol S1}} \left| \frac{100\ \text{mol S1}}{} \right. = 8\ \text{mol } SO_3$$

SO_3 absorbed in the tower = 8 (0.985) = 7.88 mol (the overall absorption)
SO_3 in stream S2 = (8 - 7.88) = 0.12 mol

Inerts in stream S2 = inerts in stream S1 = 92 mol
Calculate the composition of stream S2 (in mole fraction):

$$SO_2 = \frac{0.12}{(92 + 0.12)} = 0.0013 \qquad \text{inerts} = \frac{92}{(92 + 0.12)} = 0.9987$$

New Basis : S1 = 28 lb mol gas with 8 % SO_3 (equivalent to 1 hr).

6 unknown variables : F, G, P, P1, P2, S2.

For steady state systems : In - Out + Generated - Consumed = 0

Overall

$$H_2SO_4 : 0.959\,F - 0.980\,P + 28\,(0.08)\,(0.985) \left|\frac{1 \text{ mol } H_2SO_4}{1 \text{ mol } SO_3}\right| \frac{98 \text{ lb } H_2SO_4}{1 \text{ lb mol } H_2SO_4} - 0 = 0 \qquad (1)$$

$$SO_3 : 28\,(0.08) - 28\,(0.08)\,(0.015) + 0 - 28\,(0.08)\,(0.985) = 0 \qquad (2)$$

$$H_2O : 0.041\,F - 0.020\,P + 0 - 28\,(0.08)\,(0.985) \left|\frac{1 \text{ mol } H_2O}{1 \text{ mol } SO_3}\right| \frac{18 \text{ lb } H_2O}{1 \text{ lb mol } H_2O} = 0 \qquad (3)$$

Mixing point B

Total : F + P2 = G (4)
H_2SO_4 : 0.959 F + 0.980 P2 = 0.973 G (5)
H_2O : 0.041 F + 0.020 P2 = 0.027 G (6)

Separation point A

Total : P1 = P2 + P (7)

Equation (1): 0.959 F - 0.980 P + 216.22 = 0 (8)
Equation (3): 0.041 F - 0.020 P - 39.72 = 0 (9)

Solving (8) and (9) **F = 2060 lb** **P = 2240 lb**

Equation (4) : 2060 + P2 = G (10)
Equation (5) : 1975 + 0.980 P2 = 0.973 G (11)

Solving (10) and (11) **G = 6470 lb** **P2 = 4410 lb**

Use equation (6) as a check: 0.041 (2060) + 0.020 (4410) $\overset{?}{=}$ 0.027 (6470)
84.4 + 88.2 ≅ 175 lb
173 lb ≅ **175 lb**

Problem 3

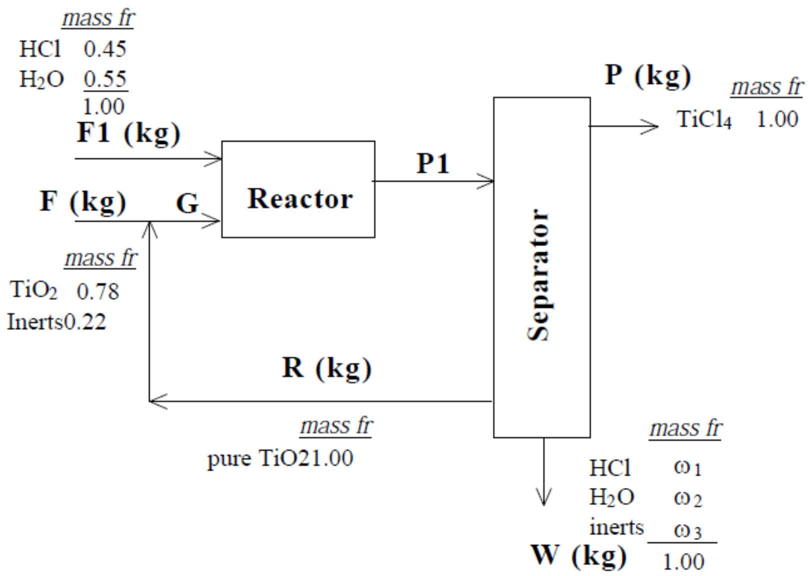
$TiCl_4$ can be formed by reacting titanium dioxide (TiO_2) with hydrochloric acid. TiO_2 is available as an ore containing 78 % TiO_2 and 22 % inerts. The HCl is available as 45 wt% solution (the balance is water). The per pass conversion of TiO_2 is 75 %. The HCl is fed into the reactor in 20 % excess based on the reaction. Pure unreacted TiO_2 is recycled back to mix with the TiO_2 feed.

