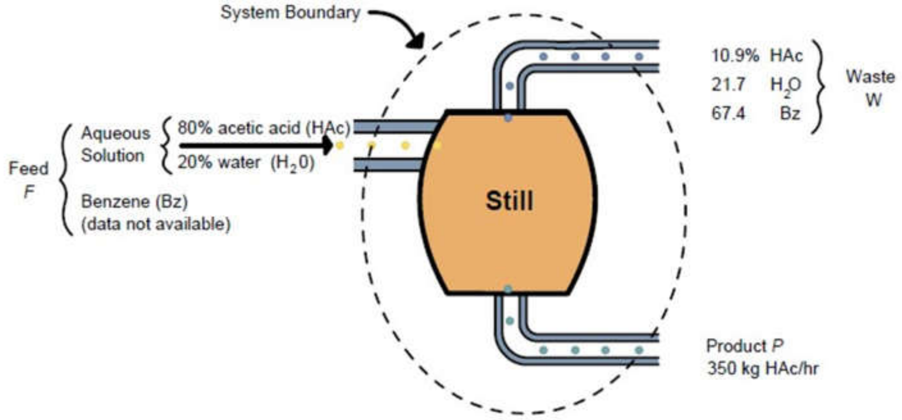
Answers:

1. (a) Two; (b) two of these three: acetic acid, water, total; (c) two; (d) feed of the 10% solution (say F) and mass fraction ω of the acetic acid in P; (e) 14% acetic acid and 86% water
2. Not for a unique solution because only two of the equations are independent.
3. F, D, P, ω_{D2}, ω_{P1}
4. Three unknowns exist. Because only two independent material balances can be written for the problem, one value of F, D, or P must be specified to obtain a solution. Note that specifying values of ω_{D2} or ω_{P1} will not help.

Supplementary Problems (Chapter Seven):

Problem 1

A continuous still is to be used to separate acetic acid, water, and benzene from each other. On a trial run, the calculated data were as shown in the figure. Data recording the benzene composition of the feed were not taken because of an instrument defect. The problem is to calculate the benzene flow in the feed per hour. How many independent material balance equations can be formulated for this problem? How many variables whose values are unknown exist in the problem?



Solution

Three components exist in the problem, hence three mass balances can be written down (the units are kg):

Balance	*F in*		*W out*		*P out*	
HAc:	$0.80(1 - \omega_{Bz,F})F$	=	0.109W	+	350	(a)
H_2O:	$0.20(1 - \omega_{Bz,F})F$	=	0.217W	+	0	(b)
Benzene:	$\omega_{Bz,F}F$	=	0.67W	+	0	(c)

The total balance would be: F = W + 350 (in kg).

Problem 8.1

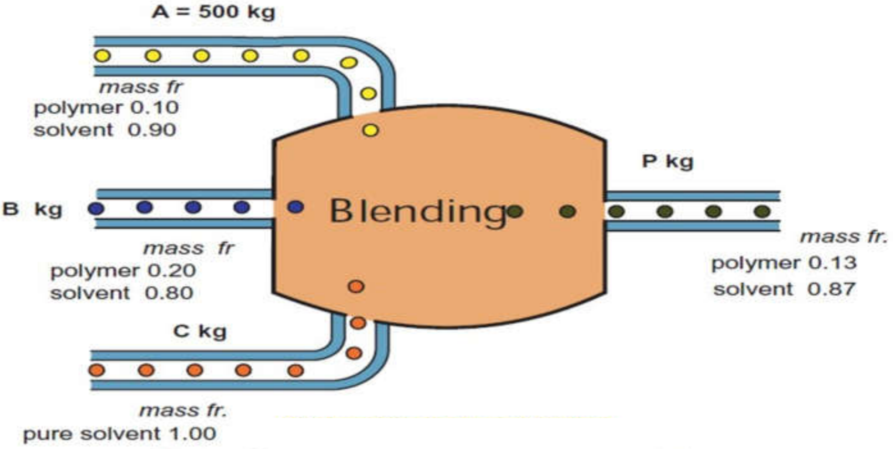
Problem 2

A liquid adhesive, which is used to make laminated boards, consists of a polymer ... lvent. The amount of polymer in the solution has to be carefully controlled for this ...n the supplier of the adhesive receives an order for 3000 kg of an adhesive solution containing 13 wt % polymer, all it has on hand is (1) 500 kg of a 10 wt % solution, (2) a very large quantity of a 20 wt % solution, and (3) pure solvent.

