Reactor plus Separator To avoid calculating the reactor output stream properties, we will make the system the reactor plus the separator. First we need to calculate the pounds of water consumed in the reaction per pound of sucrose consumed in the reaction.

1 mole sucrose uses 1 mole water

$$\frac{1 \text{ mol } W}{1 \text{ mol } S} \bigg| \frac{1 \text{ mol } S}{342.35 \text{ lb } S} \bigg| \frac{18 \text{ lb } W}{1 \text{ mol } W} = 0.0526 \frac{\text{lb } W}{\text{lb } S}$$

Total: $F' = R + P = R + 100$ [redundant equation to (a)]

Water: *In* — *Out* — *Consumed* (d)

$$F'(1 - 0.05 - \omega_{S,F'}) - (R + 100)(1 - \omega_{S,R} - \omega_{I,R}) - (F'\omega_{S,F'})(0.90)(0.0526) = 0$$

Sucrose: *In* — *Out* — *Consumed* (e)

$$F'\omega_{S,F'} - (R + 100)\omega_{S,R} - (F'\omega_{S,F'})(0.90) = 0$$

We have five independent equations (a)–(e) that can be solved for the five unknown values of the variables listed in steps 5 and 6; the value of P is given by the overall total materials balance. Either by successive substitution of Eqs. (a)–(e) into each other or by use of a computer program (see Sec. 2.7), you can find

$$R = 20.9 \text{ lb}$$

$$\omega_{I,R} = \omega_{I,P} = 0.279$$

2.6-3 Bypass and Purge

Two additional commonly encountered types of process streams are shown in Fig. 2.19.

- **(a)** A **bypass** stream—one that skips one or more stages of the process and goes directly to another stage
- **(b)** A **purge** stream—a stream bled off to remove an accumulation of inerts or unwanted material that might otherwise build up in the recycle stream

A bypass stream is 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.

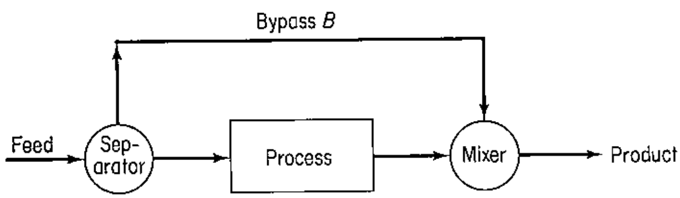

Figure 2.19a

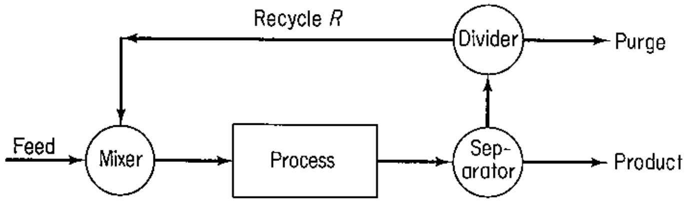

Figure 2.19b Recycle stream with purge.

As an example of the use of a purge stream, consider the production of NH_3. Steam reforming, with feedstock natural gas, LPG, or naphtha, is the most widely accepted process for ammonia manufacture. The route includes four major chemical steps:

Reforming:	$CH_4 + H_2O$	$\longrightarrow$	$CO + 3H_2$
Shift:	$CO + H_2O$	$\longrightarrow$	$CO_2 + H_2$
Methanation:	$CO + 3H_2$	$\longrightarrow$	$H_2O + CH_4$
Synthesis:	$3H_2 + N_2$	$\longrightarrow$	$2NH_3$

In the final stage, for the fourth reaction, the synthesis gas stream is approximately a 3:1 mixture of hydrogen to nitrogen, with the remainder about 0.9% methane and 0.3% argon.

Compressors step up the gas pressure from atmospheric to about 3000 psi—the high pressure that is needed to favor the synthesis equilibrium. Once pressurized and mixed with recycle gas, the stream enters the synthesis converter, where ammonia is catalytically formed at 400 to 500°C. The NH_3 is recovered as liquid via refrigeration, and the unreacted syngas is recycled.

In the synthesis step, however, some of the gas stream must be purged to prevent buildup of argon and methane. But purging causes a significant loss of hydrogen that could be used for additional ammonia manufacture, a loss that process designers seek to minimize.