$$TiO_2 + 4\,HCl \longrightarrow TiCl_4 + 2H_2O$$

For 1 kg of $TiCl_4$ produced, determine:

a. the kg of TiO_2 ore fed.
b. the kg of 45 wt % HCl solution fed.
c. the ratio of recycle stream to fresh TiO_2 ore (in kg).
(MW : TiO_2 79.9; HCl 36.47; $TiCl_4$ 189.7)

Solution



TiO_2 mass. fr.		HCl mass fr.		$TiCl_4$ mass fr.	
Ti	0.599	H	0.0274	Ti	0.252
O	0.401	Cl	0.9726	Cl	0.748

Though P could be selected as the basis, it is equally valid and easier to choose F = 100 kg because F1 can then be calculated immediately.

Calculate F1

$$\frac{1.00\ \text{kg F}}{} \left| \frac{0.78\ \text{kg } TiO_2}{1\ \text{kg F}} \right| \frac{1\ \text{kg mol } TiO_2}{79.9\ \text{kg } TiO_2} \left| \frac{4\ \text{kg mol HCl}}{1\ \text{kg mol } TiO_2} \right| 1.20$$

$$\times \frac{36.47\ \text{kg HCl}}{1\ \text{kg mol HCl}} \left| \frac{1\ \text{kg F1}}{0.45\ \text{kg HCl}} \right. = F1 = 3.80\ \text{kg}$$

System: Let the system be all of the units and mixing points jointly.

The unknowns are: P, m^W_{HCl} (or ω_1), $m^W_{H_2O}$ (or ω_2), m^W_{inerts} (or ω_3), and W.

The element balances are Ti, O, H, Cl, and also $\sum m_i = W\left(\text{or} \sum \omega_i = 1\right)$ and the inerts balance. If 5 of these are independent, we can solve for the variables whose values are unknown.

Ti: $(0.78)\,(1.00)\,(0.599) = (1.00)\,(P)\,(0.252)$

P = 1.85 kg (this value would be sufficient to calculate the answers to parts a and b)

Total: $1.00 + 3.80 = P + W = 1.85 + W$

$$W = 2.94\ \text{kg}$$

O: $$\frac{(3.80)(0.55)}{} \left| \frac{16}{18} \right. + (1.00)\,(0.78)\,(0.401) = \frac{(2.94)(\omega_2)}{} \left| \frac{16}{18} \right.$$

$$\omega_2 = 0.83$$

Cl: $$\frac{(3.80)(0.45)}{} \left| \frac{35.45}{36.47} \right. = \frac{1.85}{} \left| \frac{}{189.7} \right| 4 \left| \frac{35.45}{1} \right. + \frac{2.94\,(\omega_1)}{1} \left| \frac{35.45}{36.47} \right.$$

$$\omega_1 = 0.096$$

Inerts: $\omega_3 = 0.22\,(1.00)/(2.94) = 0.075$

As a check, $\Sigma\omega_i = 0.096 + 0.83 + 0.075 = 1.00$

a. $\frac{\text{kg F}}{\text{kg P}} = \frac{1.00}{1.854} = \mathbf{0.54} \frac{\textbf{kg}}{\textbf{kg}}$

b. $\frac{\text{kg F1}}{\text{kg P}} = \frac{3.798}{1.854} = \mathbf{2.05} \frac{\textbf{kg}}{\textbf{kg}}$

These values can be calculated solely from the data given and the Ti balance.

