

Chapter 2 Solutions

P2.1

(a) mass fraction of each = $\frac{1 \text{ g}}{1 \text{ g} + 1 \text{ g} + 1 \text{ g}} = 0.3\bar{3}$

$$\begin{aligned}\text{mol fraction H}_2 &= \frac{1 \text{ g H}_2 \left(\frac{\text{gmol H}_2}{2 \text{ g H}_2} \right)}{1 \text{ g H}_2 \left(\frac{\text{gmol H}_2}{2 \text{ g H}_2} \right) + 1 \text{ g C}_6\text{H}_6 \left(\frac{\text{gmol C}_6\text{H}_6}{78 \text{ g C}_6\text{H}_6} \right) + 1 \text{ g C}_6\text{H}_{12} \left(\frac{\text{gmol C}_6\text{H}_{12}}{84 \text{ g C}_6\text{H}_{12}} \right)} \\ &= \frac{0.5 \text{ gmol}}{0.5 \text{ gmol} + 0.0128 \text{ gmol} + 0.0119 \text{ gmol}} = 0.953\end{aligned}$$

$$\begin{aligned}\text{mol fraction C}_6\text{H}_6 &= \frac{1 \text{ g C}_6\text{H}_6 \left(\frac{\text{gmol C}_6\text{H}_6}{78 \text{ g C}_6\text{H}_6} \right)}{1 \text{ g H}_2 \left(\frac{\text{gmol H}_2}{2 \text{ g H}_2} \right) + 1 \text{ g C}_6\text{H}_6 \left(\frac{\text{gmol C}_6\text{H}_6}{78 \text{ g C}_6\text{H}_6} \right) + 1 \text{ g C}_6\text{H}_{12} \left(\frac{\text{gmol C}_6\text{H}_{12}}{84 \text{ g C}_6\text{H}_{12}} \right)} \\ &= \frac{0.0128 \text{ gmol}}{0.5 \text{ gmol} + 0.0128 \text{ gmol} + 0.0119 \text{ gmol}} = 0.024\end{aligned}$$

$$\begin{aligned}\text{mol fraction C}_6\text{H}_{12} &= \frac{1 \text{ g C}_6\text{H}_{12} \left(\frac{\text{gmol C}_6\text{H}_{12}}{84 \text{ g C}_6\text{H}_{12}} \right)}{1 \text{ g H}_2 \left(\frac{\text{gmol H}_2}{2 \text{ g H}_2} \right) + 1 \text{ g C}_6\text{H}_6 \left(\frac{\text{gmol C}_6\text{H}_6}{78 \text{ g C}_6\text{H}_6} \right) + 1 \text{ g C}_6\text{H}_{12} \left(\frac{\text{gmol C}_6\text{H}_{12}}{84 \text{ g C}_6\text{H}_{12}} \right)} \\ &= \frac{0.0119 \text{ gmol}}{0.5 \text{ gmol} + 0.0128 \text{ gmol} + 0.0119 \text{ gmol}} = 0.023\end{aligned}$$

(b) mole fraction of each = $\frac{1 \text{ gmol}}{1 \text{ gmol} + 1 \text{ gmol} + 1 \text{ gmol}} = 0.3\bar{3}$

mass fraction H₂

$$\begin{aligned} & \frac{1 \text{ gmol H}_2 \left(\frac{2 \text{ g H}_2}{\text{gmol H}_2} \right)}{1 \text{ gmol H}_2 \left(\frac{2 \text{ g H}_2}{\text{gmol H}_2} \right) + 1 \text{ gmol C}_6\text{H}_6 \left(\frac{78 \text{ g C}_6\text{H}_6}{\text{gmol C}_6\text{H}_6} \right) + 1 \text{ gmol C}_6\text{H}_{12} \left(\frac{84 \text{ g C}_6\text{H}_{12}}{\text{gmol C}_6\text{H}_{12}} \right)} \\ &= \frac{2 \text{ g}}{2 \text{ g} + 78 \text{ g} + 84 \text{ g}} = 0.012 \end{aligned}$$

mass fraction C₆H₆

$$\begin{aligned} & \frac{1 \text{ gmol C}_6\text{H}_6 \left(\frac{78 \text{ g C}_6\text{H}_6}{\text{gmol C}_6\text{H}_6} \right)}{1 \text{ gmol H}_2 \left(\frac{2 \text{ g H}_2}{\text{gmol H}_2} \right) + 1 \text{ gmol C}_6\text{H}_6 \left(\frac{78 \text{ g C}_6\text{H}_6}{\text{gmol C}_6\text{H}_6} \right) + 1 \text{ gmol C}_6\text{H}_{12} \left(\frac{84 \text{ g C}_6\text{H}_{12}}{\text{gmol C}_6\text{H}_{12}} \right)} \\ &= \frac{78 \text{ g}}{2 \text{ g} + 78 \text{ g} + 84 \text{ g}} = 0.476 \end{aligned}$$

mass fraction C₆H₁₂

$$\begin{aligned} & \frac{1 \text{ gmol C}_6\text{H}_{12} \left(\frac{84 \text{ g C}_6\text{H}_{12}}{\text{gmol C}_6\text{H}_{12}} \right)}{1 \text{ gmol H}_2 \left(\frac{2 \text{ g H}_2}{\text{gmol H}_2} \right) + 1 \text{ gmol C}_6\text{H}_6 \left(\frac{78 \text{ g C}_6\text{H}_6}{\text{gmol C}_6\text{H}_6} \right) + 1 \text{ gmol C}_6\text{H}_{12} \left(\frac{84 \text{ g C}_6\text{H}_{12}}{\text{gmol C}_6\text{H}_{12}} \right)} \\ &= \frac{84 \text{ g}}{2 \text{ g} + 78 \text{ g} + 84 \text{ g}} = 0.512 \end{aligned}$$

P2.2

$$\frac{15.90 \text{ g fructose}}{105.97 \text{ g total}} \times 100\% = 15.0\text{wt}\% \text{ fructose}$$

$$\frac{15.90 \text{ g fructose} \left(\frac{\text{gmol fructose}}{180 \text{ g fructose}} \right)}{15.90 \text{ g fructose} \left(\frac{\text{gmol fructose}}{180 \text{ g fructose}} \right) + 90.07 \text{ g fructose} \left(\frac{\text{gmol water}}{18 \text{ g water}} \right)} \times 100\% = 1.73\text{mol}\% \text{ fructose}$$

P2.3

$$0.79 \text{ gmol N}_2 \left(\frac{28 \text{ g N}_2}{\text{gmol N}_2} \right) + 0.21 \text{ gmol O}_2 \left(\frac{32 \text{ g O}_2}{\text{gmol O}_2} \right) = 28.8 \text{ g}$$

$$\frac{0.79 \text{ gmol N}_2 \left(\frac{28 \text{ g N}_2}{\text{gmol N}_2} \right)}{1 \text{ gmol air} \left(\frac{28.8 \text{ g air}}{\text{gmol air}} \right)} \times 100\% = 76.8 \text{ wt\% N}_2$$

$$\frac{0.21 \text{ gmol O}_2 \left(\frac{32 \text{ g O}_2}{\text{gmol O}_2} \right)}{1 \text{ gmol air} \left(\frac{28.8 \text{ g air}}{\text{gmol air}} \right)} \times 100\% = 23.3 \text{ wt\% O}_2$$

P2.4

All numbers must be mol%. (To see this, think about water, one of the most abundant chemicals in the human body. H₂O is 66.7 mol% H but only 11 mass% H.)

In 100 lbmole human, one would have

63 lbmol H, or 63 lb

25.5 lbmol O, or 408 lb

9.45 lbmol C, or 113 lb

1.35 lbmol N, or 18.9 lb

0.31 lbmole Ca or 12.4 lb

0.22 lbmol P, or 6.8 lb

Total mass is 622 lb. Scale to 150 lb (typical person): scale factor is 150/622 or 0.24

Typical person is therefore

15 lb H, or 15 lbmol H

98 lb O, or 6 lbmol O

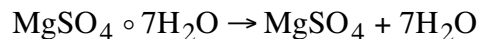
27 lb C, or 2.3 lbmol C

4.5 lb N, or 0.3 lbmol N

3.0 lb Ca, or 0.07 lbmol Ca

1.6 lb P, or 0.05 lbmol P

P2.5



MgSO₄ molar mass = 24 + 32 + 4(16) = 120 g/gmol

MgSO₄·7H₂O molar mass = 24 + 32 + 4(16) + 8(18) = 264 g/gmol

$$100 \text{ g MgSO}_4 \cdot 7\text{H}_2\text{O} \times \frac{120 \text{ g MgSO}_4 / \text{gmol MgSO}_4}{264 \text{ g MgSO}_4 \cdot 7\text{H}_2\text{O} / \text{gmol MgSO}_4 \cdot 7\text{H}_2\text{O}} = 45.4 \text{ g MgSO}_4$$

P2.6

$$\text{One sheet: } (8.5 \times 11) \text{ in}^2 \left(\frac{1 \text{ m}}{39.36 \text{ in}} \right)^2 \left(\frac{75 \text{ g}}{\text{m}^2} \right) = 4.53 \text{ g}$$

$$\text{Entire package: } 500 \text{ sheets} \left(\frac{4.53 \text{ g}}{\text{sheet}} \right) \left(\frac{\text{lb}}{454 \text{ g}} \right) = 5 \text{ lb}$$

P2.7

$$\left(\frac{0.25 \text{ oz}}{\text{package}} \right) \left(\frac{453.59 \text{ g}}{16 \text{ oz.}} \right) = 7.087 \text{ g/package}$$

$$\left(\frac{1 \text{ yeast}}{6 \times 10^{-5} \mu\text{g}} \right) \left(\frac{10^6 \mu\text{g}}{\text{g.}} \right) \left(\frac{7.087 \text{ g}}{\text{package}} \right) = 1.2 \times 10^{11} \text{ yeast critters/package}$$

P2.8

$$1 \text{ cup} \left(\frac{8 \text{ fl. oz.}}{\text{cup}} \right) \left(\frac{1 \text{ liter}}{33.814 \text{ fl. oz.}} \right) \left(\frac{1000 \text{ g}}{\text{liter.}} \right) = 236 \text{ g}$$

$$236 \text{ g} \left(\frac{1 \text{ gmol H}_2\text{O}}{18 \text{ g H}_2\text{O}} \right) = 13.1 \text{ gmol H}_2\text{O}$$

P2.9

$$\frac{n}{V} = \frac{P}{RT} = \frac{1 \text{ atm}}{(0.08206 \text{ l atm/gmol K})(277\text{K})} = 0.044 \text{ gmol/liter}$$

$$\text{mass density} = 0.044 \text{ gmol/liter} (28.8 \text{ g/gmol}) = 1.267 \text{ g/l}$$

$$1 \text{ mi}^3 \left(\frac{5280 \text{ ft}}{\text{mi}} \right)^3 \left(\frac{28.316847 \text{ L}}{\text{ft}^3} \right) = 4.168 \times 10^{12} \text{ L}$$

$$4.168 \times 10^{12} \text{ L} \left(\frac{1.267 \text{ g}}{\text{L}} \right) \left(\frac{\text{lb}}{454 \text{ g}} \right) \left(\frac{\text{ton}}{2000 \text{ lb}} \right) = 5.8 \text{ million tons}$$

Assume typical book is 9" x 12" x 2", then book is 216 cu. in. or 3500 cu. cm.

$$\text{If made of air: } 3500 \text{ cm}^3 \times \frac{\text{L}}{1000 \text{ cm}^3} \times \frac{1.267 \text{ g}}{\text{L}} = 4.4 \text{ g} = 4.4 \times 10^{-3} \text{ kg}$$

$$\text{If made of water: } 3500 \text{ cm}^3 \times \frac{1 \text{ g}}{\text{cm}^3} = 3500 \text{ g} = 3.5 \text{ kg}$$

$$\text{If made of gold: } 3500 \text{ cm}^3 \times \frac{19.31 \text{ g}}{\text{cm}^3} = 67585 \text{ g} = 67.6 \text{ kg (about the weight of a person!)}$$

P2.10

Fuel usage at German rate:

$$\left(\frac{20 \text{ mi}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{yr}} \right) \left(\frac{1.6 \text{ km}}{\text{mi}} \right) \left(\frac{5.97 \text{ L}}{100 \text{ km}} \right) \left(\frac{0.26417 \text{ gal}}{\text{L}} \right) = 184 \text{ gal/yr}$$

Fuel usage at U.S. rate:

$$\left(\frac{20 \text{ mi}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{1 \text{ gal}}{27.5 \text{ mi}}\right) = 265 \text{ gal/yr}$$

Difference is about 80 gallons/yr savings.

P2.11

$$1970: \left(\frac{1100 \times 10^9 \text{ mi}}{\text{year}}\right)\left(\frac{14 \text{ g}}{\text{mi}}\right)\left(\frac{1 \text{ lb}}{454 \text{ g}}\right)\left(\frac{1 \text{ ton}}{2000 \text{ lb}}\right) = 17 \text{ million tons/yr}$$

$$2000: \left(\frac{2600 \times 10^9 \text{ mi}}{\text{year}}\right)\left(\frac{1 \text{ g}}{\text{mi}}\right)\left(\frac{1 \text{ lb}}{454 \text{ g}}\right)\left(\frac{1 \text{ ton}}{2000 \text{ lb}}\right) = 2.9 \text{ million tons/yr}$$

$$(17-2.9)/17 \times 100\% = 83\% \text{ decrease in emissions.}$$

P2.12

$$10 \text{ atm} \times \frac{101.325 \text{ kPa}}{\text{atm}} = 1013.25 \text{ kPa}, 250^\circ\text{C} + 273^\circ\text{C} = 523\text{K}$$

$$10 \text{ atm} \times \frac{14.7 \text{ psia}}{\text{atm}} - 14.7 \text{ psi} = 132.3 \text{ psig}, 250^\circ\text{C}(1.8) + 32 = 482^\circ\text{F}$$

$$10 \text{ atm} \times \frac{1.01325 \text{ bar}}{\text{atm}} = 10.1325 \text{ bar}, 482^\circ\text{F} + 459.67 = 942^\circ\text{R}$$

P2.13

$$T = 100^\circ\text{C} = 212^\circ\text{F} = 672^\circ\text{R}$$

$$P = 75 \text{ psia}$$

$$\left(\frac{115 \text{ lb}}{\text{min}}\right)\left(\frac{\text{lbmol}}{32 \text{ lb}}\right) = 3.59 \text{ lbmol/min}$$

$$\text{From ideal gas law, } \frac{V}{n} = \frac{RT}{P} = \frac{(10.73 \text{ ft}^3 \text{ psia/lbmol } ^\circ\text{R})(672^\circ\text{R})}{75 \text{ psia}} = 96.1 \text{ ft}^3/\text{lbmol}$$

$$\left(\frac{3.59 \text{ lbmol}}{\text{min}}\right)\left(\frac{96.1 \text{ ft}^3}{\text{lbmol}}\right) = 345 \text{ ft}^3/\text{min}$$

At STP: same molar flow rate, molar volume = 359 ft³/lbmol

$$\left(\frac{3.59 \text{ lbmol}}{\text{min}}\right)\left(\frac{359 \text{ ft}^3}{\text{lbmol}}\right) = 1289 \text{ ft}^3/\text{min}$$

P2.14

$$\text{Gas: } \left(\frac{\$0.25}{100 \text{ ft}^3}\right)\left(\frac{1 \text{ ft}^3}{28.31 \text{ L}}\right)\left(\frac{22.414 \text{ L}}{\text{gmol}}\right)\left(\frac{\text{gmol}}{28 \text{ g}}\right)\left(\frac{1000 \text{ g}}{\text{kg}}\right) = \$0.071/\text{kg}$$

$$\text{Liquid: } \left(\frac{\$0.28}{\text{L}}\right)\left(\frac{1 \text{ L}}{1000 \text{ cm}^3}\right)\left(\frac{\text{cm}^3}{0.808 \text{ g}}\right)\left(\frac{1000 \text{ g}}{\text{kg}}\right) = \$0.35/\text{kg}$$

The difference in price can be attributed to the costs of cooling and compressing nitrogen to liquefy it.

