5. Methane burns with O_2 to produce a gaseous product that contains CH_4, O_2, CO_2, CO, H_2O, and H_2. How many independent element balances can you write for this system?
6. Solve the problems (1, 2 & 3) using element balances.
7. Pure carbon is burned in oxygen. The flue gas analysis is: CO_2 75 mol%, CO l4 mol% & O_2 11 mol%. What was the percent excess oxygen used?
8. Toluene, C_7H_8, is burned with 30% excess air. A bad burner cause 15% of the carbon to form soot (pure C) deposited on the walls of the furnace, what is the Orsat analysis of the gases leaving the furnace?
9. A synthesis gas analyzing CO_2: 6.4%, O_2: 0.2%, CO: 40.0% and H_2: 50.8% (the balance is N_2) is burned with excess dry air. The problem is to determine the composition of the flue gas. How many degrees of freedom exist in this problem, that is, how many additional variables must be specified?
10. A coal analyzing 65.4% C, 5.3% H, 0.6% S, 1.1% N, 18.5% O, and 9.1% ash is burned so that all combustible is burnt out of the ash. The flue gas analyzes 13.00% CO_2, 0.76% CO, 6.17% O_2, 0.87% H_2, and 79.20% N_2. All of the sulfur burns to SO_2, which is included in the CO_2 in the gas analysis (i.e., CO_2 + SO_2 = 13%). Calculate:
    a. Pounds of coal fired per 100 lb mol of dry flue gas as analyzed;
    b. Ratio of moles of total combustion gases to moles of dry air supplied;
    c. Total moles of water vapor in the stack gas per 100 lb of coal if the entering air is dry;
    d. Percent excess air.
11. A hydrocarbon fuel is burnt with excess air. The Orsat analysis of the flue gas shows 10.2% CO_2, 1.0% CO, 8.4% O_2, and 80.4% N_2. What is the atomic ratio of H to C in the fuel?

Answers:

1. 186 kg
2. 887 lb
3. (a) C_6H_{12} = 139 mol/hr; (b) H_2O = 453 mol/hr; (c) CO = 347 mol/hr; (d) H_2 = 640 mol/hr; (e) C_6H_{14} = 53.3 mol/hr.
4. Two
5. Three
6. See the answers to the problems (1, 2 &3).
7. 4.5%
8. 9.1% CO_2, 8.9% O_2, 82% N_2
9. 1
10. (a) 252; (b)1.063; (c) 2.31; (d) 33.8%
11. 0.81

2.6 Material Balance Problems Involving Multiple Units

- A **process flowsheet (flowchart)** is a graphical representation of a process. A flowsheet describes the **actual process** in sufficient detail that you can use it to formulate material (and energy) balances.

Figure 1l.1a illustrates a serial combination of mixing and splitting stages. In a **mixer**, two or more entering streams of different **compositions are combined**. In a **splitter**, two or more streams exit, all of which have the **same composition**. In a **separator**, the exit streams can be of **different compositions**.

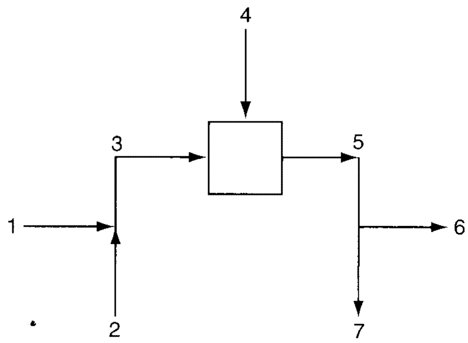

Figure 11.1a serial mixing and splitting in a system without reaction. Streams 1 plus 2 mix to form Stream 3, and Stream 5 is split into Streams 6 and 7.

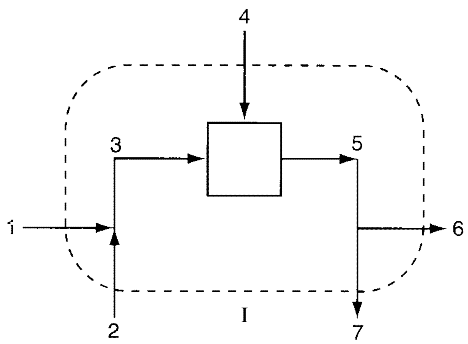

Figure 11.1b the dashed line I designates the boundary for overall material balances made on the process in Figure l1.1a.