To calculate the third part of the problem, we need to involve the recycle stream in the balances. Let the system be the mixing point. No reaction occurs. The balances are in kg.

Total: $100 + R = G$

TiO_2: $100\,(0.78) + R\,(1.00) = m^{G}_{TiO_2}$

Inerts: $100\,(0.22) = m^{G}_{inerts}$

Next use the system of reactor plus separator.

Total $G + 3.80 = 1.85 + 2.94 + R$

The component balances will not add any independent equations, hence the information about the fraction conversion must be used via a compound balance on TiO_2:

	In		*Out*		*Generation*		*Consumption*
TiO_2:	$100(0.78) + R(1.00)$	–	$R(1.00)$	+	0	–	$0.75[100(0.78) + R] = 0$

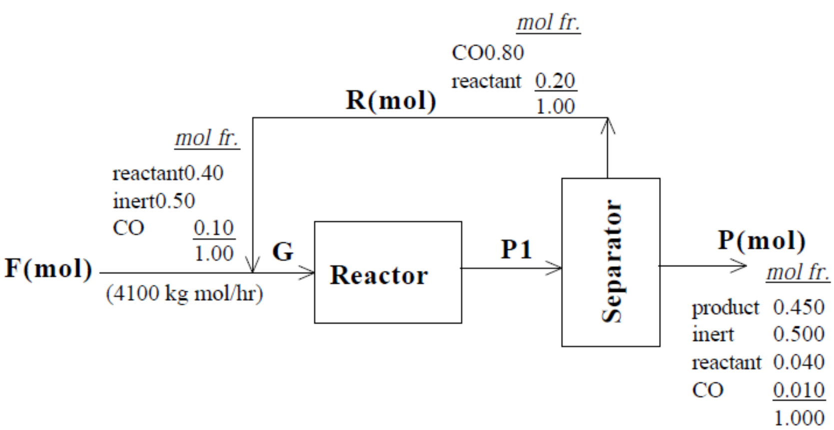
$R = 26$ kg

c.

$$\frac{\text{kg R}}{\text{kg F}} = \frac{26}{100} = \mathbf{0.26}$$

Problem 4

Many chemicals generate emissions of volatile compounds that need to be controlled. In the process shown in the accompanying figure, the CO in the exhaust is substantially reduced by separating it from the reactor effluent and recycling the unreacted CO together with the reactant. Although the product is proprietary, information is provided that the fresh feed stream contains 40 % reactant, 50 % inert and 10 % CO, and that on reaction 2 moles of reactant yield 2.5 moles of product. Conversion of the reactant to product is 73 % on one pass through the reactor, and 90 % for the over all process. The recycle stream contains 80% CO and 20% reactant. Calculate the ratio of moles of the recycle stream to moles of the product stream.



Solution

This is a steady state process with reaction and recycle.

Basis : 4100 kg mol F

Unknowns : P and its components

Calculate the composition of stream P

Product

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{40 \text{ mol reactant}}{100 \text{ mol F}} \right| \frac{90 \text{ mol react}}{100 \text{ mol reactant}} \left| \frac{2.5 \text{ mol product}}{2 \text{ mol reactant}} \right.$$

$$= 1845 \text{ kg mol product}$$

Inert

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{50 \text{ mol inert}}{100 \text{ mol F}} \right. = 2050 \text{ kg mol inert}$$

Reactant

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{40 \text{ mol reactant}}{100 \text{ mol F}} \right| \frac{0.10 \text{ mol unreacted}}{1.0 \text{ mol reactant}} = 164 \text{ kg mol reactant}$$

CO

$$\frac{4100 \text{ kg mol F}}{} \left| \frac{10 \text{ mol CO}}{100 \text{ mol F}} \right| \frac{0.10 \text{ mol unreacted CO}}{1.0 \text{ mol CO}} = 41 \text{ kg mol CO}$$

$$P = 1845 + 2050 + 164 + 41 = 4100 \text{ kg mol}$$

Mixing point

No reaction occurs so that a total balance is satisfactory: $G = 4100 + R$

Reactor plus separator

Because a reaction occurs, an overall balance is not appropriate, but a reactant balance (a compound balance) is.