Calculate the weight of each of the three stocks that must be blended together to fill the order. Use all of the 10 wt % solution.

Solution

This is a steady state process without reaction.



Basis: 3000 kg 13 wt % polymer solution

Two unknowns: B and C . (A is not an unknown since all of it must be used).

Total balance: $500 + B + C = 3000$ (1)

Polymer balance: $0.10\,(500) + 0.20\,B + 0.00\,(C) = 0.13\,(3000)$ (2)

Solvent balance: $0.90\,(500) + 0.80\,B + 1.00\,(C) = 0.87\,(3000)$ (3)

We will use equations (1) and (2).

from (2) $0.1\,(500) + 0.20\,B = 0.13\,(3000)$

from (1) $500 + 1700 + C = 3000$

B = 1700 kg

C = Ê800 kg

Equation (3) can be used as a check,

$0.90\,A + 0.80\,B + C = 0.87\,P$

$0.90\,(500) + 0.80\,(1700) + 800 = 2610 = 0.87\,(3000) = 2610$

The use of material balances in a process allows you **(a)** to calculate the values of the total flows and flows of species in the streams that enter and leave the plant equipment, and **(b)** to calculate the change of conditions inside the equipment.

Example 8.1

Determine the mass fraction of Streptomycin in the exit organic solvent assuming that no water exits with the solvent and no solvent exits with the aqueous solution. Assume that the density of the aqueous solution is 1 g/cm^3 and the density of the organic solvent is 0.6 g/cm^3. Figure E8. 1 shows the overall process.

Solution

This is an **open** (flow), **steady-state** process without reaction. Assume because of the low concentration of Strep. in the aqueous and organic fluids that the **flow rates** of the **entering** fluids **equal** the flow rates of the **exit** fluids.

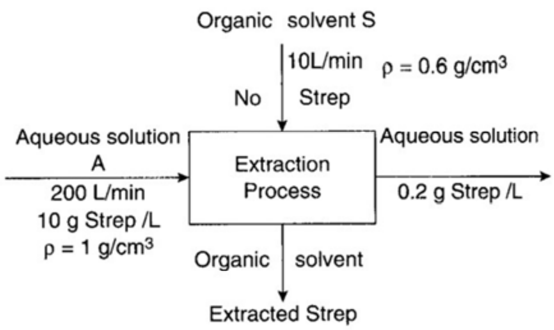


Figure E8.1

Basis: 1 min

Basis: Feed = 200 L (flow of aqueous entering aqueous solution)

- Flow of exiting aqueous solution (same as existing flow)
- Flow of exiting organic solution (same as existing flow)

The material balances are **in = out** in **grams**. Let **x** be the **g** of Strep per **L** of solvent **S**

Strep. balance:

$$\frac{200\text{ L of A}}{}\left|\frac{10\text{ g Strep}}{1\text{ L of A}}\right. + \frac{10\text{ L of S}}{}\left|\frac{0\text{ g Strep}}{1\text{ L of S}}\right. = \frac{200\text{ L of A}}{}\left|\frac{0.2\text{ g Strep}}{1\text{ L of A}}\right. + \frac{10\text{ L of S}}{}\left|\frac{x\text{ g Strep}}{1\text{ L of S}}\right.$$

x = 196 g Strep/L of solvent

To get the g Strep/g solvent, use the density of the solvent:

$$\frac{196 \text{ g Strep}}{1 \text{ L of S}}\left|\frac{1 \text{ L of S}}{1000 \text{ cm}^3 \text{ of S}}\right|\frac{1 \text{ cm}^3 \text{ of S}}{0.6 \text{ g of S}} = 0.3267 \text{ g Strep/g of S}$$

$$\text{The mass fraction Strep} = \frac{0.3267}{1 + 0.3267} = 0.246$$

Example 8.2

Membranes represent a relatively new technology for the separation of gases. One use that has attracted attention is the separation of nitrogen and oxygen from air. Figure E8.2a illustrates a nanoporous membrane that is made by coating a very thin layer of polymer on a porous graphite supporting layer. What is the composition of the waste stream if the waste stream amounts to 80% of the input stream?