P2.15

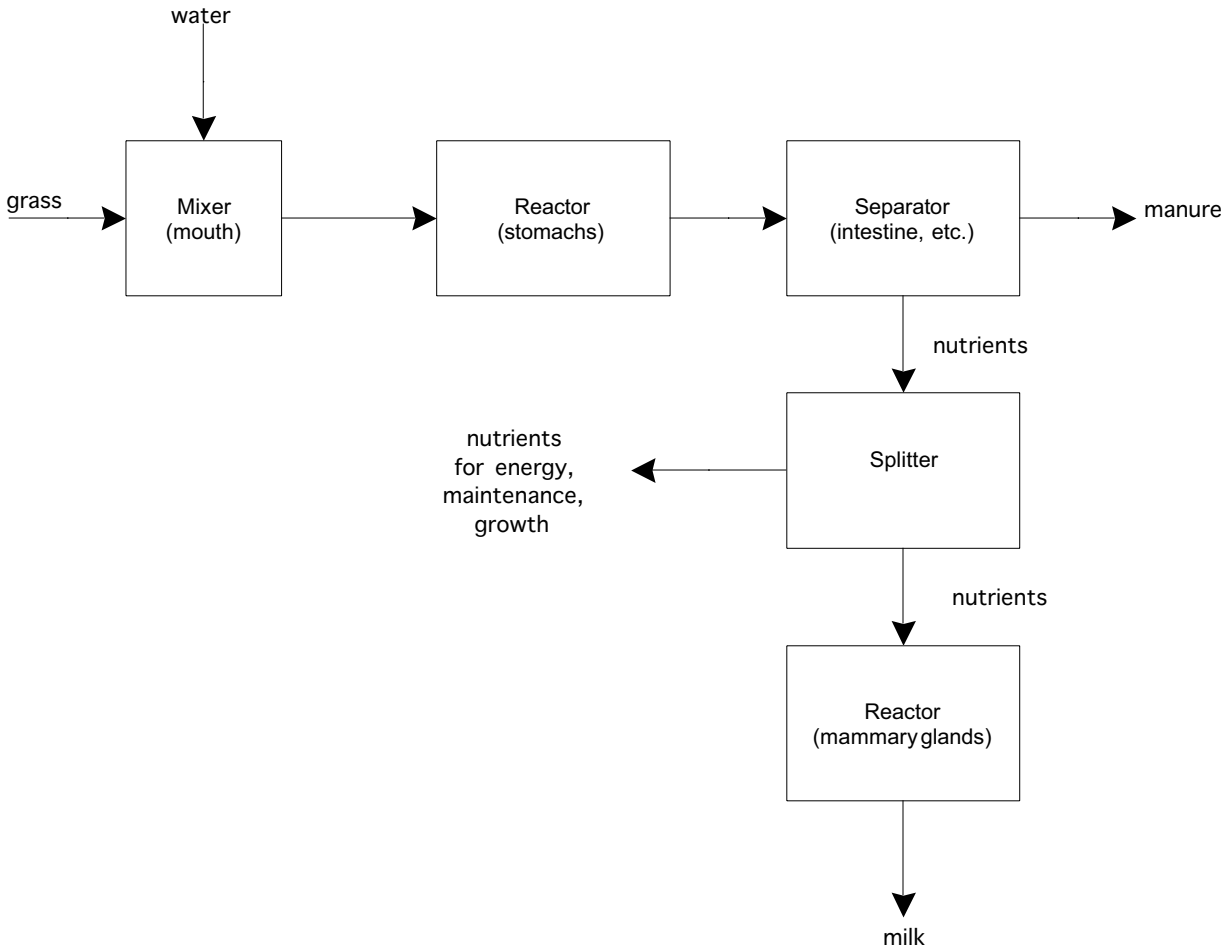
$$\text{Area of glass window: } \left(6 \times 4 \text{ ft}^2\right)\left(\frac{12 \text{ in}}{\text{ft}}\right)^2\left(\frac{2.54 \text{ cm}}{\text{in}}\right)^2 = 22297 \text{ cm}^2$$

$$\text{Volume of TiO}_2 \text{ coating: } 22297 \text{ cm}^2 \times 60 \times 10^{-7} \text{ cm} = 0.1338 \text{ cm}^3$$

$$\text{Mass of TiO}_2 \text{ required: } 0.1338 \text{ cm}^3 \times \frac{3.84 \text{ g}}{\text{cm}^3} = 0.514 \text{ g}$$

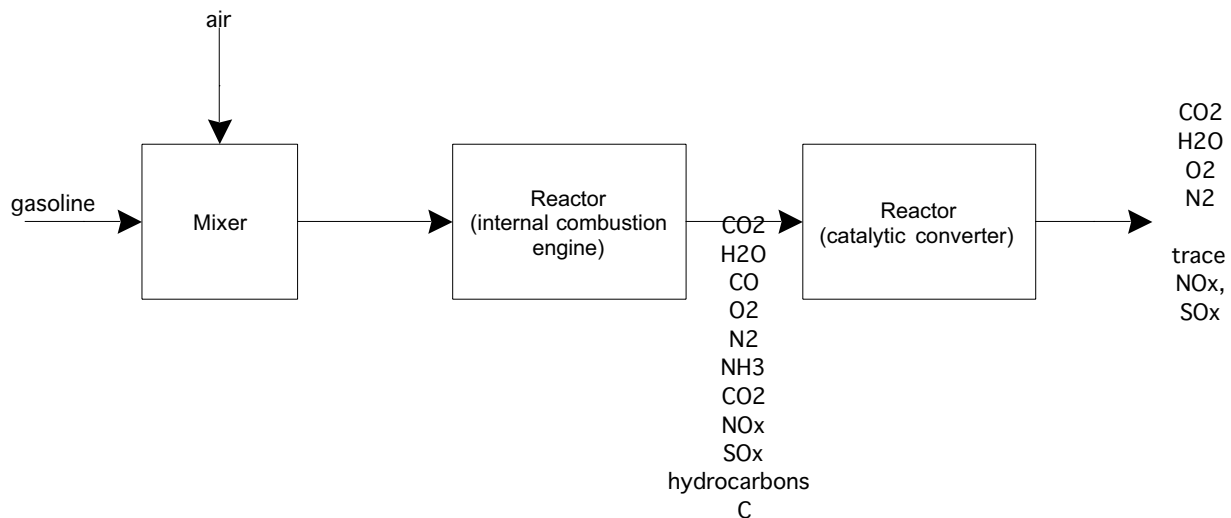
P2.16

Here's one conception of a dairy cow, as a process that takes in grass and water as raw materials and produces milk and waste products.

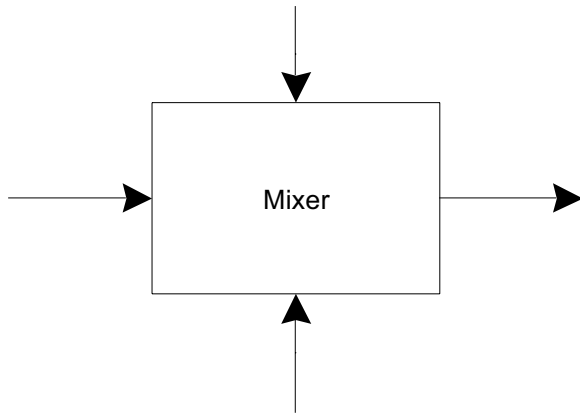


P2.17

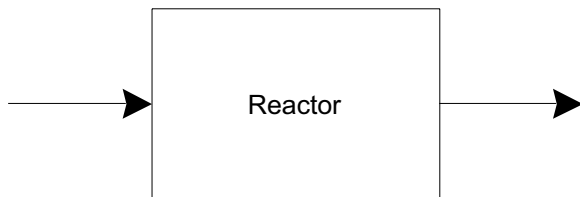
When engine is running, the system is continuous-flow, but the flows vary with time as the load on the engine varies (due to changes in speed or topography), so the system is unsteady-state.



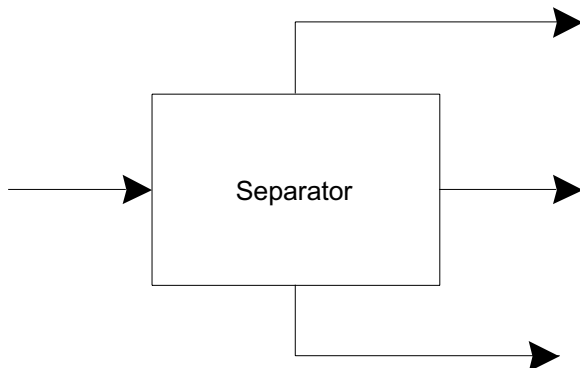
P2.18



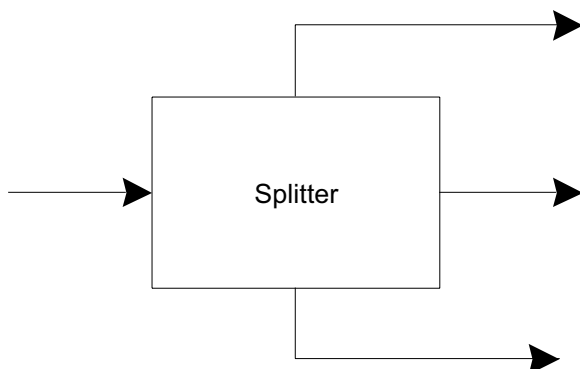
Example: a blender



Example: microwave oven



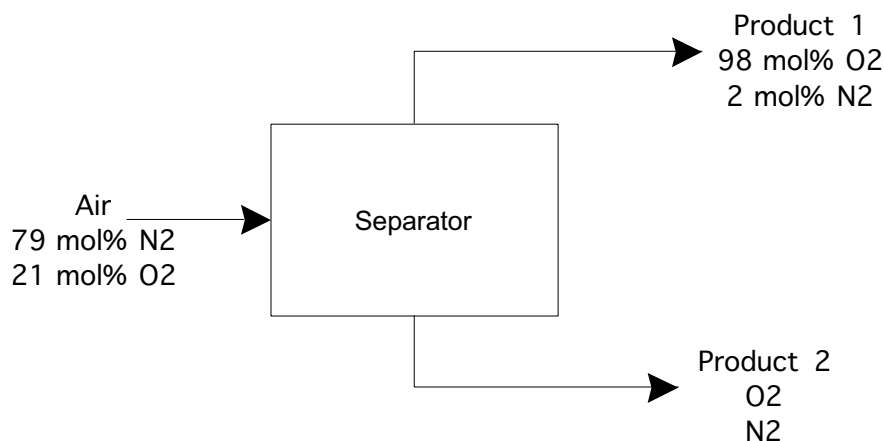
Example: Gravy strainer



Example: cookie press (a tool in which cookie dough is placed, and then the dough is squeezed out in small shaped blobs onto a cookie sheet).

P2.19

- (a) In = Accumulation
 (b) – Out = Accumulation
 (c) In – Out – Consumption = 0, or Out = In - Consumption
 (d) – Out + Generation = 0, or Out = Generation
 (e) In – Out = 0, or Out = In

P2.20

- (a) stream composition specifications:
 air is 79 mol% nitrogen
 product contains 98 mol% oxygen
 (b) system performance specification:
 80% of oxygen fed is recovered in one product

P2.21

I measured about 1 gal in 10 sec, or about 6 gal/min

$$\left(\frac{6 \text{ gal}}{\text{min}}\right)\left(\frac{1000 \text{ cm}^3}{0.26417 \text{ gal}}\right)\left(\frac{\text{min}}{60 \text{ s}}\right)\left(\frac{1 \text{ g}}{\text{cm}^3}\right) = 380 \text{ g/s} \quad (\text{assuming density of water of } 1 \text{ g/cm}^3).$$

$$\left(\frac{380 \text{ g}}{\text{s}}\right)\left(\frac{3600 \text{ s}}{\text{h}}\right)\left(\frac{\text{lb}}{454 \text{ g}}\right)\left(\frac{\text{lbmol}}{18 \text{ lb}}\right) = 170 \text{ lbmol/h}$$

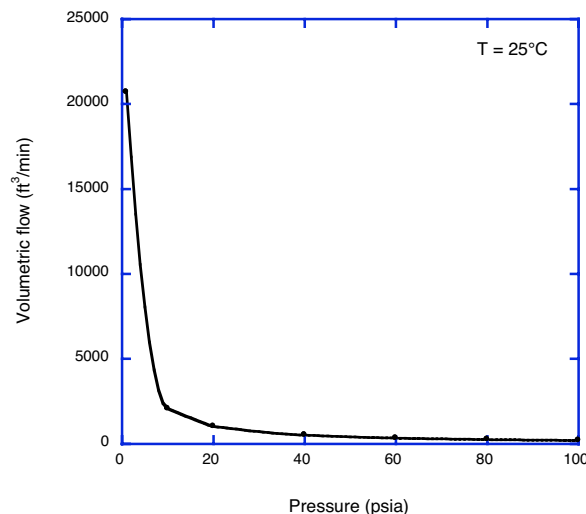
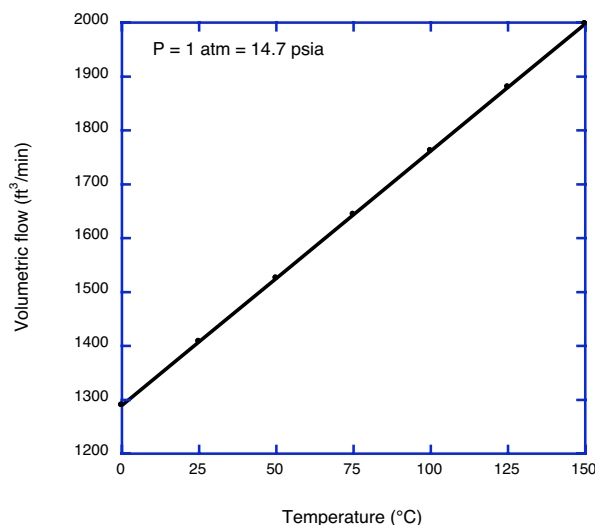
$$\left(\frac{380 \text{ g}}{\text{s}}\right)\left(\frac{3600 \text{ s}}{\text{h}}\right)\left(\frac{24 \text{ h}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{\text{lb}}{454 \text{ g}}\right)\left(\frac{\text{ton}}{2000 \text{ lb}}\right) = 13,000 \text{ tons/yr}$$

This flow rate falls in the lower range of the commodity chemicals.

P2.22

The model equation is

$$\dot{V} = \frac{\dot{n}RT}{P} = \frac{(115 \text{ lb/min}) \left(10.73 \text{ ft}^3 \text{ psi/lbmol } ^\circ\text{R} \right) (1.8T^\circ\text{C} + 491.67)}{(32 \text{ lb/lbmol})(P \text{ psia})} = 38.56 \frac{(1.8T^\circ\text{C} + 491.67)}{P} \text{ ft}^3/\text{min}$$



P2.23

$$\left(\frac{0.02 \text{ ton gold}}{100 \text{ tons ore}} \right) \left(\frac{2000 \text{ lb}}{\text{ton}} \right) \left(\frac{16 \text{ oz.}}{\text{lb}} \right) = 6.4 \text{ oz gold/ton ore}$$

or, you need 0.156 tons ore for one ounce of gold.

$$\left(\frac{5 \text{ ton gold}}{10^{12} \text{ tons seawater}} \right) \left(\frac{2000 \text{ lb}}{\text{ton}} \right) \left(\frac{16 \text{ oz.}}{\text{lb}} \right) = 1.6 \times 10^{-7} \text{ oz gold/ton seawater}$$

or, you need 6,250,000 tons seawater for one ounce of gold.