Do you understand why the recycle process without a purge stream will cause an impurity to build up even though the recycle rate is constant? The purge rate is adjusted so that the amount of purged material remains below an acceptable specified economic level or so that the

$$\begin{Bmatrix}\text{rate of}\\ \text{accumulation}\end{Bmatrix} = 0 = \begin{Bmatrix}\text{rate of entering material}\\ \text{and/or production}\end{Bmatrix} - \begin{Bmatrix}\text{rate of purge}\\ \text{and/or loss}\end{Bmatrix}$$

Calculations for bypass and purge streams introduce no new principles or techniques beyond those presented so far. Two examples will make this clear.

EXAMPLE 2.28 Bypass Calculations

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 Fig. E2.28. What fraction of the butane-free gasoline is

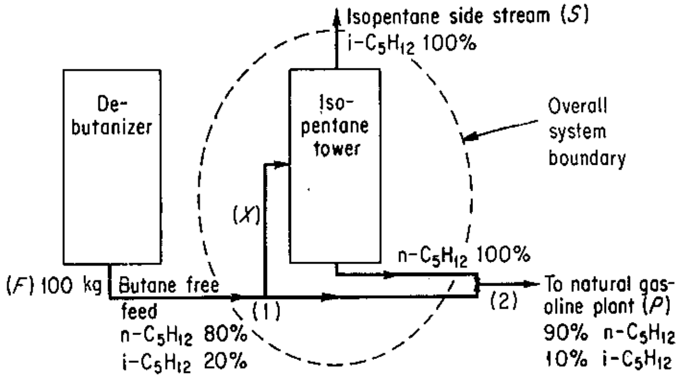

Figure E2.28

passed through the isopentane tower? Detailed steps will not be listed in the analysis and solution of this problem.

Solution

By examining the flow diagram you can see that part of the butane-free gasoline bypasses the isopentane tower and proceeds to the next stage in the natural gasoline plant. All the compositions are known. What kind of balances can we write for this process? We can write the following:

Basis: 100 kg feed

(a) *Overall balances* (each stream is designated by the letter *F*, *S*, or *P*):

Total material balance:

$$\underline{In} \quad \underline{Out}$$

$$100 = S + P \tag{a}$$

Component balance (n-C_5), *tie component:*

$$\underline{In} \quad \underline{Out}$$

$$100(0.80) = S(0) + P(0.90) \tag{b}$$

Consequently,

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

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

The overall balances will not tell us the fraction of the feed going to the isopentane tower; for this we need another balance.

(b) *Balance around isopentane tower:* Let x = lb of butane-free gas going to isopentane tower and y be the n–C_5H_{12} stream leaving the isopentane tower.

Total material balance:

$$\underline{In} \quad \underline{Out}$$

$$x = 11.1 + y \tag{c}$$

Component (n–C_5), *a tie component:*

$$x(0.80) = y \tag{d}$$

Consequently, combining (c) and (d),

$$x = 11.1 + 0.8x$$

$x = 55.5$ kg or the desired fraction is 0.555

Another approach to this problem is to make a balance at mixing points (1) or (2). Although there are no pieces of equipment at those points, you can see that streams enter and leave the junction.

(c) *Balance around mixing point* (2):

material into junction = material out

Total material:

$$(100 - x) + y = 88.9 \tag{e}$$

Component (iso-C_5):

$$(100 - x)(0.20) + 0 = 88.9(0.10) \tag{f}$$

Equation (f) avoids the use of y. Solving yields

$$20 - 0.2x = 8.89$$

$$x = 55.5 \text{ kg as before}$$

EXAMPLE 2.29 Purge

Considerable interest exists in the conversion of coal into more convenient liquid products for subsequent combustion. Two of the main gases that can be generated under suitable conditions from insitu coal combustion in the presence of steam (as occurs naturally in the presence of groundwater) are H_2 and CO. After cleanup, these two gases can be combined to yield methanol according to the following equation

$$CO + 2H_2 \longrightarrow CH_3OH$$

Figure E2.29 illustrates the process.

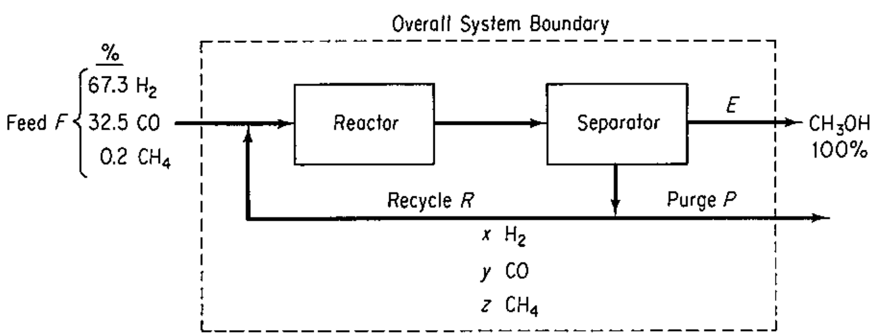

Figure E2.29

You will note in Fig. E2.29 that some CH_4 enters the process, but the CH_4 does not participate in the reaction. A purge stream is used to maintain the CH_4 concentration in the exit to the separator at no more than 3.2 mol%. 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