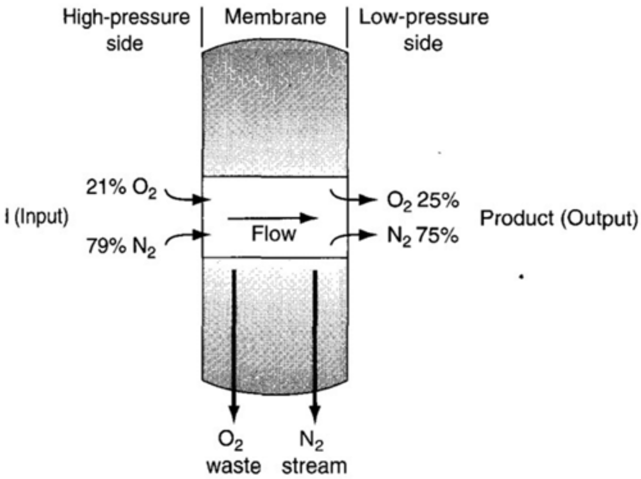
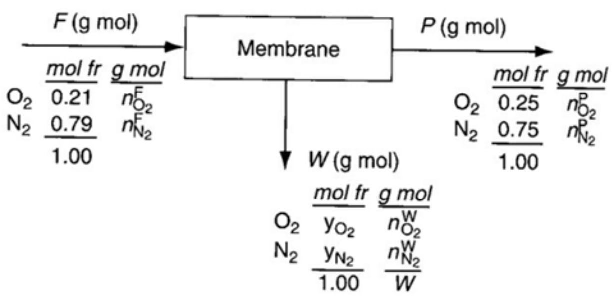


Figure E8.2a

Solution

This is an **open**, **steady-state process** without chemical reaction.



Basis: 100 g mol = F

Basis: F = 100

Specifications: $n_{O_2}^F = 0.21(100) = 21$

$n_{N_2}^F = 0.79(100) = 79$

$$y_{O_2}^P = n_{O_2}^P/P = 0.25 \qquad n_{O_2}^P = 0.25P$$
$$y_{N_2}^P = n_{N_2}^P/P = 0.75 \qquad n_{N_2}^P = 0.75P$$
$$W = 0.80(100) = 80$$

Material balances: O_2 and N_2

Implicit equations: $\Sigma n_i^W = W$ or $\Sigma y_i^W = 1$

	In	Out		In	Out
O_2:	0.21 (100)	$= 0.25P + y_{O_2}^W (80)$	or	0.21 (100)	$= 0.25P + n_{O_2}^W$
N_2:	0.79 (100)	$= 0.75P + y_{N_2}^W (80)$	or	0.79 (100)	$= 0.75P + n_{N_2}^W$
	1.00	$= y_{O_2}^W + y_{N_2}^W$	or	80	$= n_{O_2}^W + n_{N_2}^W$

The solution of these equations is

$n_{O_2}^W = 16$ and $n_{N_2}^W = 64$, or $y_{O_2}^W = 0.20$ and $y_{N_2}^W = 0.80$, and $P = 20$ g mol.

Check: total balance 100 = 20 + 80 OK

- **Another method for solution**

The overall balance is easy to solve because

F = P + W or 100=P+ 80

Gives P = 20 straight off. Then, the oxygen balance would be

$$0.21(100) = 0.25(20) + n_{O_2}^W$$

$n_{O_2}^W = 16$ g mol, and $n_{O_2}^W = 80 - 16 = 64$ g mol.

Note (Example 8.2)

$n_{O_2}^F + n_{N_2}^F = F$ is a redundant equation because it repeats some of the specifications.

Also, $n_{O_2}^P + n_{N_2}^P = P$ is redundant. Divide the equation by P to get $y_{O_2}^P + y_{N_2}^P = 1$, a relation that is equivalent to the sum of two of the specifications.

Example 8.3

A novice manufacturer of ethyl alcohol (denoted as EtOH) for gasohol is having a bit of difficulty with a distillation column. The process is shown in Figure E8.3. It appears that too much alcohol is lost in the bottoms (waste). Calculate the composition of the bottoms and the mass of the alcohol lost in the bottoms based on the data shown in Figure E8.3 that was collected during 1 hour of operation.

Solution

The process is an **open system**, and we assume it is in the **steady state**. No **reaction** occurs.