Surface area of the earth: $4\pi r^2 = 4\pi(12500 \text{ mi})^2 = 1.96 \times 10^9 \text{ mi}^2$. Assume the oceans cover about 3/4th of the earth's surface. Therefore, the total volume of seawater on earth is approximately

$$0.70 \left(1.96 \times 10^9 \text{ mi}^2 \right) (2.4 \text{ mi}) \left(\frac{5280 \text{ ft}}{\text{mi}} \right)^3 \left(\frac{12 \text{ in}}{\text{ft}} \right)^3 \left(\frac{2.54 \text{ cm}}{\text{in}} \right)^3 = 1.4 \times 10^{25} \text{ cm}^3$$

and the total mass of seawater on earth is approximately

$$\left(1.4 \times 10^{25} \text{ cm}^3 \right) \left(\frac{1.05 \text{ g}}{\text{cm}^3} \right) \left(\frac{\text{lb}}{454 \text{ g}} \right) \left(\frac{\text{ton}}{2000 \text{ lb}} \right) = 1.6 \times 10^{19} \text{ tons}$$

Therefore the total amount of gold dissolved in the ocean's water is about

$$\left(1.6 \times 10^{19} \text{ tons seawater}\right) \left(\frac{5 \text{ tons gold}}{10^{12} \text{ seawater}}\right) = 80 \text{ million tons}$$

P2.24

(a) At STP,

$$(60000 \text{ lb}) \left(\frac{\text{lbmol}}{17 \text{ lb}}\right) \left(\frac{359 \text{ ft}^3}{\text{lbmol}}\right) = 1.267 \times 10^6 \text{ ft}^3, \text{ so radius of vessel is } 66.7 \text{ ft} - \text{huge!}$$

(b) at 80°F, 5 atm, the density is 78.8 ft³/lbmol.

$$(60000 \text{ lb}) \left(\frac{\text{lbmol}}{17 \text{ lb}}\right) \left(\frac{78.8 \text{ ft}^3}{\text{lbmol}}\right) = 278,000 \text{ ft}^3, \text{ so radius of vessel is } 36.9 \text{ ft} - \text{still big!}$$

(c) at -30°F, 1 atm,

$$(60000 \text{ lb}) \left(\frac{\text{ft}^3}{42.6 \text{ lb}}\right) = 1.41 \times 10^3 \text{ ft}^3, \text{ so radius of vessel is } 6.95 \text{ ft} - \text{much better!}$$

(d) at 80°F, 11 atm,

$$(60000 \text{ lb}) \left(\frac{\text{ft}^3}{37.5 \text{ lb}}\right) = 1.6 \times 10^3 \text{ ft}^3, \text{ so radius of vessel is } 7.26 \text{ ft}.$$

I'd choose alternative (d). The size is much more manageable (and the vessel therefore much cheaper) than alternative (a). In (c), the temperature is very cold, requiring specialized materials of construction. Furthermore, there is a safety issue – if the insulation and cooling system fail, the vessel would heat up, causing the pressure to rise. In alternative (d), we are operating at ambient temperature, so heating is not as much of a concern, but pressures are still moderate.

P2.25

Molar flow rate: $100 + 400 = 500 \text{ kgmol/min}$

$$\text{Mass flow rate: } \frac{100 \text{ kgmol}}{\text{min}} \times \frac{16 \text{ kg}}{\text{kgmol}} + \frac{400 \text{ kgmol}}{\text{min}} \times \frac{32 \text{ kg}}{\text{kgmol}} = \frac{14,400 \text{ kg}}{\text{min}}$$

Volumetric flow rate:

$$\frac{500 \text{ kgmol}}{\text{min}} \times \frac{1000 \text{ g/mol}}{\text{kgmol}} \times \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{g/mol} \cdot \text{K}} \times \frac{(200 + 273) \text{ K}}{10 \text{ atm}} = \frac{1.94 \times 10^6 \text{ L}}{\text{min}}$$

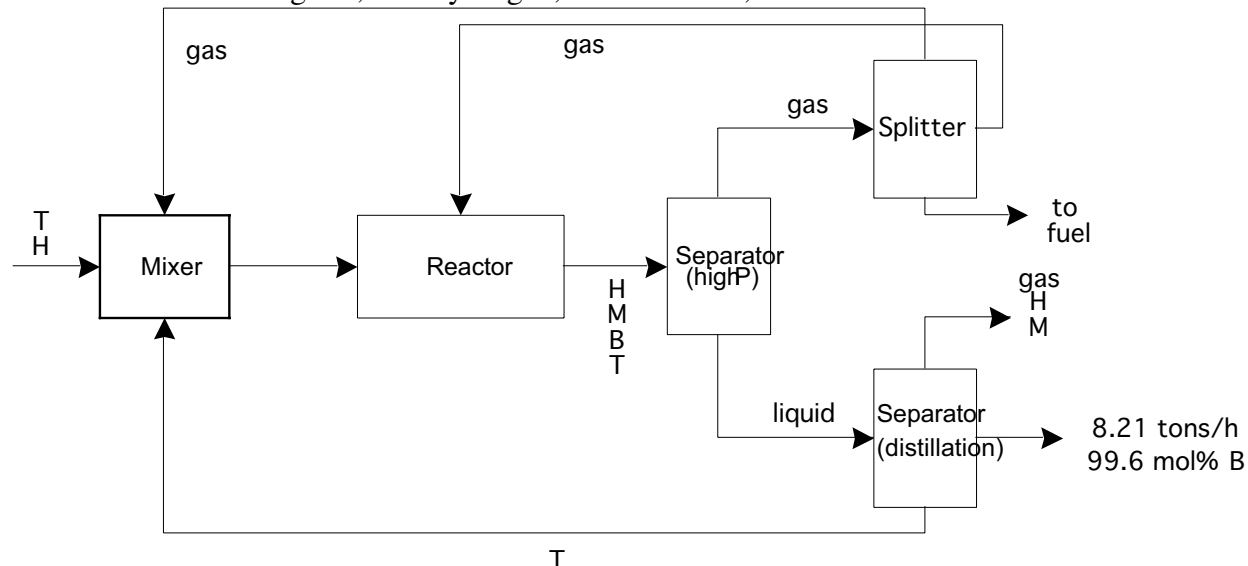
Mass fraction methane = 0.11...

P2.26

$$\text{Mass rate of accumulation} = \frac{\frac{\pi(100 \text{ cm}^2)}{4} \times 60 \text{ cm} \times \frac{2.329 \text{ g}}{\text{cm}^3}}{50 \text{ h}} = 219 \text{ g/h}$$

P2.27

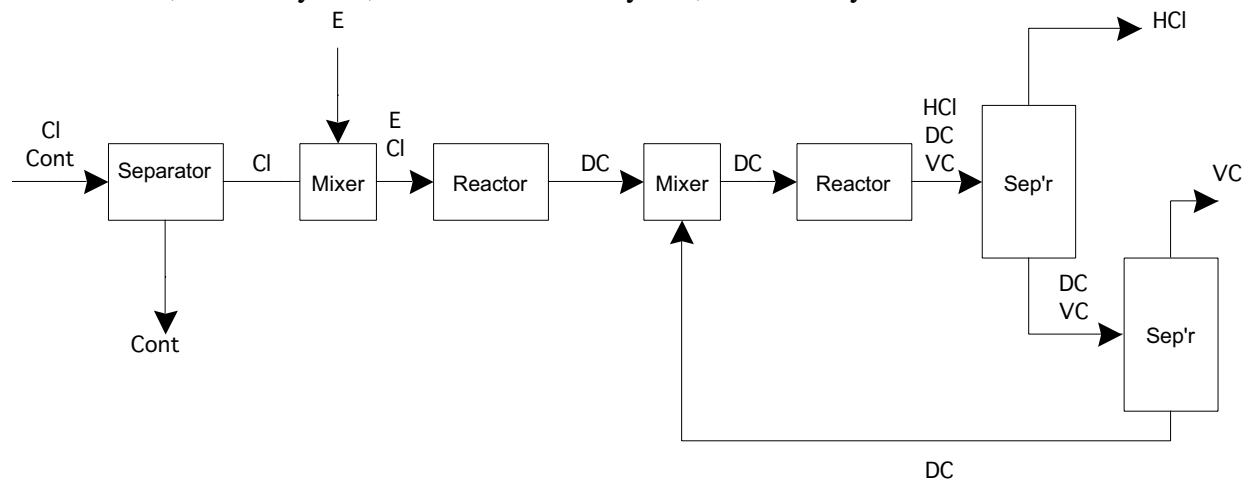
On the block flow diagram, H is hydrogen, M is methane, B is benzene and T is toluene.



- (a) 8.21 tons/h benzene produced
- (b) liquid stream contains 0.014 mol% hydrogen
liquid stream contains 0.062 mol% methane
distillation product is 99.6 mol% benzene
- (c) 75% toluene converted to benzene
75% of gas stream recycled
5 % of gas stream sent to reactor

P2.28

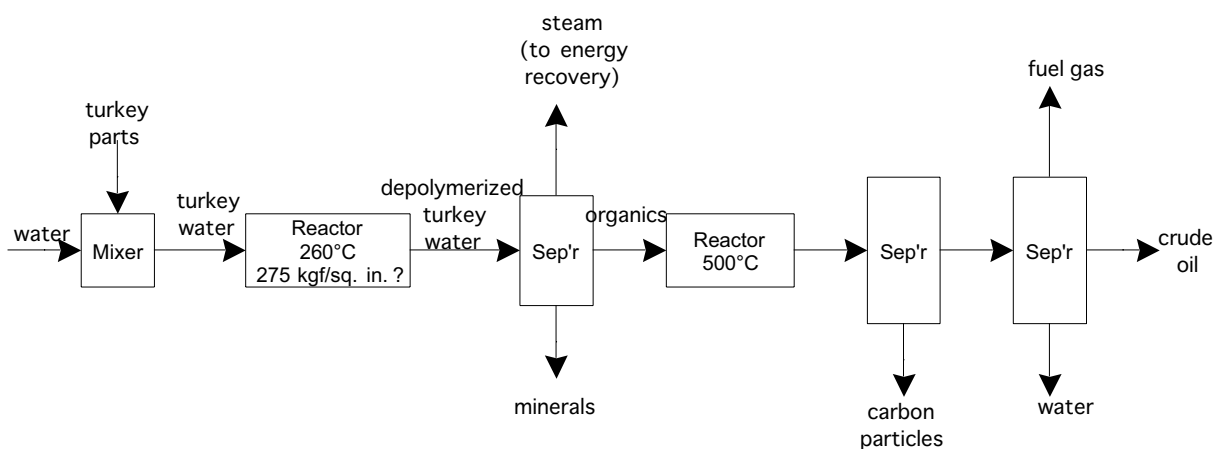
Components in each stream are indicated on the flow diagram, using Cl for chlorine, Cont for contaminant, E for ethylene, DC for dichloroethylene, VC for vinyl chloride:



P2.29

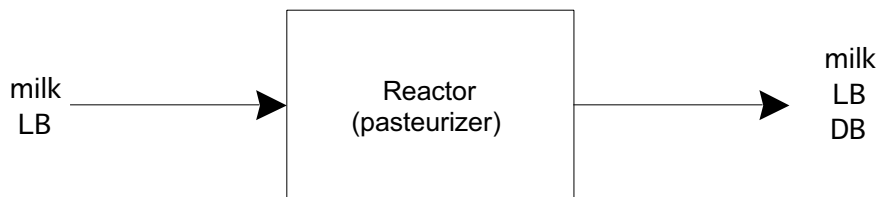
Metallurgical grade silicon is fed to a reactor along with hydrogen and HCl. In the reactor, silicon and HCl are reacted to make tetrachlorosilane and trichlorosilane. The reactor effluent is then sent to a gas-liquid separator, where the silanes come off as a liquid stream, and H_2 and HCl exit as a gas product. The liquid stream is sent to another (silane) separator, where tetrachlorosilane is removed and exits the process, and trichlorosilane is recovered for further processing. The gas product from the gas-liquid separator is also sent to gas purification separator, where HCl is separated from H_2 . The HCl is sent to a mixer for recycle to the reactor. Hydrogen gas from the gas purification separator along with a hydrogen recycle stream is mixed with the trichlorosilane and sent to a second reactor chamber. In that reactor, the trichlorosilane is reduced to Si by the hydrogen, with HCl as a byproduct. The Si grows on a rod that remains in the reactor chamber. Unreacted silanes, hydrogen, and HCl are recovered and sent to a separator. H_2 from this separator is recycled to the mixer just upstream of the reactor chamber. HCl is mixed with fresh HCl and recycled back to the first reactor. The unreacted silanes are sent to a separator, where impurities are removed, then recycled back to the silane separator for removal of tetrachlorosilane and recycle of trichlorosilane.

P2.30



P2.31

The pasteurizer is a reactor. Let LB = live bacteria, DB = dead bacteria. I'll also assume steady-state operation.



Balance on milk: Milk does not undergo a reaction, so the balance is In = Out.
(Actually, there are other reactions that subtly change the flavor of milk.)

Balance on LB: $\text{In} - \text{Out} - \text{Consumption} = 0$, or $\text{Out} = \text{In} - \text{Consumption}$. I'll assume that the time in the pasteurizer is short enough that we can neglect bacteria reproducing.

Balance on DB: $-\text{Out} + \text{Generation} = 0$, or $\text{Out} = \text{Generation}$. I'll assume that there are no dead bacteria in the milk fed to the pasteurizer.

P2.33

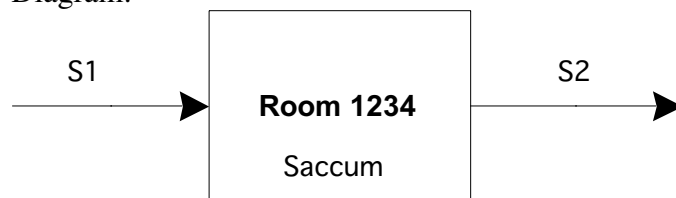
System: Room 1234

Component: Students

Stream and system variable names: S = students, 1 = inlet stream, 2 = outlet stream.

Units: are consistent

Diagram:



Stream composition and system performance specifications: none (in particular, we assume no generation or consumption of students)

DOF analysis: Variables: 2 stream and 1 system (accumulation); 3 total

Constraints: 2 specified flows, 1 material balance; 3 total

DOF = $3 - 3 = 0$. Correctly specified

Material balance equation: $S_1 - S_2 = S_{\text{accum}} = 37 - 1 = 36$ students.

Note: from this analysis we only know the change in the number of students in the classroom.

We need to consider the initial condition to determine the total number of students in the classroom at the end of this time interval: initially 6 students in classroom, so final count = initial + accumulated = $6 + 36 = 42$ students.

P 2.34

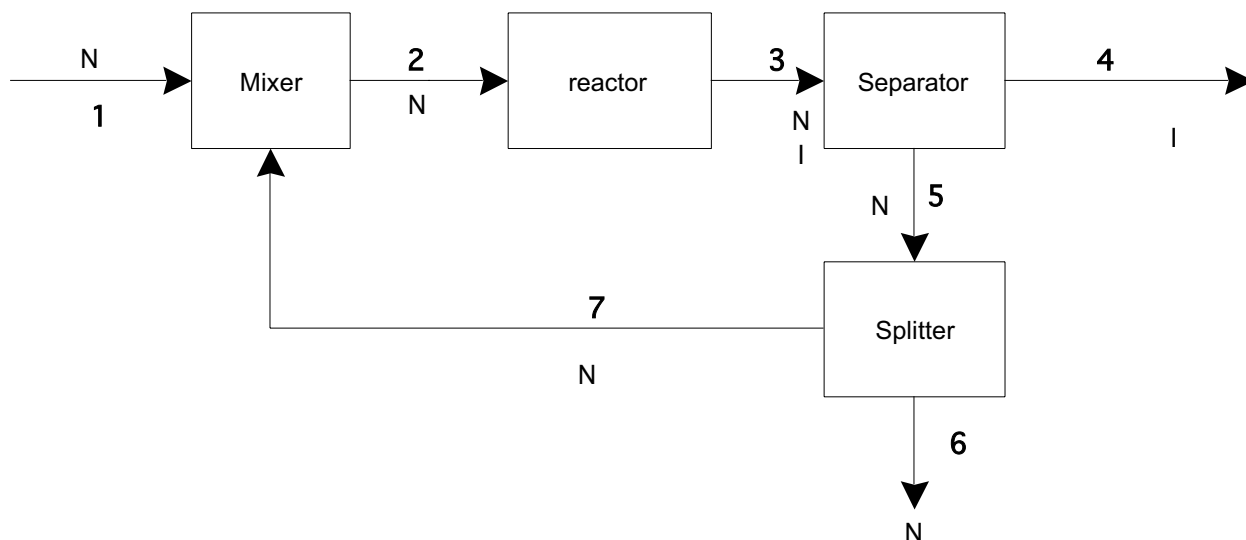
System: CE 101

Component: Novice students (ones who have not yet passed CE101) and initiates (those who have passed CE101).