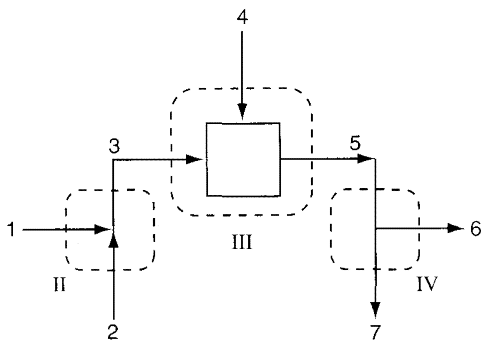

Figure 11.1c Dashed lines II, III and IV designate the boundaries for material balances around each of the individual units comprising the overall process.

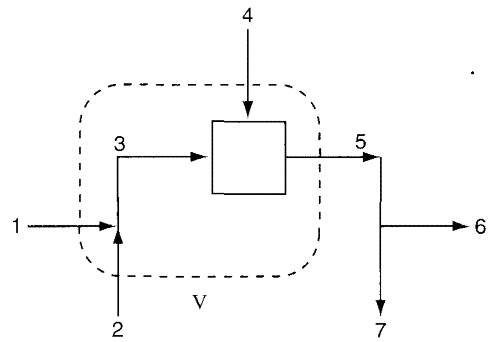

Figure 11.1d the dashed line V designates the boundary for material balances around a system comprised of the mixing point plus the unit portrayed by the box.

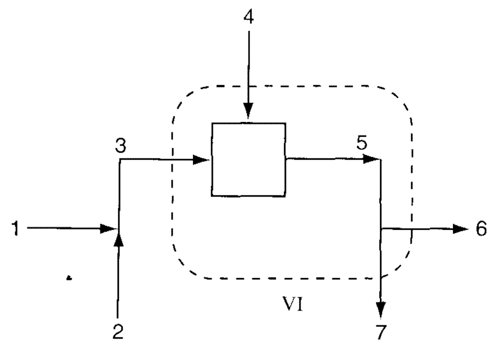

Figure 11.1e the dashed line VI designates the boundary for material balances about a system comprised of the unit portrayed by the box plus the splitter.

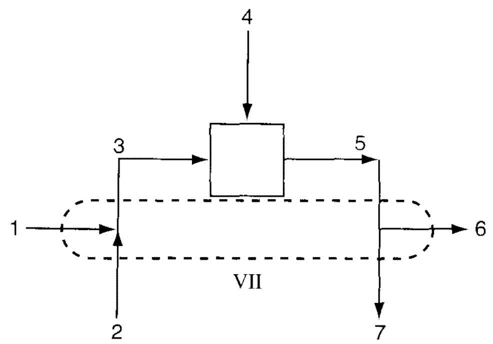

Figure 11.1f the dashed line VII designates the boundary for material balances about a system comprised of the mixer plus the splitter.

Example 32

Acetone is used in the manufacture of many chemicals and also as a solvent. In its latter role, many restrictions are placed on the release of acetone vapor to the environment. You are asked to design an acetone recovery system having the flow sheet illustrated in Figure El1.1. All the concentrations shown in El1.1 of both the gases and liquids are specified in weight percent in this special case to make the calculations simpler. Calculate, A, F, W, B, and D per hour. G = 1400 kg/hr.

Solution

This is an **open, steady-state process** without reaction. **Three subsystems** exist.

Pick 1 hr as a basis so that G = 1400 kg.