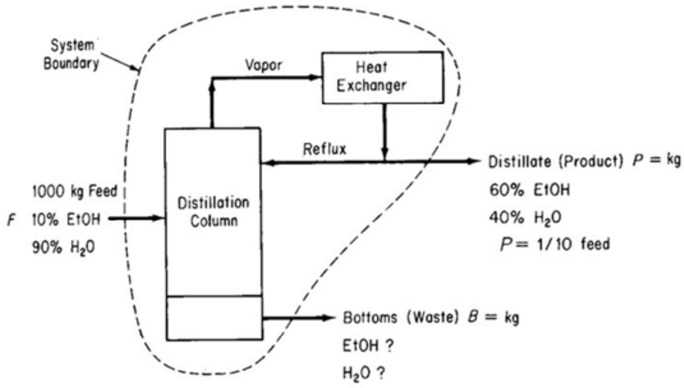


Figure E8.3

Basis: 1 hour so that **F = 1000 kg** of feed

We are given that P is (1/10) of F, so that P = 0.1(1000) = 100 kg

Basis: F= 1000 kg Specifications: $m^F_{EtOH} = 1000(0.10) = 100$

$$m^F_{H_2O} = 1000(0.90) = 900$$

$$m^P_{EtOH} = 0.60P$$

$$m^P_{H_2O} = 0.40P$$

P = (0.1) (F) = 100 kg

Material balances: EtOH and
H_2O Implicit equations:

$\Sigma m_i^B = B$ or $\Sigma \omega_i^B = 1$

The total mass balance: F = P + B

B = 1000 – 100 = 900 kg

The solution for the composition of the **bottoms** can then be computed directly from the material balances:

	kg feed in		*kg distillate out*		*kg bottoms out*	*Mass fraction*
EtOH balance:	0.10(1000)	–	0.60(100)	=	40	0.044
H_2O balance:	0.90(1000)	–	0.40(100)	=	860	0.956
					900	1.000

As a **check** let's use the redundant equation

$$m_{EtOH}^{B} + m_{H_2O}^{B} = B \quad \text{or} \quad \omega_{EtOH}^{B} + \omega_{H_2O}^{B} = 1$$

40 + 860 = 900 = B

Example 8.4

You are asked to prepare a batch of 18.63% battery acid as follows. A tank of old weak battery acid (H_2SO_4) solution contains 12.43% H_2SO_4 (the remainder is pure water). If 200 kg of 77.7% H_2SO_4 is added to the tank, and the final solution is to be 18.63% H_2SO_4, how many kilograms of battery acid have been made? See Figure E8.4.

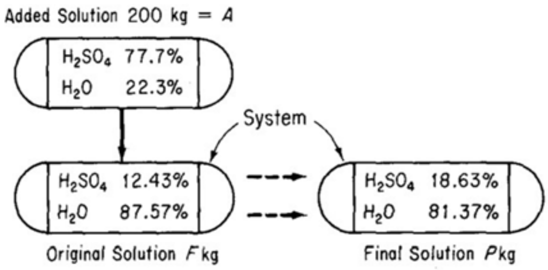


Figure E8.4

Solution

1. An unsteady-state process (the tank initially contains sulfuric acid solution).

Accumulation = In – Out

2. Steady-state process (the tank as initially being empty)

In = Out (Because no **accumulation** occurs in the tank)

1) Solve the problem with the mixing treated as an **unsteady-state process**.

Basis = 200 kg of A

Material balances: H_2SO_4 and H_2O The balances will be in **kilograms**.

Type of Balance	*Accumulation in Tank*				*In*		*Out*
	Final		Initial				
H_2SO_4	$P(0.1863)$	–	$F(0.1243)$	=	200(0.777)	–	0
H_2O	$P(0.8137)$	–	$F(0.8757)$	=	200(0.223)	–	0
Total	P	–	F	=	200	–	0

<u>Note</u> that any **pair** of the three equations is **independent**.

P = 2110 kg acid & F = 1910 kg acid

2) The problem could also be solved by considering the mixing to be a **steady- state process**.

	A in		*F in*		*P out*
H_2SO_4	200(0.777)	+	F(0.1243)	=	P(0.1863)
H_2O	200(0.223)	+	F(0.8757)	=	P(0.8137)
Total	*A*	+	*F*	=	*P*

Note: You can see by inspection that these equations are no different than the first set of mass balances except for the arrangement and labels.

Example 8.5

In a given batch of fish cake that contains 80% water (the remainder is dry cake), 100 kg of water is removed, and it is found that the fish cake is then 40% water. Calculate the weight of the fish cake originally put into the dryer. Figure E8.5 is a diagram of the process.