Stream and system variable names: N = novices, I = initiates, streams numbered as shown. Units: are consistent

Basis: $N_1 = 100$ students

Diagram: We imagine the class as a reactor, consuming Novices and generating Initiates.



System performance specifications:

1. 60% of students entering reactor pass (are converted from novice to initiate), 40% do not.
 $N_3 = 0.4N_2$
2. 70% split, $N_7 = 0.7N_5$

DOF analysis:

	Variables	Constraints
Stream	8	
System	1	
Specified flows		1
Specified composition		0
Specified system performance		2
Material balance		6

$$\text{DOF} = 9 - 9 = 0$$

Material balances;

$$N_1 + N_7 = N_2$$

$$N_2 - N_3 = N_{\text{cons}}$$

$$N_5 = N_3$$

$$N_7 + N_6 = N_5$$

$$I_3 = I_{\text{gen}}$$

$$I_4 = I_3$$

From stoichiometry, $I_{\text{gen}}/N_{\text{cons}} = 1/1$.

Now we can combine these material equations with the basis and specification equations. We want to solve for N_2 , the number of students taking the class:

$$N_7 = 0.7N_5 = 0.7N_3 = 0.7(0.4)N_2 = 0.28N_2$$

$$N_1 + N_7 = N_2 = 100 + 0.28N_2$$

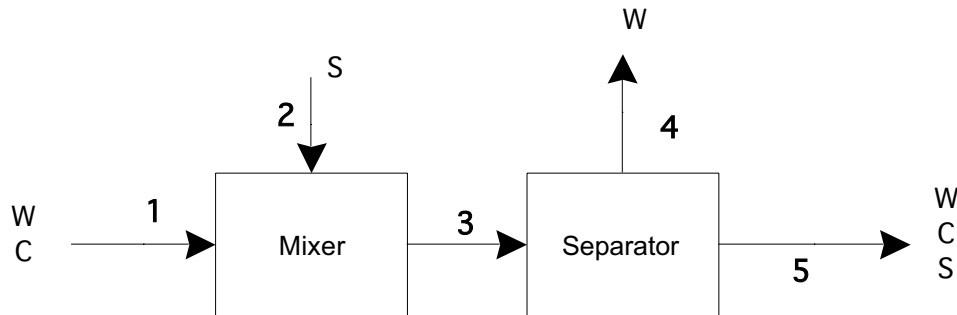
$$N_2 = 139 \text{ students}$$

P2.35

System: Mixer plus evaporator

Component: cherry solids, water, sugar

Diagram:



DOF analysis:

	Variables	Constraints
Stream	7 (taking the 2 units together as the system)	
System	0	
Specified flows		0
Specified composition		2
Specified system performance		1
Material balance		3 (taking the 2 units together as the system)

DOF = 7 - 6 = 1. Problem is underspecified.

Stream and system variable names: S = sugar, C = cherry solids, W = water; streams numbered as shown.

Units: all lb, or wt%, no additional conversion needed

Specifications: Stream 1 composition is 18% solids and 82% water:

$$C_1/W_1 = 18/82$$

Sugar is fed at 2:1 ratio to cherries:

$$S_2/(W_1 + C_1) = 2$$

Separator removes 2/3 of water fed to it:

$$W_4 = \frac{2}{3}W_1$$

Material balance equations are In = Out:

$$W_1 = W_4 + W_5$$

$$S_2 = S_5$$

$$C_1 = C_5$$

We need one more piece of information (a basis) to solve this problem.

(a) Basis is provided of $C_1 + W_1 = 10 \text{ lb/h}$

We combine the equations to find

$$C_1 = 0.18(10 \text{ lb/h}) = 1.8 \text{ lb/h} = C_5$$

$$W_1 = 0.82(10 \text{ lb/h}) = 8.2 \text{ lb/h}$$

$$W_4 = \frac{2}{3}(8.2) = 5.47 \text{ lb/h}$$

$$W_5 = 8.2 - 5.47 = 2.73 \text{ lb/h}$$

$$S_2 = 2(10 \text{ lb/h}) = 20 \text{ lb/h} = S_5$$

$$\text{Jam production rate} = 1.8 + 2.37 + 20 = 24.5 \text{ lb/h}$$

(b) We can scale from part (a):

$$\frac{10 \text{ lb cherries}}{24.5 \text{ lb jam}} = \frac{x \text{ lb cherries}}{10 \text{ lb jam}}$$

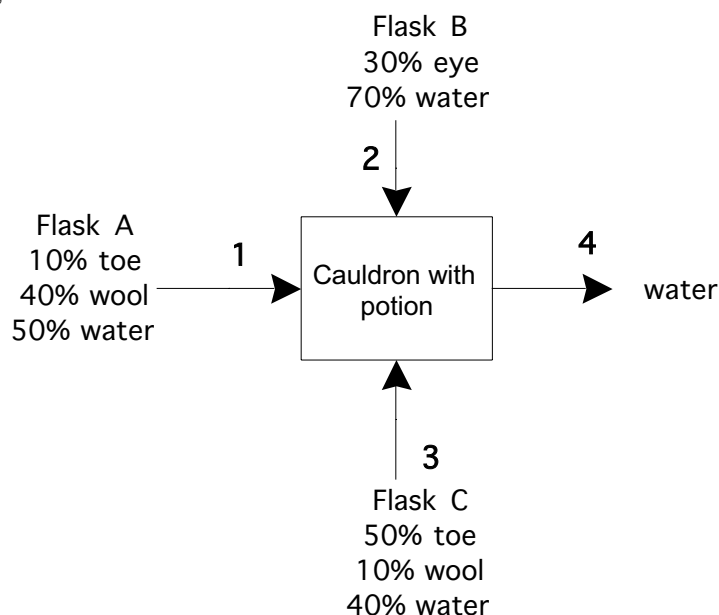
$$x = 4.1 \text{ lb cherries}$$

(c) The system is the pot. The material balance is: In – Out = Accumulation. We can write a balance on the total mass

$$(30 \text{ lb}) - (0.2 \text{ lb/min} \times 30 \text{ min}) = 24 \text{ lb}$$

P2.36

Diagram:



System: cauldron

Components: eye (E), toe (T), wool of bat (B) and water (W)

DOF analysis:

	Variables	Constraints
Stream	9	
System	4 (accumulated)	
Specified quantity		1
Specified compositions		8
Specified system performance		0
Material balance		4

$$\text{DOF} = 13 - 13 = 0$$

Stream variables: easier to work with total quantities of flasks A, B, and C, (M_1 , M_2 , M_3) and mass fractions: w_{T1} , w_{E2} , etc. .

System variables: the liquid potion accumulates in the cauldron. M_{pot} = total accumulated, the mass fraction of each component in the pot is denoted as $w_{T,\text{pot}}$, etc.

Units: g, and wt % - everything is consistent

Basis: 100 g of potion accumulated in pot.

$$M_{\text{pot}} = 100$$

Stream compositions: compositions of flasks A, B, and C, and potion in pot, are specified.

$$w_{T1} = 0.10, w_{B1} = 0.40, w_{W1} = 0.50$$

$$w_{E2} = 0.30, w_{W2} = 0.70$$

$$w_{T3} = 0.50, w_{B3} = 0.10, w_{W3} = 0.40$$

$$w_{T,\text{pot}} = 0.27, w_{E,\text{pot}} = 0.22, w_{B,\text{pot}} = 0.11, w_{W,\text{pot}} = 0.40$$

(Note: not all these mass fractions are independent!)

Material balance equations:

In – Out = Accumulation

$$w_{T1}M_1 + w_{T3}M_3 = w_{T,\text{pot}}M_{\text{pot}}$$

$$w_{E2}M_2 = w_{E,\text{pot}}M_{\text{pot}}$$

$$w_{B1}M_1 + w_{B3}M_3 = w_{B,\text{pot}}M_{\text{pot}}$$

$$w_{W1}M_1 + w_{W2}M_2 + w_{W3}M_3 - M_4 = w_{W,\text{pot}}M_{\text{pot}}$$

Solve: combine equations, starting with the eye of newt balance:

$$M_2 = \frac{w_{E,\text{pot}}M_{\text{pot}}}{w_{E2}} = \frac{0.22(100)}{0.30} = 73.3 \text{ g}$$

Next solve toe and wool balances simultaneously to find:

$$M_1 = 14.75 \text{ g}$$

$$M_3 = 51 \text{ g}$$

Finally, solve water balance:

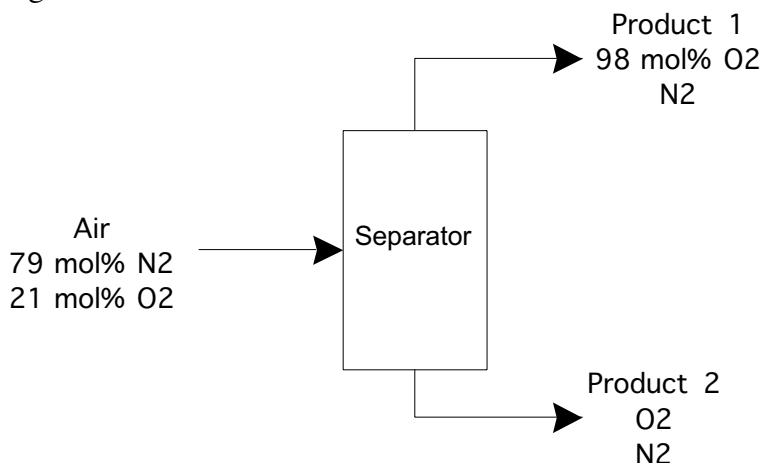
$$0.50(14.75) + 0.70(73.3) + 0.40(51) - M_4 = 0.40(100)$$

$$M_4 = 39 \text{ g}$$

To make the magic potion, mix 14.75 g of flask A, 73.3 g of flask B, and 51 g of flask C, then evaporate of 39 g water.

P2.37

Diagram:



System: Separator

Components: N₂ and O₂

DOF analysis:

	Variables	Constraints
Stream	6	
System	0	
Specified flows		1 (1 ton/yr Product 1)
Specified compositions		2
Specified system performance		1 (80% recovery)
Material balance		2

$$\text{DOF} = 6 - 6 = 0$$

Basis: 1 ton/day product 1

Units: The compositions are given in mol% but the problem asks for flow rates in tons/day, with a basis given in tons/day. It will be simplest to assign a new basis as a molar flow rate, complete calculations, then convert to mass flow rate and scale up or down. Let's use as a new basis 100 gmol/day of air fed to the separator

System variables: N = nitrogen, O = oxygen, fed, P1, P2 for feed stream, product 1, and product 2, respectively.

Stream variables: none (no reaction, no accumulation)

Stream composition specifications:

$$N_{fed} = 0.79(100) = 79 \text{ gmol/day}$$

$$O_{fed} = 0.21(100) = 21 \text{ gmol/day}$$

$$\frac{O_{P1}}{O_{P1} + N_{P1}} = 0.98$$

System performance specification: (Note the difference between 98% oxygen in stream, and 80% recovery of oxygen in stream – the first is a stream composition, the second is a system performance. The first can be described in an equation involving variables of one stream only, while the second requires relating one stream to another, or a system variable to a stream variable.)

$$O_{P1} = 0.8O_{fed} = 0.8(21) = 16.8 \text{ gmol/day}$$

Combining with stream composition specification: $\frac{16.8}{16.8 + N_{P1}} = 0.98 \rightarrow$

$$N_{P1} = 0.34 \text{ gmol/day}$$

Material balance equations:

$$O_{fed} = O_{P1} + O_{P2} \rightarrow O_{P2} = 21 - 16.8 = 4.2 \text{ gmol/day}$$

$$N_{fed} = N_{P1} + N_{P2} \rightarrow N_{P2} = 79 - 0.34 = 78.66 \text{ gmol/day}$$

The mol% nitrogen in the second stream is

$$\frac{N_{P2}}{N_{P2} + O_{P2}} \times 100\% = \frac{78.66}{78.66 + 4.2} \times 100\% = 95 \text{ mol\% N}_2$$

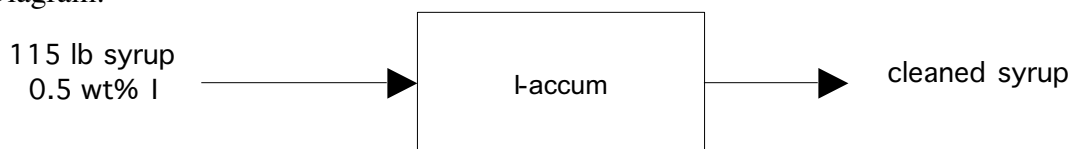
To scale up to 1 ton/day (2000 lb/day) Product 1, convert to mass flow by multiplying by molar mass, then multiply by scale factor.

Stream	gmol/day (old basis)	M _i	g/day	Lb/day (new basis SF = 2000/547.1)
N _{fed}	79	28	2212	
O _{fed}	21	32	672	
total			2884	10,543
N _{P1}	0.34	28	9.52	
O _{P1}	16.8	32	537.6	
total			547.1	2000
N _{P2}	78.66	28	2202.5	
O _{P2}	4.2	32	134.4	
total			2336.9	8,543

About 10, 540 lb/day air (5.27 tons/day) must be fed to make 1 ton/day oxygen-rich product.

P2.38

Diagram:



Components: I (impurities)

We assume that all impurities are removed from the syrup.

DOF analysis:

	Variables	Constraints
Stream	1	
System	1 (accumulation)	
Specified flows		1
Specified compositions		0
Specified system performance		0
Material balance		1

$$\text{DOF} = 2 - 2 = 0$$

Basis: $(0.005 \times 115) = 0.575 \text{ lb/h}$ impurities feed

Units:

Material balance: $I_{in} = I_{acc} = 0.575 \text{ lb/h}$

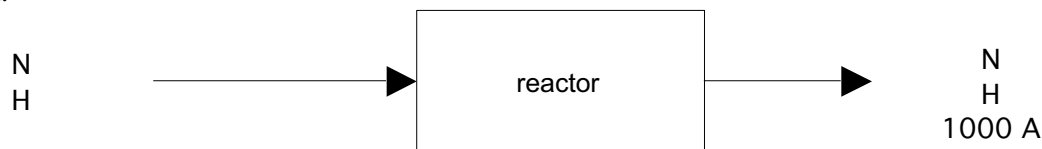
Total accumulation of impurities in the system in a 7 day period = $0.575 \times 24 \times 7 = 96.6 \text{ lb}$.

If the charcoal adsorbs 0.4 kg impurities per kg charcoal, (or 0.4 lb/lb) then the amount of charcoal that is required per 7 day period =

$$\frac{96.6 \text{ lb impurities}}{0.4 \text{ lb impurities/lb charcoal}} = 242 \text{ lb charcoal}$$

P2.39

Diagram:



Components: N (nitrogen as N_2), H (hydrogen as H_2), A (ammonia)

DOF analysis:

	Variables	Constraints
Stream	5	
System	1 (reaction)	
Specified flows		1
Specified compositions		1 (3:1 ratio in feed)
Specified system performance		1 (25% conversion)
Material balance		3

$$\text{DOF} = 6 - 6 = 0$$

Units: ok for now (lbmol/h and mol ratios), will have to convert answer to volumetric flow using ideal gas law.