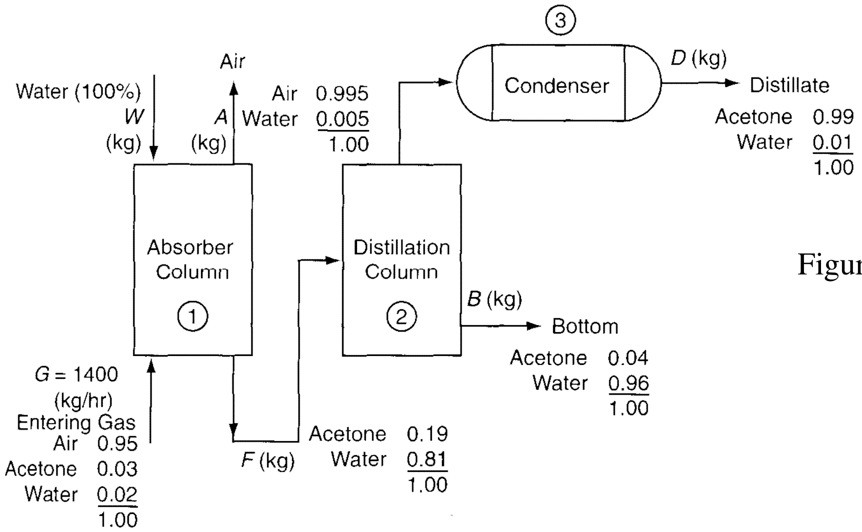

Figure E11.1

The mass balances for **Unit 1 (Absorber Column)**

	In		*Out*	
Air:	1400 (0.95)	=	$A(0.995)$	(a)
Acetone:	1400 (0.03)	=	$F(0.19)$	(b)
Water:	1400 (0.02) + $W(1.00)$	=	$F(0.81)$ + $A(0.005)$	(c)

Solve Equations (a), (b), and (c) to get A =1336.7 kg/hr, F = 221.05 kg/hr and W = 157.7 kg/hr

(**Check**) Use the total balance (Absorber Column).

G + W	=	A + F
1400		1336
157.7		221.05
1557.7	≅	1557.1

The mass balances for the combined **Units 2 plus 3** (**Distillation & Condenser**) are:

Acetone: $221.05(0.19) = D(0.99) + B(0.04)$ (d)

Water: $221.05(0.81) = D(0.01) + B(0.96)$ (e)

Solve Equations (d) and (e) simultaneously to get D = 34.90kg/hr and B = 186.1 kg/hr

(**Check**) Use the total balance (Distillation & Condenser)

$$F = D + B \text{ or } 221.05 \cong 34.90 + 186.1 = 221.0$$

Note

As a matter of interest, what other mass balances could be written for the system and substituted for any one of the Equations (a) through (e)? Typical balances would be **the overall balances**

	In		*Out*					
Air:	$G\,(0.95)$	=	$A(0.995)$					(f)
Acetone:	$G(0.03)$	=			$D(0.99)$	+	$B(0.04)$	(g)
Water:	$G\,(0.02) + W$	=	$A(0.005)$	+	$D(0.01)$	+	$B(0.96)$	(h)
Total	$G + W$	=	A	+	D	+	B	(i)

Example 33

In the face of higher fuel costs and the uncertainty of the supply of a particular fuel, many companies operate two furnaces, one fired with natural gas and the other with fuel oil. The gas furnace uses air while the oil furnace uses an oxidation stream that analyzes: O_2, 20%; N_2, 76%; and CO_2, 4%. The stack gases go up a common stack, See Figure El1.2.

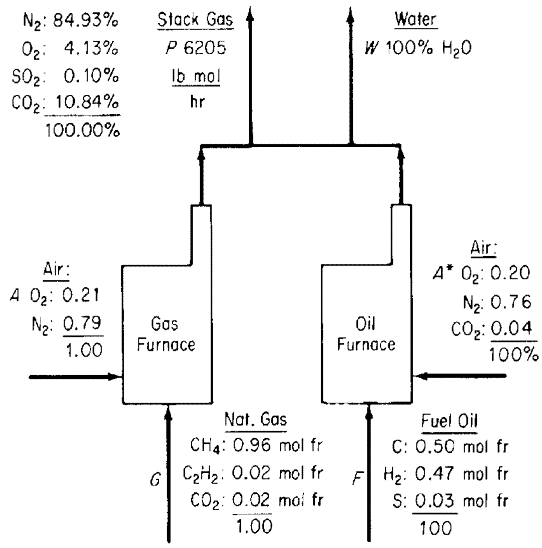

Figure E11.2

The reserve of fuel oil was only 560 bbl. How many hours could the company operate before shutting down if no additional fuel oil was attainable? How many lb mol/hr of natural gas were being consumed? The minimum heating load for the company when translated into the stack gas output was 6205 lb mol/hr of dry stack gas. The molecular weight of the fuel oil was 7.91 lb/lb mol, and its density was 7.578 lb/gal.

Solution

This is an **open**, **steady-state process** with **reaction**. Two **subsystems** exist.