Steps 1, 2 and 3 Figure E2.29 is the sketch of the process. We will make balances about the whole process using the system designated by the dashed line, and also make a balance about the reactor plus separator to calculate the amount of recycle. Each of the stream flows has been labeled, and because the composition of the recycle and purge stream is not known, we have designated by x, y, and z, respectively, the mole fractions of H_2, CO, and CH_4. The ethanol stream is 100% CH_3OH; the purge and recycle streams have the same compositions.

Step 4 Take a basis of 100 moles of feed.

Step 5 The unknown stream flows and mole fractions of the components are R, E, P, x, y, and z.

Step 6 We can make three independent elemental material balances for the overall process: H_2, C, and O balances. A CO balance on the reactor plus separator will provide one additional balance. How can we obtain fifth and sixth balances so that the system of equations is determinate? One piece of information given in the problem statement that we have not used is the information about the upper limit on the CH_4 concentration in the purge stream. This limit can be expressed as $z \leqq 0.032$. Let us make

$$z = 0.032 \tag{a}$$

Another piece of information is the implicit balance,

$$x + y + z = 1 \tag{b}$$

Steps 7 and 8 The overall balances are (in moles):

$$H_2: \quad 67.3 + 0.2(2) = E(2) + P(x + 2z) \tag{c}$$

$$C: \quad 32.5 + 0.2 = E(1) + P(y + z) \tag{d}$$

$$O: \quad 32.5 = E(1) + P(y) \tag{e}$$

For a system composed of the reactor plus the separator (chosen to avoid calculating the unknown information about the reactor direct output), the CO balance is

$$CO: \quad \underbrace{32.5 + Ry}_{\textit{In}} - \underbrace{y(R + P)}_{\textit{Out}} = \underbrace{(32.5 + Ry)(0.18)}_{\textit{Consumed}} \tag{f}$$

Would a H_2 balance on the reactor plus separator yield any additional information not given in Eq. (f)? The balance would be

$$H_2: \quad 67.3 + Rx - x(R + P) = (67.3 + Rx)(0.18) \tag{g}$$

Experienced engineers would say that the hydrogen balance is redundant. You can verify this conclusion by looking at the coefficient matrix of Eqs. (f) and (g):

$$0.82(32.5 + Ry) = (R + P)y = Ry + Py$$

$$0.82(67.3 + Rx) = (R + P)x = Rx + Px$$

or

$$0.82(32.5) = (0.18y)R + (y)P$$
$$0.82(67.3) = (0.18x)R + (x)P$$

What is the rank of

$$M = \begin{bmatrix} 0.18y & y \\ 0.18x & x \end{bmatrix}$$

The det $[M] = 0.18yx - 0.18yx = 0$, hence the rank of M is one, and Eqs. (f) and (g) are not independent.

Step 9 Equation (a) can be substituted into Eqs. (b)–(f) and the resulting five equations solved by successive substitution or by using one of the computer programs on the disk in the pocket in the back of this book. 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

Step 10 Check to see that each of the balances (b)–(f) is satisfied.

Up to now we have discussed material balances of a rather simple order of complexity. If you try to visualize all the calculations that might be involved in even a moderate-sized plant, as illustrated in Fig. 2.4, the stepwise or simultaneous solution of material balances for each phase of the entire plant may seem to be a staggering task, but is a task that can be eased considerably by the use of computer codes as discussed in Sec. 2.7. Keep in mind that a plant can be described by a number of individual, interlocking material balances each of which, however tedious they are to set up and solve, can be set down according to the principles and techniques discussed in this chapter. In application there is always the problem of collecting suitable information and evaluating its accuracy, but this matter calls for detailed familiarity with any specific process and is not a suitable topic for discussion here. We can merely remark that some of the problems you will encounter have such conflicting data or so little useful data that the ability to perceive what kind of data are needed is the most important attribute you can bring to bear in their solution.

Self-Assessment Test

1. Explain what recycle and bypassing involve by means of words and also by a diagram.
2. Repeat for the term "purge."
3. If the components in the feed to a process appear in stoichiometric quantities and the subsequent separation process is complete so that all the unreacted reactants are recycled, what is the ratio of reactants in the recycle stream?