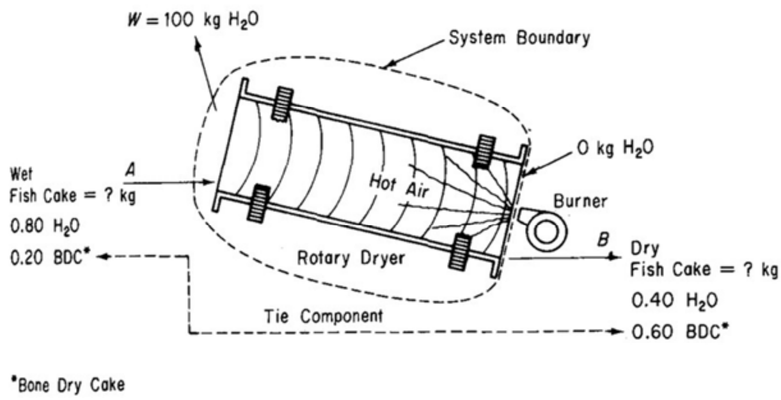


Figure E8.5

Solution

This is a steady-state process without reaction.

Basis: 100 kg of water evaporated = W

	In	Out	
Total balance:	A	$= B + W = B + 100$	mass balances
BDC balance:	$0.20A$	$= 0.60B$	

A = 150 kg initial cake and B = (150)(0.20/0.60)

= 50kg Check via the water balance: 0.80 A =

0.40 B + 100

$$0.80(150) \approx 0.40(50) + 100$$

$$120 = 120$$

Note

In Example 8.5 the BDC in the wet and dry fish cake is known as a **tie component** because the BDC goes from a single stream in the process to another single stream **without loss, addition, or splitting**.

Example 8.6

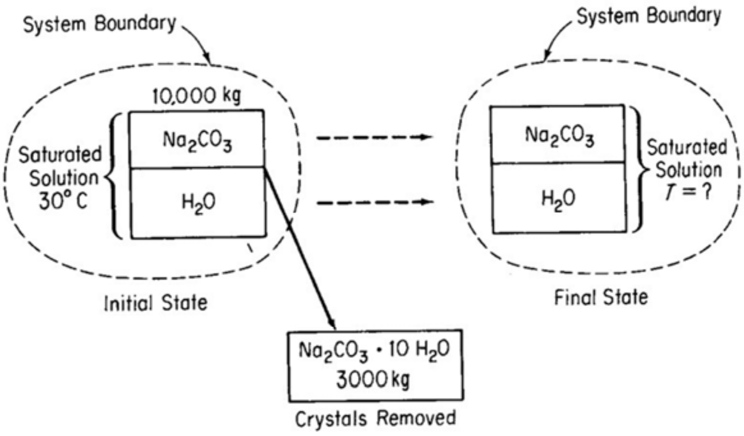
A tank holds 10,000 kg of a saturated solution of Na_2CO_3 at 30°C. You want to crystallize from this solution 3000 kg of $Na_2CO_3.10\ H_2O$ without any accompanying water. To what temperature must the solution be cooled?

You definitely need solubility data for Na_2CO_3 as a function of the temperature:

Temp.(°C)	Solubility (g Na_2CO_3/100 g H_2O)
0	7
10	12.5
20	21.5
30	38.8

Solution

No **reaction** occurs. Although the problem could be set up as a **steady-state problem** with flows in and out of the system (the tank), it is equally justified to treat the process as an -**unsteady-state process**.



Because the initial solution is saturated at 30°C, you can calculate the composition of the initial solution:

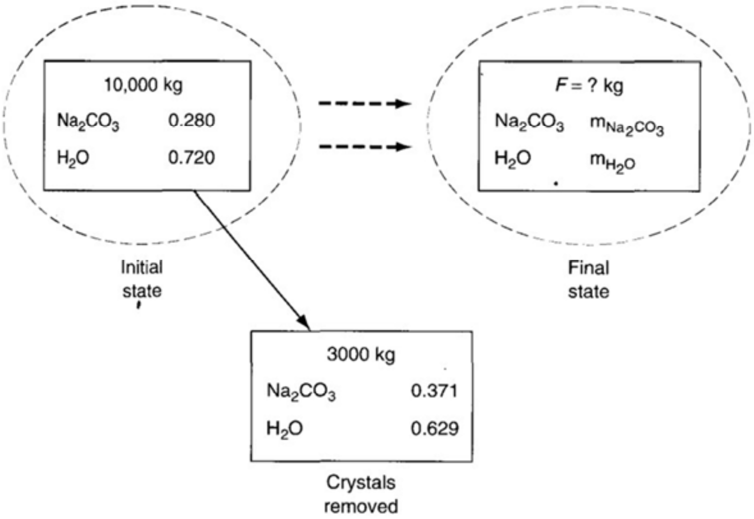
$$\frac{38.8\ g\ Na_2CO_3}{38.8\ g\ Na_2CO_3 + 100\ g\ H_2O} = 0.280 \text{ mass fraction } Na_2CO_3$$

Next, you should calculate the composition of the crystals.