Basis: 1000 lbmol/h NH_3 in outlet stream.

$$A_{out} = 1000$$

Material balances:

$$N_{in} - N_{cons} = N_{out}$$

$$H_{in} - H_{cons} = H_{out}$$

$$A_{gen} = A_{out}$$

From stoichiometry:

$$N_{cons}/H_{cons} = 1/3, \quad A_{gen}/N_{cons} = 2/1$$

From inlet stream specifications:

$$N_{in}/H_{in} = 1/3$$

From system performance specification:

$$N_{cons} = 0.25N_{in}$$

These equations are solved to find:

$$A_{gen} = 1000$$

$$N_{cons} = 500$$

$$H_{cons} = 1500$$

$$N_{in} = 2000$$

$$H_{in} = 6000$$

$$N_{out} = 1500$$

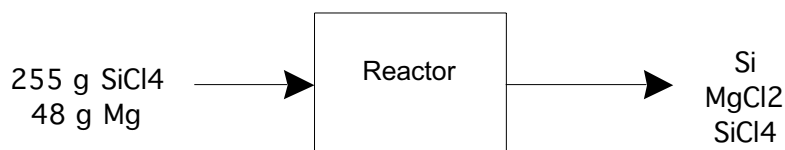
$$H_{out} = 4500$$

The volumetric feed rate to the reactor is calculated from the inlet molar flows and the ideal gas law:

$$(8000 \text{ lbmol/h}) \left(\frac{0.7302 \text{ atm ft}^3}{\text{lbmol } ^\circ\text{R}} \right) \left(\frac{1440 \text{ } ^\circ\text{R}}{100 \text{ atm}} \right) = 8.4 \times 10^4 \text{ ft}^3/\text{h}$$

P2.40

Diagram:



System: batch reactor

Components: Si, SiCl₄, Mg, MgCl₂. (an alternative is to use elements as components: Mg, Si, Cl)

DOF analysis:

	Variables	Constraints
Stream	5	
System	1 (reaction)	
Specified flows		2 (reactants added)
Specified compositions		0
Specified system performance		0
Material balance		4

$$\text{DOF} = 6 - 6 = 0$$

Stream variables: let S = Si, TS = tetrachlorosilane, M = Mg, and MC = magnesium chloride. The streams will be designated by “in” and “out”.

System variables: S_{gen} , TS_{cons} , M_{cons} , MC_{gen} .

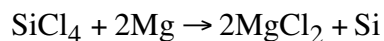
Units: all in g, but we have a chemical reaction so will need to convert to moles

$$TS_{\text{in}} = \frac{255 \text{ g}}{170 \text{ g/gmol}} = 1.5 \text{ gmol}$$

$$M_{\text{in}} = \frac{48 \text{ g}}{24 \text{ g/gmol}} = 2 \text{ gmol}$$

Stream composition and system performance specifications: None!

Reaction stoichiometry:



$$\frac{M_{\text{cons}}}{TS_{\text{cons}}} = \frac{2}{1}, \frac{MC_{\text{gen}}}{TS_{\text{cons}}} = \frac{2}{1}, \frac{S_{\text{gen}}}{TS_{\text{cons}}} = \frac{1}{1}$$

Material balance equations:

$$M_{out} = M_{in} - M_{cons}$$

$$TS_{out} = TS_{in} - TS_{cons}$$

$$S_{out} = S_{gen}$$

$$MC_{out} = MC_{gen}$$

Now we solve by combining these equations, starting with the Mg balance:

$$M_{out} = 0 = M_{in} - M_{cons} = 2 - M_{cons}$$

$$M_{cons} = 2$$

$$T_{cons} = \frac{1}{2} M_{cons} = 1$$

$$TS_{out} = 1.5 - 1 = 0.5$$

$$S_{out} = S_{gen} = T_{cons} = 1$$

$$MC_{gen} = 2T_{cons} = 2$$

$$MC_{out} = MC_{gen} = 2$$

We have to convert back to mass flow rate: out of the reactor comes

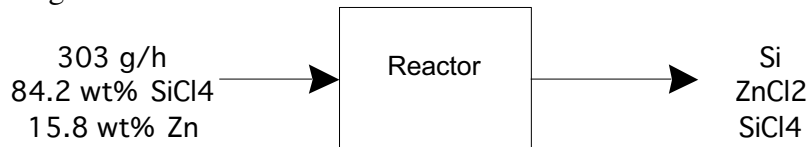
$$1 \text{ gmol (28 g/gmol)} = 28 \text{ g/day Si}$$

$$0.5 \text{ gmol (170 g/gmol)} = 85 \text{ g/day SiCl}_4$$

$$2 \text{ gmol (95 g/gmol)} = 190 \text{ g/day MgCl}_2$$

P2.41

Diagram:



System: Reactor

Components: Compounds: SiCl_4 , Zn, ZnCl_2 , and Si. (could alternatively solve using elements Si, Cl, Zn)

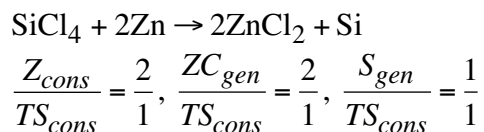
DOF analysis:

	Variables	Constraints
Stream	5	
System	1	
Specified flows		1 (reactants added)
Specified compositions		1
Specified system performance		0
Material balance		4

$$\text{DOF} = 6 - 6 = 0$$

Stream variables: TS for tetrachlorosilane, S for Si, Z for zinc, ZC for zinc chloride, “in”, ‘out’ for the streams.

System variables: From reaction stoichiometry:



Units: Because there is a reaction, we need to convert to molar units.

Basis: 303 g/h fed to reactor.

Stream composition specification: 84.2% SiCl₄ and 15.8 wt% Zn. Combine with basis and convert to molar units

$$TS_{\text{in}} = \frac{0.842(303)}{170 \text{ g/gmol}} = 1.5 \text{ gmol/h}$$

$$Z_{\text{in}} = \frac{0.158(303)}{65 \text{ g/gmol}} = 0.7365 \text{ gmol/h}$$

System performance specification: none

Material balance equations:

$$Z_{\text{out}} = 0 = Z_{\text{in}} - Z_{\text{cons}} = 0.7365 - Z_{\text{cons}}, Z_{\text{cons}} = 0.7365 \text{ gmol/h}$$

$$TS_{\text{out}} = TS_{\text{in}} - TS_{\text{cons}} = 1.5 - \frac{0.7365}{2} = 1.13 \text{ gmol/h}$$

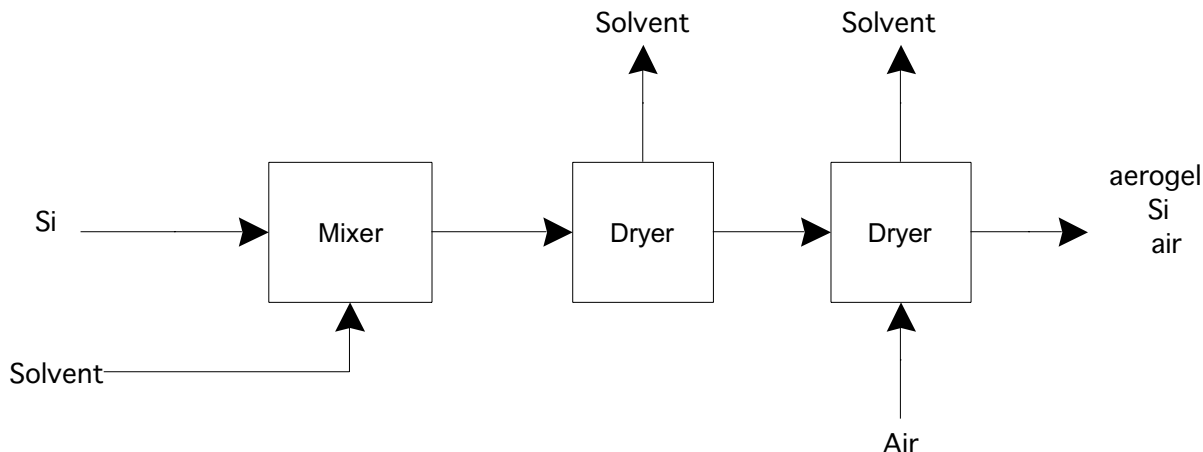
$$S_{\text{out}} = S_{\text{gen}} = 0.368 \text{ gmol/h}$$

$$ZC_{\text{out}} = ZC_{\text{gen}} = 0.7365 \text{ gmol/h}$$

To convert back to a mass flow rate, we multiply by the molar masses of each compound and find that the outlet flow is 192 g/h SiCl₄, 10 g/h Si, and 101 g/h ZnCl₂. Total flow rate is 303 g/h, composition is 63.5 wt% SiCl₄, 3.4 wt% Si, and 33.1 wt% ZnCl₂.

P2.42

Diagram:



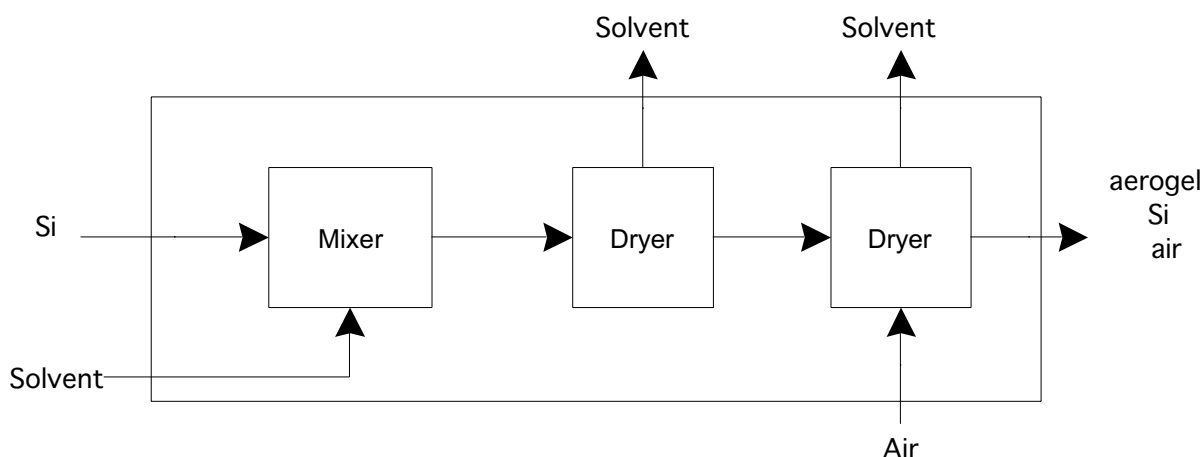
Components: Solvent, Si, and air (we can treat as a single component).

Units: We have both mass (g and mg) and volume (cm³).

System: the entire process will be lumped together, as shown.

Stream variables: S for solvent, A for air, Si for silicon, in and out for streams

System variables: none needed, no reaction or accumulation



Basis: 10 cm³ silica aerogel. At 3 mg/cm³, this is 30 mg, or

$$Si_{out} + A_{out} = 30 \text{ mg} = 0.030 \text{ g.}$$

Stream composition specification: Si and solvent are fed at a 1:1 weight ratio, or

$$Si_{in} = S_{in}$$

System performance specifications: there are none to worry about. All of the solvent is removed in the two dryers.

Material balances:

$$Si_{out} = Si_{in}$$

$$S_{out} = S_{in}$$

$$A_{out} = A_{in}$$

Let's start by making the assumption that ALL the mass in the aerogel is Si, and ALL the volume is air (we'll then check this assumption). If this is true, then

$$Si_{in} = Si_{out} = 30 \text{ mg}$$

The density of solid silicon is 2.33 g/cm³. 30 mg would have a volume of 0.0129 cm³. Thus, there has been a 775-fold increase in volume, and it is a reasonably good approximation to assume that essentially all of the volume of the aerogel is air.

The moles of air corresponding to 10 cm³ volume is calculated from the ideal gas law, assuming ambient conditions (298 K and 1 atm pressure)

$$n = \frac{PV}{RT} = \frac{(1 \text{ atm})(10 \text{ cm}^3)}{(82.057 \text{ atm cm}^3/\text{gmol K})(298 \text{ K})} = 4.1 \times 10^{-4} \text{ gmol}$$

which, at 28.8 g/gmol for air, corresponds to 11.8 mg. Thus, we see that our assumption that all the mass in the aerogel is due to Si is wrong, but the assumption that all the volume is due to air is reasonable. Now we find:

$$A_{out} = 11.8 \text{ mg}$$

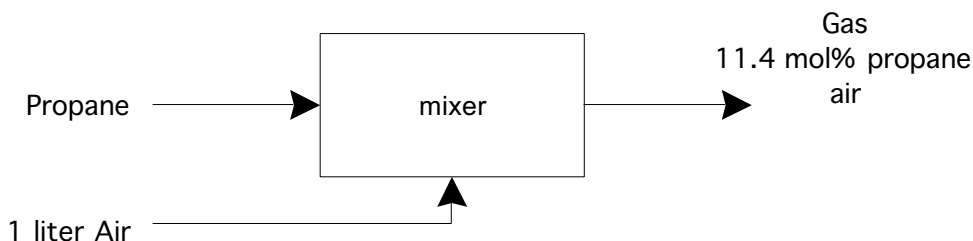
$$Si_{out} = 30 - 11.8 = 18.2 \text{ mg}$$

The mass % of air in the aerogel is 11.8/30 x 100% or 39%. The volume taken up by the silicon (from the density of pure silicon) is 0.0078 cm³, so the vol% of air in the aerogel is about 99.9%.

The quantity of solvent required is, from the stream composition specification, 18.2 mg. Since 95% of it is recovered for re-use, the fresh solvent feed to the process is only 0.91 mg solvent per 10 cm³ aerogel.

P2.43

Diagram:



System: mixer

Components: Air, Propane (Note that since the air does not undergo any separation or chemical reaction, we can treat it as a single component! The composition of the air is irrelevant for this problem. It would not be wrong to consider air as a mix of 2 components, but it is not necessary.)

DOF analysis:

	Variables	Constraints
Stream	4	
System	0	

Specified flows		1
Specified compositions		1
Specified system performance		0
Material balance		2

$$\text{DOF} = 4 - 4 = 0$$

Basis: 1 liter air fed

Stream variables: P for propane, A for air. Streams indicated as “in” or “out”.

Units: We need to convert from volume (L) to moles. We’ll use the ideal gas law:

$$n = \frac{PV}{RT} = \frac{(1 \text{ atm})(100 \text{ L})}{(0.082057 \text{ atm L/gmol K})(273 \text{ K})} = 4.464 \text{ gmol}$$

Stream composition specifications:

$$\frac{P_{out}}{A_{out} + P_{out}} = 0.114$$

System performance specifications: none

Material balances;

$$A_{in} = A_{out} = 4.464 \text{ gmol}$$

$$P_{in} = P_{out}$$

Combining the material balance with the stream composition, we find:

$$\frac{P_{out}}{4.464 + P_{out}} = 0.114, P_{out} = 0.574 \text{ gmol} = P_{in}$$

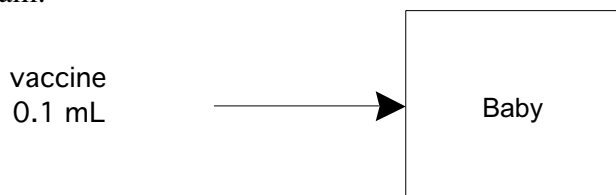
Converting to pounds:

$$0.574 \text{ gmol} \times \frac{44 \text{ g}}{\text{gmol}} \times \frac{\text{lb}}{454 \text{ g}} = 0.056 \text{ lb propane (or more) must be mixed with 100 L of}$$

air to exceed the flammability limit.

P2.44

Diagram:



System: Baby

Component: D

Stream variables: D_{in}

System variables: Deuterium accumulates in the baby. D_{accum}

Basis: The mass of deuterium in one vaccine dose, assuming that water density is 1 g/mL, is

$$D_{in} = 0.1 \text{ mL} \times \frac{1 \text{ g}}{\text{mL}} \times \frac{0.87 \text{ g D}_2\text{O}}{\text{g vaccine}} \times \frac{4 \text{ g D}}{20 \text{ g D}_2\text{O}} = 0.0174 \text{ g D}$$

Material balance:

$$D_{in} = D_{accum} = 0.0174 \text{ g}$$

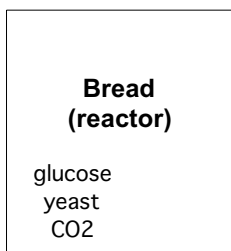
This is the change in deuterium in the infant's body. We should compare this to the total amount of deuterium naturally in the infant. From Problem 2.4, a human is about 10 wt% H. A 3 kg infant therefore contains 0.3 kg hydrogen (includes H and D). If 0.014% of the total is D, this corresponds to $(0.00014)(0.3) = 4.2 \times 10^{-5} \text{ kg D}$ or 0.042 g D initially. The deuterium after injection of the vaccine is 0.042 + 0.0174 or 0.0594 g. H does not change much with the small amount injected with the vaccine, therefore, we can estimate that the deuterium loading in the infant increases from 0.014% to $0.0594/300.0594$ or 0.0198%, for a ~40% increase. This is rather significant! Additional safety testing is warranted; in particular, it would be interesting to see how rapidly deuterium levels drop back to normal. Any new risk due to deuterium loading must be balanced against the reduced risk of disease due to vaccination.