Basis: 1 hr, so that P = 6205 lb mol

The **overall balances** for the **elements** are (in pound moles)

	In				*Out*
2H:	$G(1.94)$	+	$F(0.47)$	=	$W(1)$
2N:	$A(0.79)$	+	$A^*(0.76)$	=	$6205(0.8493)$
2O:	$A(0.21)$	+	$A^*(0.20 + 0.04)$		$6205(0.0413 + 0.001 + 0.1084)$
			$+ G(0.02)$	=	$+W(^1/_2)$
S:	$F(0.03)$			=	$6205(0.0010)$
C:	$G(0.96)$	+	$(2)(0.02) + 0.02$		
		+	$F(0.50) + 0.04A^*$	=	$6205(0.1084)$

Solve the **S** balance **for F**; the sulfur is a **tie component**. Then solve for the other four balances simultaneously for G. The results are:

F = 207 lb mol/hr and G = 499 lb mol/hr

Finally, the fuel oil consumption is

$$\frac{207 \text{ lb mol}}{\text{hr}}\left|\frac{7.91 \text{ lb}}{\text{lb mol}}\right|\frac{\text{gal}}{7.578 \text{ lb}}\left|\frac{\text{bbl}}{42 \text{ gal}}\right. = 5.14 \text{ bbl/hr}$$

If the fuel oil reserves were only 560 bbl,

$$\frac{560 \text{ bbl}}{5.14 \frac{\text{bbl}}{\text{hr}}} = 109 \text{ hr}$$

Example 34

Figure E11.3 shows the process and the known data. You are asked to calculate the compositions of every flow stream, and the fraction of the sugar in the cane that is recovered.

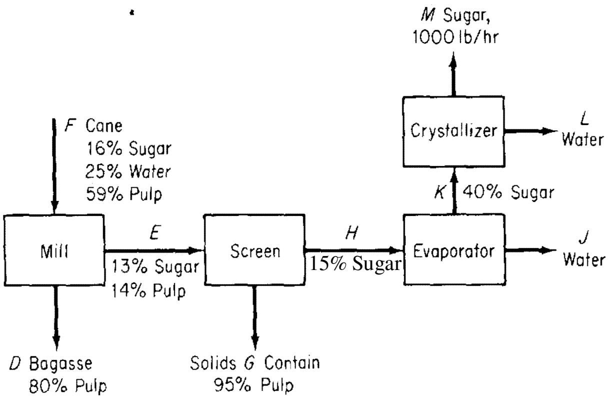

Figure E11.3

Solution

Basis: l hour (M= 1000lb)

Let S = sugar, P = pulp, and W = water.

For the crystallizer the equations are (using $\omega_W^K = 1 - 0.40 = 0.60$)

Sugar: K (0.40) = L (0) + 1000

Water: K (0.60) = L + 0

From which you get K = 2500 lb and L = 1500 lb.

Check using the total flows: 2500 = 1500 + 1000 = 2500

Using same method for solution: **evaporator**, **screen**, and lastly solve the equations for the **mill**.
The results for all of the variables are:

lb	*mass fraction*
$D = 16{,}755$	$\omega_S^D = 0.174$
$E = 7{,}819$	$\omega_W^D = 0.026$
$F = 24{,}574$	$\omega_W^E = 0.73$
$G = 1{,}152$	$\omega_S^G = 0.014$
$H = 6{,}667$	$\omega_W^G = 0.036$
$J = 4{,}167$	$\omega_W^H = 0.85$
$K = 2{,}500$	$\omega_W^K = 0.60$
$L = 1{,}500$	
$M = 1000$	

The fraction of sugar recovered = [product (sugar) / in (sugar)]
= [1000/(24,574)*(0.16)] = 0.25

Problems

1. A two-stage separations unit is shown in Figure SAT11P1. Given that the input stream Fl is 1000 lb/hr, calculate the value of F2 and the composition of F2.