Reactant:

$$\underset{In}{0.40(4100) + 0.20R} - \underset{Out}{(0.20R + 0.040(4100))} + \underset{Gen.}{0} - \underset{Consumption}{0.73[0.40(4100) + 0.20R]} = \underset{Accum.}{0}$$

$$\mathbf{R = 6460 \text{ kg mol}}$$

$$\frac{R}{P} = \frac{6460}{4100} = 1.58$$

$$\frac{\text{mol recycle}}{\text{mol product}} = \frac{6460}{1845} = 3.5$$

Problem 5

Perchloric acid ($HClO_4$) can be prepared as shown in the diagram below from $Ba(ClO_4)_2$ and $HClO_4$. Sulfuric acid is supplied in 20% excess to react with $Ba(ClO_4)_2$. If 17,400 lb $HClO_4$ leave the separator and the recycle is 6125 lb $Ba(ClO_4)_2$ over the time period, calculate :

a. The overall conversion of $Ba(ClO_4)_2$.
b. The lb of $HClO_4$ leaving the separator per lb of feed.
c. The lb of H_2SO_4 entering the reactor.
d. The per pass conversion of $Ba(ClO_4)_2$.

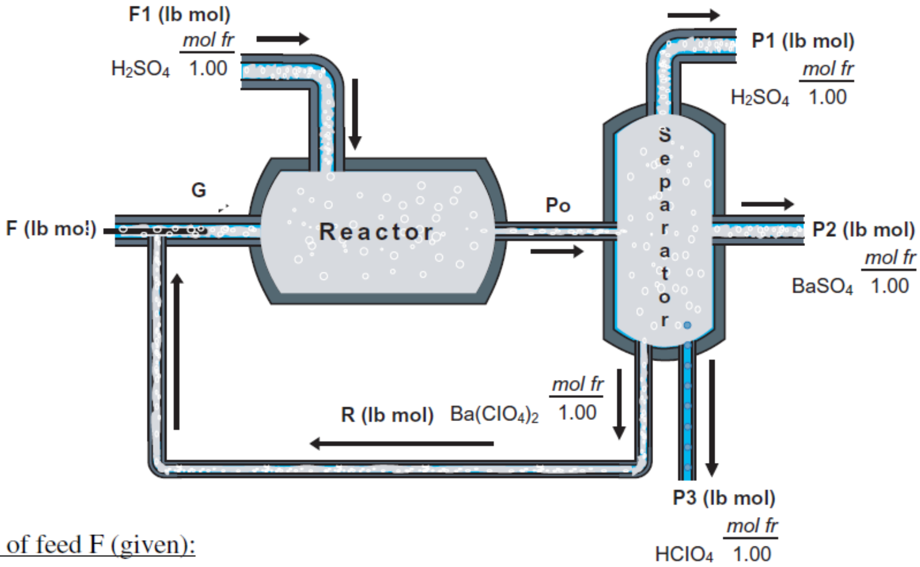
Note : 20 % H_2SO_4 is based on the total $Ba(ClO_4)_2$ entering the reactor.

$$Ba(ClO_4)_2 + H_2SO_4 \longrightarrow BaSO_4 + 2HClO_4$$

MW: $Ba(ClO_4)_2$ 336; $BaSO_4$ 233; H_2SO_4 98; $HClO_4$ 100.5

Solution

This is a steady state problem with reaction and recycle.



Composition of feed F (given):

	mass fr.	*M W*	*mol fr*
$Ba(ClO_4)_2$	0.90	336	0.729
$HClO_4$	0.10	100.5	0.271

$$\frac{17400\,\text{lb HClO}_4}{} \left| \frac{1\,\text{lb mol HClO}_4}{100.5\,\text{lb HClO}_4} \right. = 173.1\,\text{lb mol HClO}_4$$

$$\frac{6125\,\text{lb Ba(ClO}_4)_2}{} \left| \frac{1\,\text{lb mol Ba(ClO}_4)_2}{336\,\text{lb Ba(ClO}_4)_2} \right. = 18.23\,\text{lb mol Ba(ClO}_4)_2$$

This is a steady state process with reaction.

we will pick P3 = 17,400 lb as the basis equivalent to 17,400/100.5 = 173.13 lb **mol**

The unknown are: F, F1, P1, and P2.