Basis: 1 g mol $Na_2CO_3.10\ H_2O$

Comp.	*Mol*	*Mol wt.*	*Mass*	*Mass fr*
Na_2CO_3	1	106	106	0.371
H_2O	10	18	180	0.629
Total			286	1.00

Basis: 10,000 kg of saturated solution at 30°C



An **unsteady-state** problem, the mass balance reduces to (the flow in = 0)

Accumulation = In – Out

Basis: I = 10,000 kg

Material balances: Na_2CO_3, H_2O

Note that $\omega_i{}^I I = m_i^I, \omega_i{}^F F = m_i^F$, and $\omega_i{}^C C = m_i^C$ are redundant equations. C = Crystals

Also redundant are equations such as

$$\Sigma\omega_i = 1 \text{ and } \Sigma m_i = m_{total}.$$

M.B.:

	Accumulation in Tank				
	Final		*Initial*		*Transport out*
Na_2CO_3	$m^F_{Na_2CO_3}$	–	10,000(0.280)	=	–3000(0.371)
H_2O	$m^F_{H_2O}$	–	10,000(0.720)	=	–3000(0.629)
Total	F	–	10,000	=	–3000

The solution for the composition and amount of the final solution is

Component	kg
$m^F_{Na_2CO_3}$	1687
$m^F_{H_2O}$	5313
F (total)	7000

Check using the total balance: 7,000 + 3,000 = 10,000

To find the temperature of the final solution: $\frac{1{,}687 \text{ kg } Na_2CO_3}{5{,}313 \text{ kg } H_2O} = \frac{31.8 \text{ g } Na_2CO_3}{100 \text{ g } H_2O}$

Thus, the temperature to which the solution must be cooled lies between **20°C** and **30°C**. By **linear interpolation**

$$30°C - \frac{38.8-31.8}{38.8-21.5}(10.0°C) = 26°C$$

Example 8.7

This example focuses on the plasma components of the streams: water, uric acid (UR), creatinine (CR), urea (U), P, K, and Na. You can ignore the initial filling of the dialyzer because the treatment lasts for an interval of two or three hours. Given the measurements obtained from one treatment shown in Figure E8.7b, calculate the grams per liter of each component of the plasma in the outlet solution.

Solution

This is an open steady-state system.

Basis: 1 minute

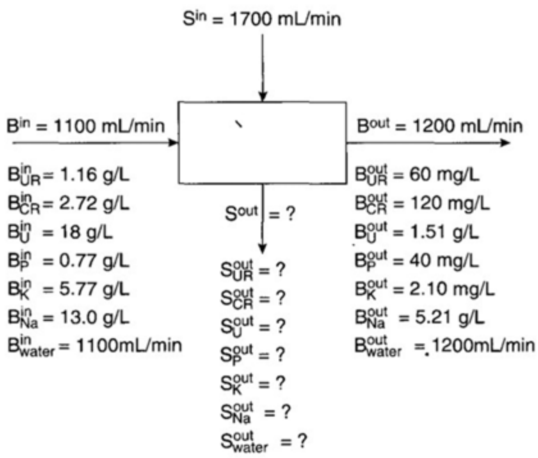


Figure E8.7b

- The **entering solution** is assumed to be essentially **water**.

The water balance in grams, assuming that 1 mL is equivalent to 1 gram, is:

$$1100 + 1700 = 1200 + S^{out}_{water} \quad \text{hence:} \quad S^{out}_{water} = 1600 \text{ mL}$$

The component balances in grams are:

$$\underline{g/L}$$

$$\text{UR:} \quad 1.1(1.16) + 0 = 1.2(0.060) + 1.6\, S^{out}_{UR} \qquad S^{out}_{UR} = 0.75$$

$$\text{CR:} \quad 1.1(2.72) + 0 = 1.2(0.120) + 1.6\, S^{out}_{CR} \qquad S^{out}_{CR} = 1.78$$