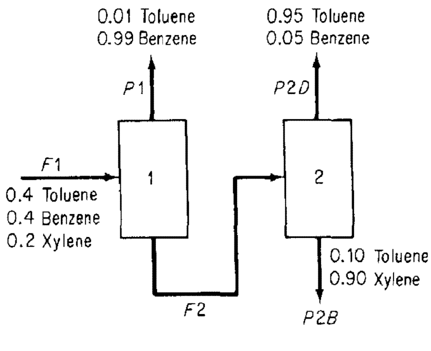

Figure SAT11P1

2. A simplified process for the production of SO_3 to be used in the manufacture of sulfuric acid is illustrated in Figure SAT11P2. Sulfur is burned with 100% excess air in the burner, but for the reaction $S + O_2 \rightarrow SO_2$, only 90% conversion of the S to SO_2 is achieved in the burner. In the converter, the conversion of SO_2 to SO_3 is 95% complete. Calculate the kg of air required per 100 kg of sulfur burned, and the concentrations of the components in the exit gas from the burner and from the converter in mole fractions.

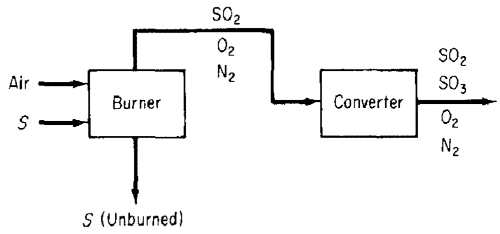

Figure SAT11P2

3. In the process for the production of pure acetylene, C_2H_2 (see Figure SAT11P3), pure methane (CH_4), and pure oxygen are combined in the burner, where the following reactions occur:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \quad (1)$$

$$CH_4 + 1\tfrac{1}{2}O_2 \rightarrow 2H_2O + CO \quad (2)$$

$$2CH_4 \rightarrow C_2H_2 + 3H_2 \quad (3)$$

a. Calculate the ratio of the moles of O_2 to moles of CH_4 fed to the burner.
b. On the basis of 100 lb mol of gases leaving the condenser, calculate how many pounds of water are removed by the condenser.
c. What is the overall percentage yield of product (pure) C_2H_2, based on the carbon in the natural gas entering the burner?

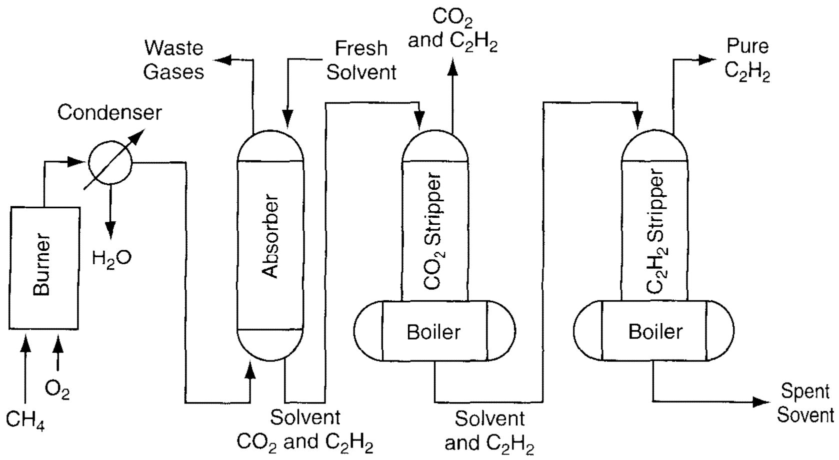

Figure SAT11P3

The gases from the burner are cooled in the condenser that removes all of the water. The analysis of the gases leaving the condenser is as follows:

	Mol %
C_2H_2	8.5
H_2	25.5
CO	58.3
CO_2	3.7
CH_4	4.0
Total	100.0

These gases are sent to an absorber where 97% of the C_2H_2 and essentially all the CO_2 are removed with the solvent. The solvent from the absorber is sent to the CO_2 stripper, where all the CO_2 is removed. The analysis of the gas stream leaving the top of the CO_2 stripper is as follows:

	Mol %
C_2H_2	7.5
CO_2	92.5
Total	100.0

The solvent from the CO_2 stripper is pumped to the C_2H_2 stripper, which removes all the C_2H_2 as a pure product.

Answers:

1. Assume that the compositions in the figure are mass fractions. Then:

	lb	mass fraction
Toluene	396	0.644
Benzene	19.68	0.032
Xylene	200	0.325

2. 863 lb air/lb S

	Converter	Burner
SO_2	0.5%	9.5%
SO_3	9.4	—
O_2	7.4	11.5
N_2	82.7	79.0

3. (a) 1.14; (b) 2240 lb; (c) 9.9%.

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

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.