We can make 5 element balances: Ba, Cl, O, H, S, hence if 4 balances are independent, a unique solution exists.

a The overall percent conversion of $Ba(ClO_4)_2$ is **100%** since no $Ba(ClO_4)_2$ leaves the overall system.

Overall element balances (lb mol)

Cl:
$$\frac{F\,\text{lb mol}}{} \left| \frac{0.729\,\text{lb mol Ba(ClO}_4)_2}{1\,\text{lb mol F}} \right| \frac{2\,\text{lb mol Cl}}{1\,\text{lb mol Ba(ClO}_4)_2}$$

$$+ \frac{F\,\text{lb mol}}{} \left| \frac{0.271\,\text{lb mol HClO}_4}{1\,\text{lb mol F}} \right| \frac{1\,\text{lb mol Cl}}{1\,\text{lb mol HClO}_4}$$

$$= \frac{173.13\,\text{lb mol P3}}{} \left| \frac{1\,\text{lb mol HClO}_4}{1\,\text{lb mol P3}} \right| \frac{1\,\text{lb mol Cl}}{1\,\text{lb mol HClO}_4}$$

F = 100.1 lb mol

$$\text{Ba:}\quad \frac{(100.1)\text{ lb mol}}{} \left| \frac{0.729\text{ lb mol Ba(ClO}_4)_2}{1\text{ lb mol F}} \right| \frac{1\text{ lb mol Ba}}{1\text{ lb mol Ba(ClO}_4)_2}$$

$$= \frac{\text{P2 lb mol}}{} \left| \frac{1\text{ lb mol Ba}}{1\text{ lb mol P2}} \right.$$

$$\text{P2} = 73.0\text{ lb mol}$$

$$\text{S:}\quad \frac{\text{F1 lb mol}}{} \left| \frac{1\text{ lb mol H}_2\text{SO}_4}{1\text{ lb mol F1}} \right| \frac{1\text{ lb mol S}}{1\text{ lb mol H}_2\text{SO}_4}$$

$$= \frac{\text{P1 lb mol}}{} \left| \frac{1\text{ lb mol S}}{1\text{ lb mol P1}} \right. + \frac{73.0\text{ lb mol BaSO}_4}{} \left| \frac{1\text{ lb mol S}}{1\text{ lb mol BaSO}_4} \right.$$

The H and O balances are not independent balances from what we have so far. We need one more equation.

Mixing point

$$\text{Total:}\ 100.1 + \frac{6125}{336} = G = 118.3\text{ lb mol}$$

Now we can calculate F1 as 1.2 times the $Ba(ClO_4)_2$ in G. The number of moles of $Ba(ClO_4)_2$ in G is

$$Ba(ClO_4)_2:\quad 100.1\,(0.729) + \frac{6125}{336} = 91.2$$

$$1.2\,(91.2) = \mathbf{109\ lb\ mol = F1}$$

b. $$\frac{\text{lb HClO}_4}{\text{lb F}} = \frac{17400\text{ lb HClO}_4\text{ exiting}}{100.1(0.729)(336) + 100.1(0.271)(100.5)} = \mathbf{0.64}\ \frac{\mathbf{lb\ HClO_4}}{\mathbf{lb\ F}}$$

c. F1 = 109 lb mol or **10,700 lb H_2SO_4**

To get the fraction conversion f on one pass through the reactor, we make a compound balance for $Ba(ClO4)_2$ for the system of the reactor plus the separator.

Accum.		*In*		*Out*		*Generation*	*Consumption*
0	=	91.2	–	$\frac{6125}{336}$	+	0	–f(91.2)

$$\mathbf{f = 0.80}$$