P2.45

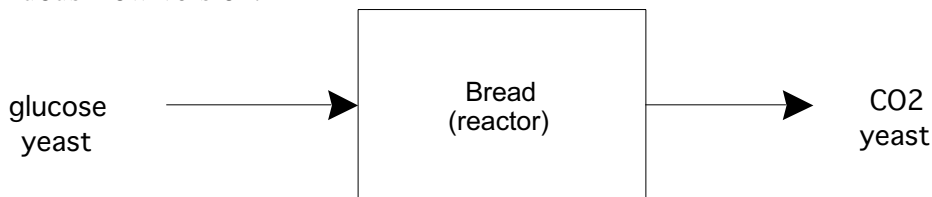
The bread acts as a chemical reactor. Glucose and ammonia are consumed, and CO₂ and yeast are produced. (In reality, other organic compounds are also made during metabolism of glucose by yeast, but we are ignoring those reactions for simplicity.)

Diagram:

Batch version:



continuous-flow version:



System: The bread dough. This is a batch reactor. We can treat it as a batch process, in which case there is no In or Out process streams (upper diagram), and we consider accumulation inside the reactor as well as reaction inside the reactor. Alternatively (lower diagram), we can consider the bread dough prior to addition of glucose and yeast as the system, and consider the CO₂ and

yeast produced as leaving the system. In this case there will be In and Out streams, reaction inside the bread, but no Accumulation. Either method is ok – but it is crucial to be clear on your choice. We will assume it is a flow reactor, with no Accumulation.

Components: We could choose glucose, CO₂, and yeast as our components. However, this would require us to know the reaction stoichiometry, which is not given, nor is it easy to figure out for the reaction of glucose and protein to yeast. In this case, elements are useful. We will choose carbon C as the element.

Stream and system variables: Given our choice of system and components, there are no system variables (elements cannot be generated or consumed).

Basis: 120 in³ CO₂ generated (to double the volume of the dough).

Units: We are given information in volume and in mass. We also have a chemical reaction to deal with. We need to convert volume to mass, and mass to moles. To calculate the moles of CO₂ produced, we use the ideal gas law and we'll assume a room temperature of 77°F (25 °C) and a room pressure of 1 atm.

$$n = \frac{PV}{RT} = \frac{(1 \text{ atm})(120 \text{ in}^3) \left(\frac{1 \text{ L}}{61.02374 \text{ in}^3} \right)}{(0.08206 \text{ L atm/gmol K})(298)} = 0.0804 \text{ gmol CO}_2$$

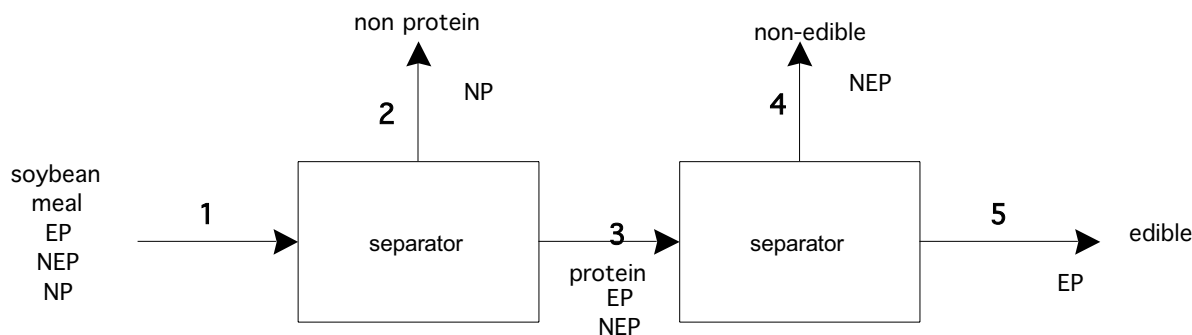
or, since the molar mass of CO₂ is 44 g/gmol, 3.54 g CO₂ must be generated. The 3.54 g CO₂ generated contains (12/44)*3.54 or 0.965g C. We were given that 1 g of yeast is generated for every 2 g of CO₂ generated. Therefore, 3.54/2 or 1.77 g yeast are generated. We note that yeast is 50 wt% C. In other words, the 1.77 g yeast generated contains 0.885 g C. Thus, C_{out} = 0.965 + 0.885 = 1.85 g C.

Material balance: This is simple: C_{in} = C_{out} = 1.85 g

The only source of C in the inlet stream is glucose. The wt fraction C in glucose is simply the molar mass of C divided by the total molar mass, or (72/180) = 0.4. Therefore, the grams of glucose required to supply the carbon converted to yeast and CO₂ is (1.85/0.4) or 4.62 g glucose is consumed.

P2.46

We can think of the soy protein calculation as a separation of meal into edible protein (EP), nonedible protein (NEP), and non-protein (NP) components as sketched on the diagram:



DOF analysis:

	Variables	Constraints
Stream	8	
System	0	
Specified flows		0
Specified compositions		1 (soybean is 44% protein)
Specified system performance		1 (70% recovered as edible protein)
Material balance		5 (3 on first separator, 2 on second separator)

$$\text{DOF} = 8 - 7 = 1$$

The problem as stated is underspecified.

Units: We'll keep everything in mass units (lb).

Components: there are 3: NEP, EP, NP.

Stream variables: Variables will be named by their component name and their stream number, as indicated on the diagram.

Basis: there is no basis, so we may choose a convenient one – say, 100 lb edible protein produced. This adds one constraint, making the problem correctly specified. We express this as

$$EP_5 = 100$$

Stream compositions: Expressed in terms of our variables:

$$\frac{EP_1 + NEP_1}{EP_1 + NEP_1 + NP_1} = 0.44$$

System performance: Expressed in terms of our variables;

$$\frac{EP_5}{EP_3 + NEP_3} = 0.7, \text{ or, when combined with basis: } EP_3 + NEP_3 = 143 \text{ lb}$$

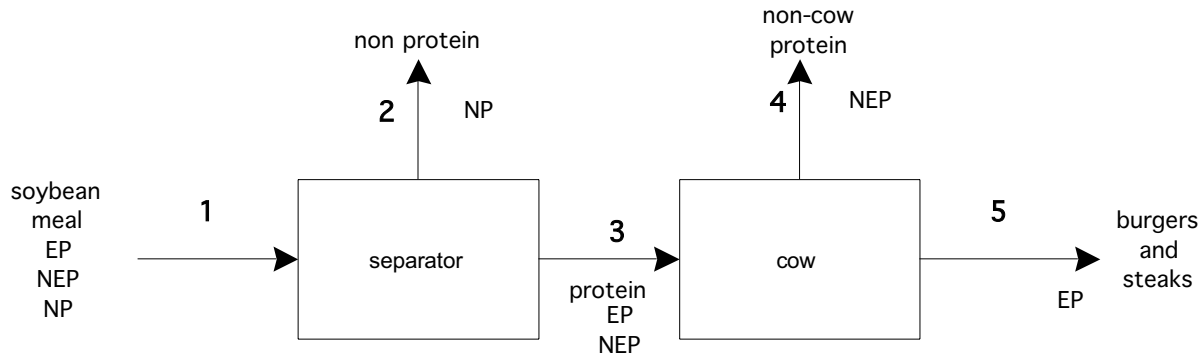
Material balances: All simplify to IN = OUT (with solutions by combining with above):

$$\begin{aligned} EP_3 &= EP_5 = EP_1 = 100 \text{ lb} \\ NEP_3 &= NEP_1 = 43 \text{ lb} \end{aligned}$$

$$\frac{EP_1 + NEP_1}{EP_1 + NEP_1 + NP_1} = 0.44 = \frac{143}{143 + NP_1}, \text{ or } NP_1 = 182 \text{ lb}$$

Therefore, it takes 100 + 43 + 183, or 326 lb meal to make 100 lb edible protein. At \$0.40/lb meal, then, it costs \$130 to pay for raw material costs for 100 lb protein, or about \$1.30/lb.

For converting soy protein to cow protein, the diagram changes a bit:



The only real difference is the system performance of the second process unit, the cow. If we use the same basis:

$$\frac{EP_5}{EP_3 + NEP_3} = 0.07 \text{ or: } EP_3 + NEP_3 = 1429 \text{ lb}$$

Therefore:

$$EP_3 = EP_5 = EP_1 = 100 \text{ lb (as before)}$$

$$NEP_3 = NEP_1 = 1329 \text{ lb}$$

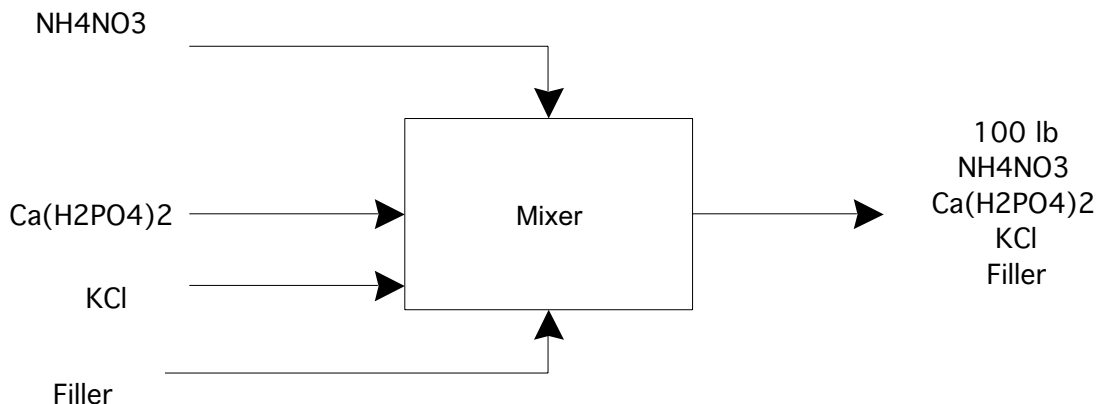
$$\frac{EP_1 + NEP_1}{EP_1 + NEP_1 + NP_1} = 0.44 = \frac{1429}{1429 + NP_1}, \text{ or } EP_1 + NEP_1 + NP_1 = 3247 \text{ lb}$$

The cost for 3247 lb soy meal is \$1300, or, per lb of burger and steak protein, this is \$13/lb protein. (Steaks are roughly 0.16 lb protein per lb steak.)

(Although this problem is simple to solve, it is useful to go through the process of choosing basis, sketching diagrams, and identifying stream composition and system performance specifications.)

P2.47

Diagram:



Components: Let's choose the three compounds (ammonium nitrate, calcium phosphate, KCl), plus filler, as our 4 components. (It is also possible to solve this problem using elements, plus filler, as components.)

Basis: 100 lb Gro-Right

Units: lb (all on consistent basis)

Stream variables: We'll call ammonium nitrate AN, calcium phosphate CP, filler F and potassium chloride PC. Streams will be denoted as IN or OUT.

Stream composition specifications: The 5-10-5 specification provides 3 compositions.

System performance specifications: none

DOF analysis:

	Variables	Constraints
Stream	8	
System	0	
Specified flows		1 (100 lb)
Specified compositions		3
Specified system performance		0
Material balance		4

$$\text{DOF} = 8 - 8 = 0$$

Material balances: These all simplify to $\text{IN} = \text{OUT}$. The trick is to convert the specified stream compositions to a more useful form.

First, we know the fertilizer contains 5 lb N. All the N comes from ammonium nitrate. From the molecular formula, we calculate that 28/80, or 0.35 of AN is N. Therefore:

$$AN_{out} = AN_{in} = \frac{5 \text{ lb N}}{0.35 \text{ lb N/lb AN}} = 14.3 \text{ lb}$$

Second, the fertilizer contains 10 lb P_2O_5 . The molar mass of P is 31 and that of P_2O_5 is 142. The source of P is calcium phosphate – which contains 62 lbs P per 234 lb $\text{Ca}(\text{H}_2\text{PO}_4)_2$. Thus:

$$CP_{out} = CP_{in} = 10 \text{ lb P}_2\text{O}_5 \times \frac{62 \text{ lb P}}{142 \text{ lb P}_2\text{O}_5} \times \frac{234 \text{ lb Ca}(\text{H}_2\text{PO}_4)_2}{62 \text{ lb P}} = 16.5 \text{ lb}$$

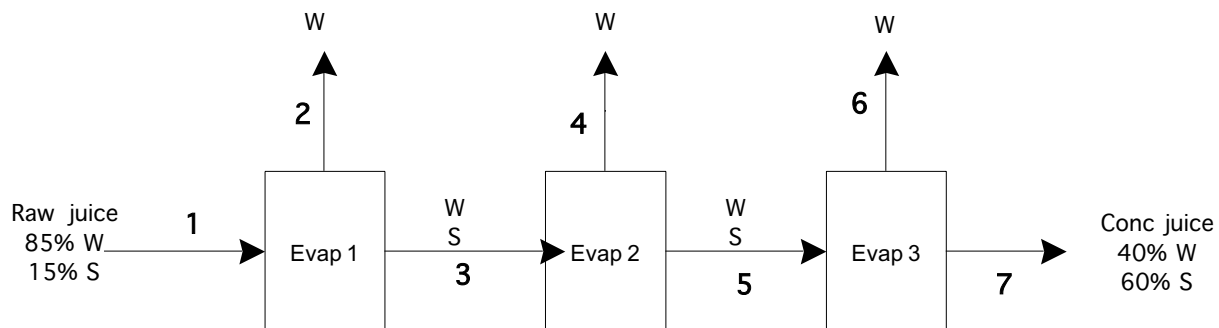
Third, the fertilizer contains 5 lb K_2O . Using the same reasoning as before,

$$PC_{out} = PC_{in} = 5 \text{ lb K}_2\text{O} \times \frac{78 \text{ lb K}}{94 \text{ lb K}_2\text{O}} \times \frac{74.5 \text{ lb KCl}}{39 \text{ lb K}} = 7.9 \text{ lb}$$

We've now accounted for 14.3 + 16.5 + 7.9, or 38.7 lb of the 100 lb fertilizer. The rest, 61.3 lb, must be filler. So about 61% of the fertilizer is simply filler.

P2.48

Diagram:



Components are water (W) and sugar solids (S). Streams are numbered.

Basis: 10,000 lb/h raw juice fed to the first separator.

Units: all in mass (lb) and wt%, no conversion needed

DOF analysis:

	Variables	Constraints
Stream	11	
System	0	
Specified flows		1
Specified compositions		2 (85% water in raw juice, 40% water in conc juice, solids content is not independent)
Specified system performance		2 (the flow rates of water from the 3 evaporators are equal – this provides 2, not 3, independent pieces of information)
Material balance		6 (2 per unit)

$$\text{DOF} = 11 - 11 = 0$$

Basis, stream composition and system performance written in terms of stream variables:

$$S_1 = 0.15(10,000) = 1500 \text{ lb/h}$$

$$W_1 = 0.85(10,000) = 8500 \text{ lb/h}$$

$$\frac{S_7}{W_7} = \frac{60}{40} = 1.5$$

$$W_2 = W_4 = W_6$$

Material balances:

$$S_1 = S_3 = S_5 = S_7 = 1500 \text{ lb/h} - \text{therefore, } W_7 = \frac{S_7}{1.5} = \frac{1500}{1.5} = 1000 \text{ lb/h}$$

$$W_1 = 8500 = W_2 + W_3$$

$$W_3 = W_4 + W_5$$

$$W_5 = W_6 + W_7 = W_6 + 1000$$

We can combine the water material balances along with knowledge that the water removal rate is equal in each evaporator into one equation;

$$8500 = W_2 + W_4 + W_6 + 1000 = 3W_2 + 1000, \text{ or } W_2 = 2500 \text{ lb/h}$$

To answer the specific questions:

(a) the flow rate of concentrated juice is $S_7 + W_7 = 1500 + 1000 = 2500 \text{ lb/h}$

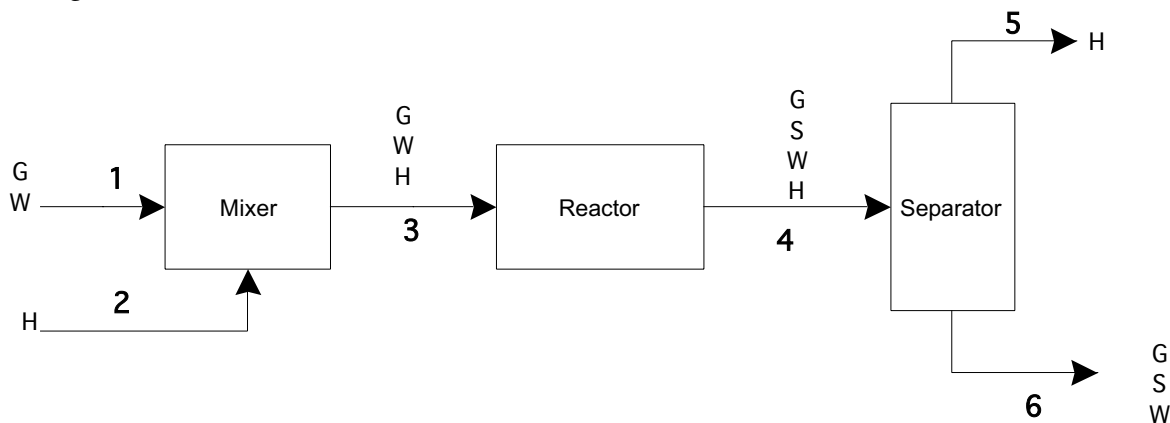
(b) the amount of water removed per evaporator is 2500 lb/h

(c) the concentration of water in the juice fed to the second evaporator is

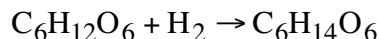
$$\frac{W_3}{S_3 + W_3} = \frac{8500 - 2500}{1500 + (8500 - 2500)} = 0.8 \text{ lb water/lb juice}$$

P.2.49

Flow diagram:



Balanced chemical reaction:



We'll solve using each process unit in turn as the system.

Components: Glucose (G), water (W), hydrogen (H) and sorbitol ((S)).

DOF analysis:

	Variables	Constraints
Stream	14	

System	1 (reaction)	
Specified flows		1
Specified compositions		2 (%glucose in feed solution, ratio of H ₂ fed to glucose fed)
Specified system performance		1 (% conversion in reactor)
Material balance		11

$$\text{DOF} = 15 - 15 = 0$$

Units: all in kg/day or wt%. Since we have a reaction of known stoichiometry, we will need to convert from mass to moles.

Basis: $G_1 + W_1 = 100$ kg/day

Stream composition specifications:

$$\frac{G_1}{G_1 + W_1} = 0.3, \text{ so } G_1 = 30 \text{ kg/day}, W_1 = 70 \text{ kg/day}$$

Hydrogen is fed at stoichiometric ratio to glucose, or 1 mol H₂ per mole glucose. Our stream variables are in mass flow units, so we need to convert through the molar masses:

$$\frac{H_2}{G_1} = \frac{1 \text{ kgmol H}_2 \times 2 \text{ kg/kgmol}}{\text{kgmol C}_6\text{H}_{12}\text{O}_6 \times 180 \text{ kg/kgmol}} = \frac{0.0111 \text{ kg H}_2}{\text{kg C}_6\text{H}_{12}\text{O}_6}, \text{ so } H_2 = 0.333 \text{ kg/day}$$

System performance specification:

$$\frac{G_{\text{cons}}}{G_3} = 0.8$$

From reaction stoichiometry 1 mole H₂ is consumed and 1 mole sorbitol is generated per mole glucose consumed. Converting to mass ratios gives:

$$\frac{H_{\text{cons}}}{G_{\text{cons}}} = \frac{2}{180}, \frac{S_{\text{gen}}}{G_{\text{cons}}} = \frac{182}{180}$$

Material balance equations:

For mixer: $G_1 = G_3 = 30$ kg/day, $W_1 = W_3 = 70$ kg/day, $H_2 = W_3 = 0.333$ kg/day

For reactor: $W_3 = W_4 = 70$ kg/day

$$G_3 - G_{\text{cons}} = G_4 = 30 - 0.8(30) = 6 \text{ kg/day}$$

$$H_3 - H_{\text{cons}} = H_4 = 0.333 - \frac{2}{180}(24) = 0.066 \text{ kg/day}$$

$$S_{\text{gen}} = S_4 = \frac{182}{180}(24) = 24.27 \text{ kg/day}$$

For separator: $W_4 = W_6 = 70$ kg/day

$$G_4 = G_6 = 6 \text{ kg/day}$$

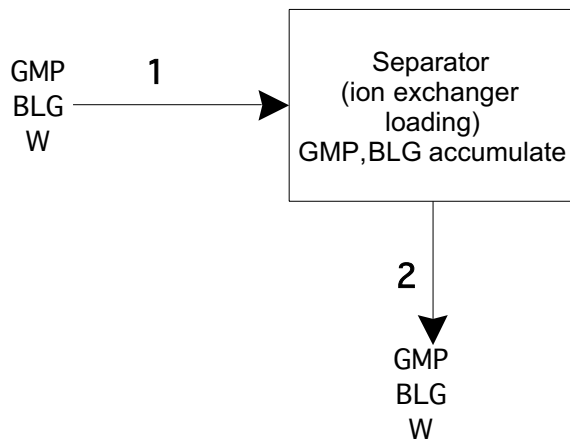
$$H_4 = H_5 = 0.066 \text{ kg/day}$$

$$S_4 = S_6 = 24.27 \text{ kg/day}$$

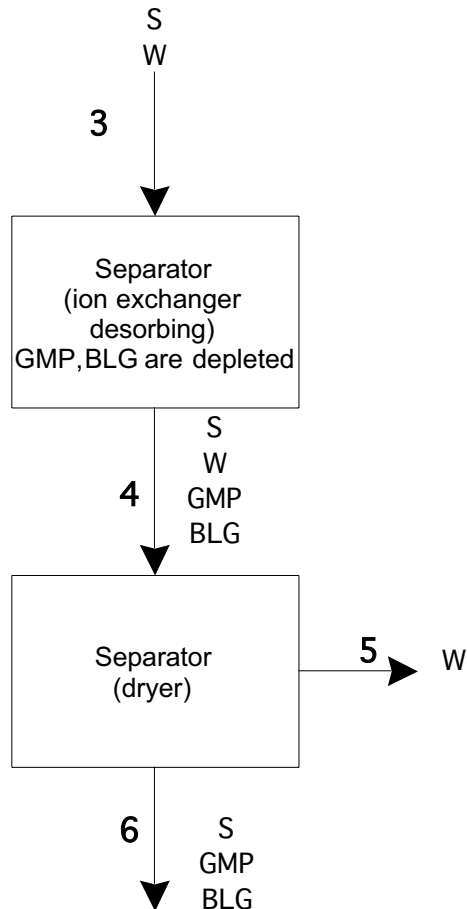
To summarize, 0.333 kg/day hydrogen is fed to the process. The total liquid flow rate out is $(70+6+24.27) = 100.3$ kg/day, and it contains 69.8 wt% water, 24.2 wt% sorbitol, and 6.0 wt% glucose.

P2.50

Flow diagram: The components are, besides GMP and BLG, water (W) and sodium chloride (S). We consider the separator at two different times, once operating in the “loading” regime,



and the other in the “desorbing” regime.



Units: Flows are given in mL/min, we have a concentration of salt in M and concentrations of protein in g/L. We will assume a density of 1 g/mL (the density of water) for all solutions, and will convert the salt concentration from moles/L to g/L. It is easiest to consider what happens over a finite period of time, therefore, we will multiply the flow rates by the time interval to calculate the quantity of material in a stream or accumulated in the system.

System: we will solve this problem in two steps, by first considering the separator in the loading mode as the system, and second considering the separator in the desorbing mode.

The loading mode lasts 30 minutes. During that time, the solution flow rate is 150 mL/min or 150 g/min, and the total amount of material fed to the system is

$$GMP_1 + BLG_1 + W_1 = 150 \text{ g/min} \times 30 \text{ min} = 4500 \text{ g}$$

From the stream composition specifications, we calculate

$$GMP_1 = \frac{1.2 \text{ g}}{\text{L}} \times \frac{0.15 \text{ L}}{\text{min}} \times 30 \text{ min} = 5.4 \text{ g}, \quad BLG_1 = \frac{0.8 \text{ g}}{\text{L}} \times \frac{0.15 \text{ L}}{\text{min}} \times 30 \text{ min} = 3.6 \text{ g}$$

and $W_1 = 4491 \text{ g}$.

There are two system performance specifications:

$$\frac{GMP_{accum}}{GMP_1} = 0.89, \text{ or } GMP_{accum} = 0.89 \times 5.4 \text{ g} = 4.8 \text{ g}$$

$$\frac{BLG_{accum}}{BLG_1 \times t} = 0.24 \text{ or } BLG_{accum} = 0.24 \times 3.6 \text{ g} = 0.86 \text{ g}$$

From material balances, we calculate (not necessary to answer the question)

$$GMP_2 = GMP_1 - GMP_{accum} = 5.4 - 4.8 = 0.6 \text{ g}$$

$$BLG_2 = BLG_1 - BLG_{accum} = 3.6 - 0.864 = 2.74 \text{ g}$$

$$W_2 = W_1 = 4491 \text{ g}$$

Now we move on to consider the desorbing mode of operation. We will calculate everything based on 10 minute of pumping salt solution across the ion exchanger.

$$\text{Basis: } S_3 = \frac{0.25 \text{ gmol NaCl}}{\text{L solution}} \times \frac{58.5 \text{ g NaCl}}{\text{gmol NaCl}} \times \frac{0.15 \text{ L}}{\text{min}} \times 10 \text{ min} = 22 \text{ g NaCl}$$

System performance: since all the adsorbed protein is desorbed in this step, GMP and BLG are “de-accumulated”

$$GMP_{accum} = -4.8 \text{ g and } BLG_{accum} = -0.86 \text{ g}$$

From material balance equations, with the ion exchanger and dryer considered as a single system:

$$S_6 = S_3 = 22 \text{ g}$$

$$GMP_6 = -GMP_{accum} = 4.8 \text{ g}$$

$$BLG_6 = -GMP_{accum} = 0.86 \text{ g}$$

The total mass of product is $22 + 4.8 + 0.86 = 27.66 \text{ g}$, of which 79.5 wt% is NaCl, 17.3 wt% is GMP, and 3.1 wt% is BLG. The ratio of GMP:BLG has changed from 1.5:1 in the cheese whey to 5.6:1 in the dried product. In a real process, another step would be added to decrease the salt content.

P2.53

The N_2 data are plotted in Figure 1. Alongside the data I plotted the ideal gas equation $P = nRT/V$, with $n = 1.000 \text{ gmol}$, and $V = 22.414 \text{ L}$ or 2.24 L . The data lie very close to the line representing the equation; there is a slight deviation only at high P. Nitrogen behaves as an ideal gas.

For CO_2 , the data plot as shown in Figure 2. At 300 K or above, CO_2 behavior is characteristic of an ideal gas. (There is one point that deviates – most likely a suspect data point.) At 200 K the data deviate from the model equation. At these conditions, CO_2 is starting to condense – and a liquid is NOT an ideal gas!

The water data are plotted in Figure 3. There is clearly deviation from the ideal gas law for water below 500 K, and even some deviation in experiment 2 above 500 K. Water is not an ideal gas when it is condensed!

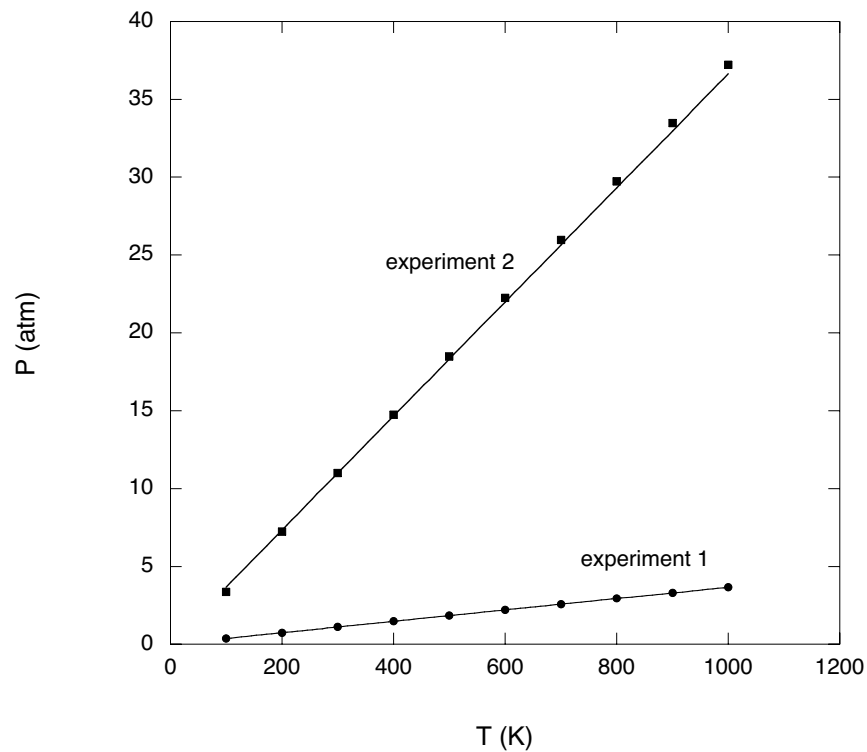


Figure 1.

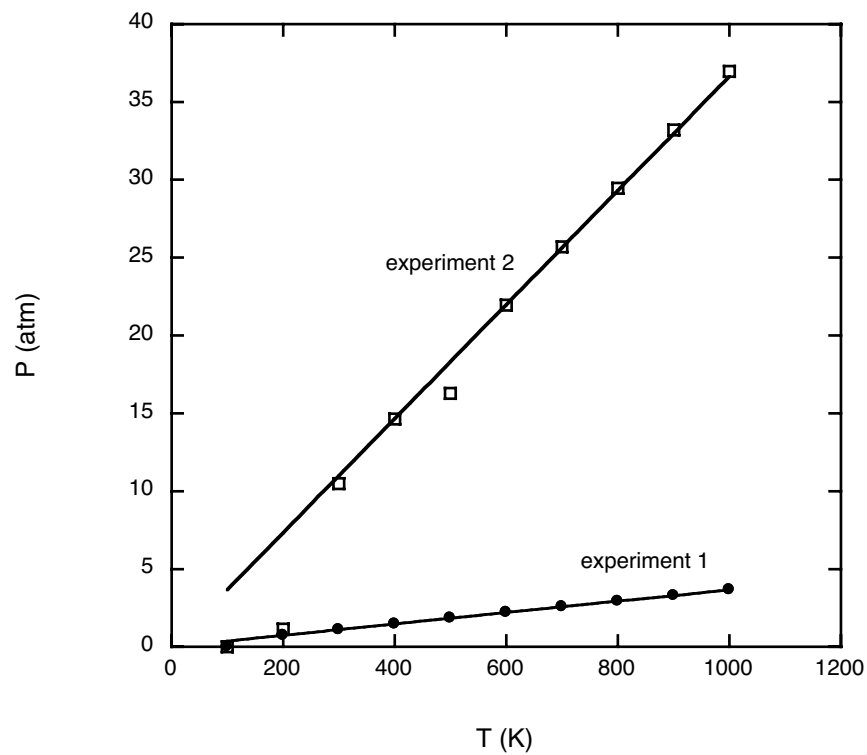


Figure 2.

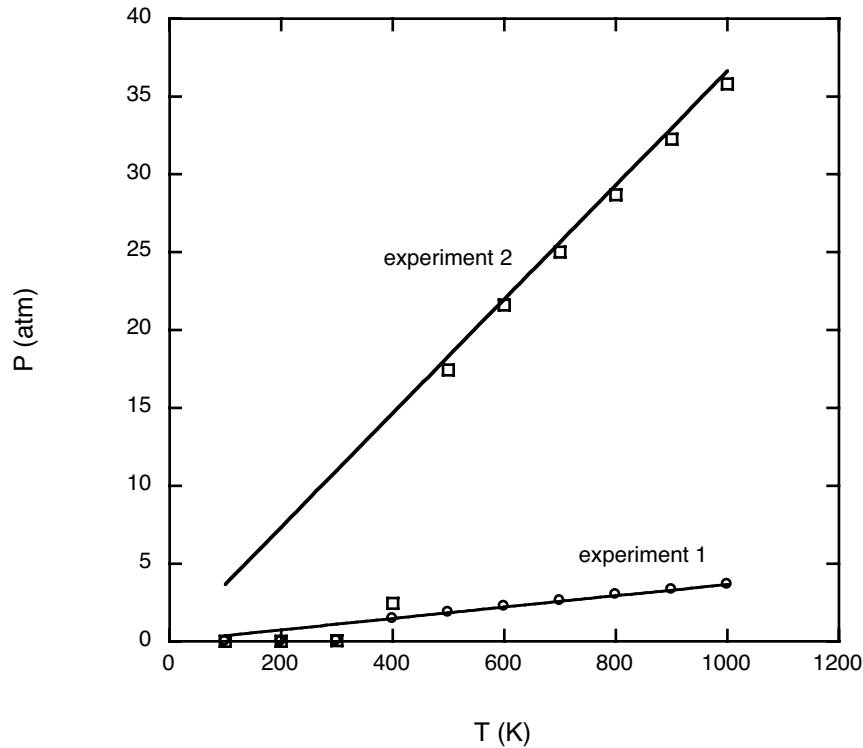


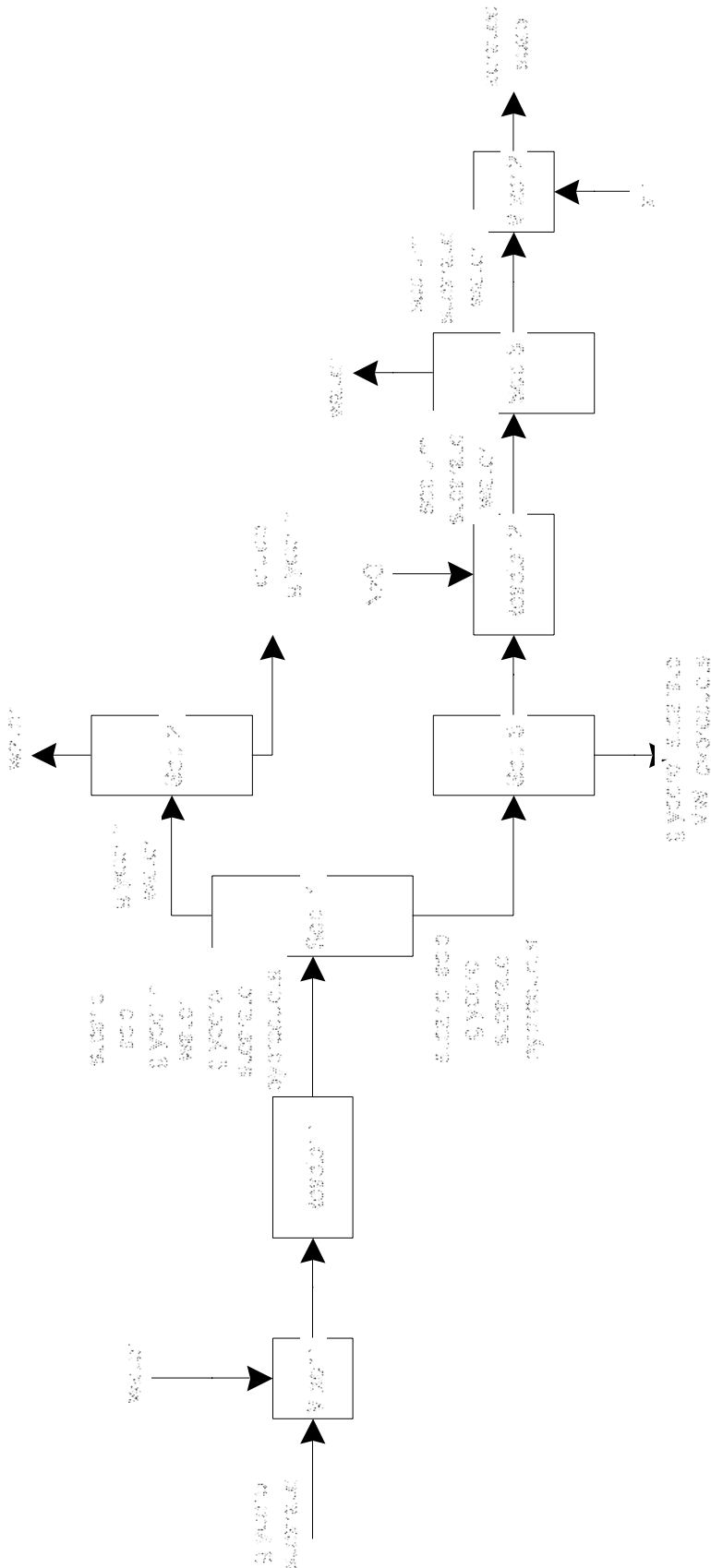
Figure 3.

P2.54

The block flow diagram is shown.

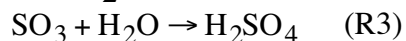
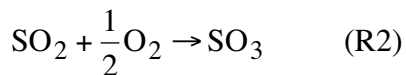
Besides the costs of the raw materials, several additional costs contribute to the prices of soap.

- (1) Energy is required to evaporate excess water, to freeze soap for cutting into bars, and to separate materials.
- (2) Some glycerol stearate is not converted to products and ends up in waste.
- (3) The selling price for crude glycerin is lower than that for pure glycerin, and the process makes only crude glycerin.
- (4) Packaging, marketing, and distribution costs for consumer products are relatively high.



P2.55

The three reactions involved are:

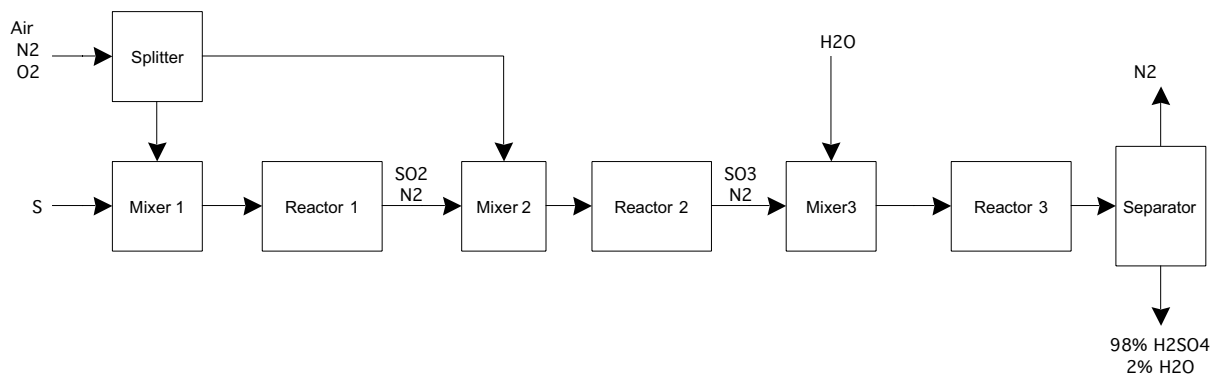


A generation consumption analysis gives:

	v_1	v_2	v_3	v_{net}
S	-1			-1
O ₂	-1	-0.5		-1.5
SO ₂	+1	-1		
SO ₃		+1	-1	
H ₂ O			-1	-1
H ₂ SO ₄			+1	+1

So the net reaction is $\text{S} + 1.5\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4$

The block flow diagram is:



To complete the raw material calculations, we can treat the entire process as a single system. We'll use the methods of Chapter 2, although we could do these calculations using methods from Chapter 1.

The basis is 200 tons/day concentrated sulfuric acid. If we convert to a molar flow rate we can take advantage of the known reaction stoichiometry:

$$SA_{out} = 0.98(200 \text{ tons/day})(1 \text{ tonmol}/98 \text{ tons}) = 2 \text{ tonmol/day}$$

$$\text{and } W_{out} = 0.02(200 \text{ tons/day})(1 \text{ tonmol}/18 \text{ tons}) = 0.22 \text{ tonmol/day}$$

where SA_{out} is the flow rate of H_2SO_4 leaving the system and W_{out} is the flow rate of water leaving the system. Since no H_2SO_4 enters the system, the material balance on sulfuric acid is simply

Generation = Output, or

$$SA_{gen} = SA_{out} = 2 \text{ tonmol/day}$$

From the overall reaction stoichiometry:

$$\frac{S_{cons}}{SA_{gen}} = \frac{1}{1}, \quad S_{cons} = 2 \text{ tonmol/day}$$
$$\frac{O_{cons}}{SA_{gen}} = \frac{1.5}{1}, \quad O_{cons} = 3 \text{ tonmol/day}$$
$$\frac{W_{cons}}{SA_{gen}} = \frac{1}{1}, \quad W_{cons} = 2 \text{ tonmol/day}$$

There is no sulfur that leaves the system, so the material balance on S is simply:

$$S_{cons} = S_{in} = 2 \text{ tonmol/day}$$

Converting back to tons/day, we find that the sulfur feed rate is
(2 tonmol/day)(32 tons/tonmol) = 64 tons/day

There is no oxygen that leaves the system, so the material balance on O₂ is simply:

$$O_{cons} = O_{in} = 3 \text{ tonmol/day}$$

From the stream composition specification, that air is 79% N₂ and 21% O₂, we can now calculate that

$$\frac{N_{in}}{O_{in}} = \frac{N_{in}}{3} = \frac{79}{21}, \text{ or } N_{in} = 11.29 \text{ tonmol/day}$$

The total air flow rate in is 3 + 11.29 or 14.29 tonmol/day, or 28,580 lbmol/day. To convert to standard cubic feet per day, we use the ideal gas law at $T = 492^\circ\text{R}$ and $P = 1 \text{ atm}$:

$$V = \frac{nRT}{P} = \frac{(28580 \text{ lbmol/day})(0.7302 \text{ ft}^3 \text{ atm/lbmol } ^\circ\text{R})(492^\circ\text{R})}{1 \text{ atm}(24 \text{ h/day})} = 428,000 \text{ ft}^3/\text{h}$$

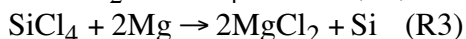
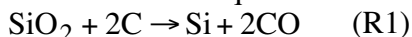
Finally, from the water material balance, which is In – Consumption = Out, we find

$$W_{in} = W_{cons} + W_{out} = 2.22 \text{ tonmol/day}$$

Converting to a mass flow rate, we find that the water feed rate is 40 tons/day.

P2.56

The balanced chemical equations are

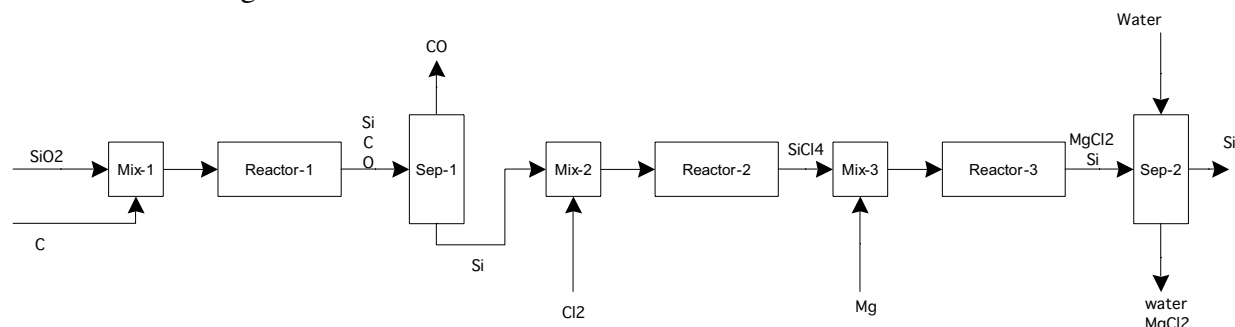


The generation-consumption analysis is:

	v_1	v_2	v_3	v_{net}	M_t	$v_i M_t$	Grams (SF=1/28)
SiO ₂	-1			-1	60	-60	-2.14
C	-2			-2	12	-24	-0.86
Si	+1	-1	+1	+1	28	+28	+1
CO	+2			+2	28	+56	+2
Cl ₂		-2		-2	71	-142	-5.07
SiCl ₄		+1	-1		170		
Mg			-2	-2	24	-48	-1.71
MgCl ₂			+2	+2	95	+190	+6.79

It takes 2.14 g SiO₂, 0.86 g C, 5.07 g Cl₂, and 1.71 g Mg to make 1 g of Si. The atom economy is abysmal: 0.102. 2 g CO and 6.79 g MgCl₂ are generated as byproducts.

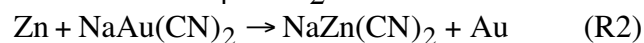
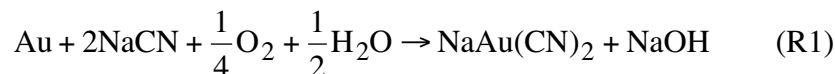
The block flow diagram is:



The three reactions help to purify Si. The first reaction produces an impure solid Si. Gaseous impurities are removed. The second step is reaction of Si with Cl₂. Because SiCl₄ is a gas, it can easily be purified from the solid impurities in sand. The reaction with Mg generates a more pure Si. Since MgCl₂ is highly soluble in water but Si is not, the byproduct of this reaction (plus any water-soluble impurities) are removed in Sep-2. Thus, gaseous, solid, and water-soluble impurities are removed in this sequence of steps.

P2.57

The balanced reactions are:



The generation-consumption analysis is:

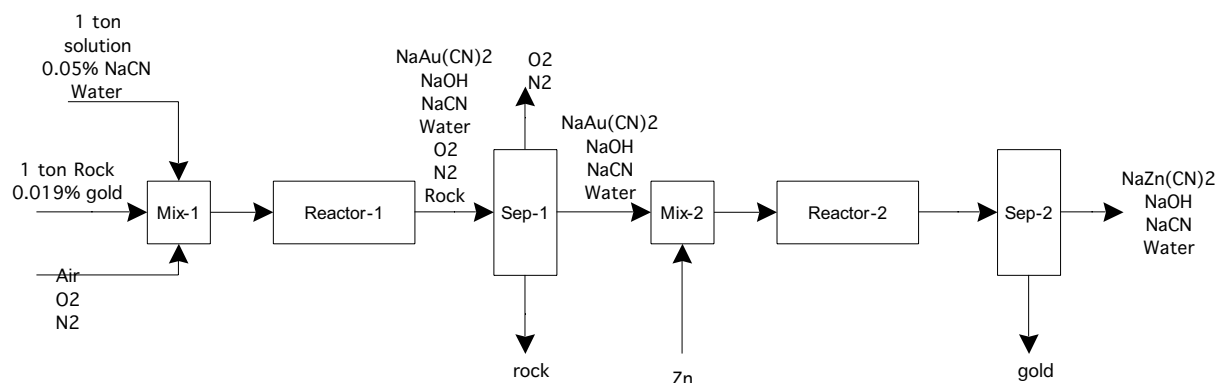
	v_1	v_2	v_{net}	M_t	$v_i M_t$	Oz. (SF=1/197)
Au	-1	+1		197	197*	1
NaCN	-2		-2	49	-98	-0.498
O ₂	-0.25		-0.25	32	-8	-0.041
H ₂ O	-0.5		-0.5	18	-9	-0.046

$\text{NaAu}(\text{CN})_2$	+1	-1		272		
NaOH	+1		+1	40	+40	+0.20
Zn		-1	-1	65	-65	-0.33
$\text{NaZn}(\text{CN})_2$		+1	+1	140	+140	+0.71

There is no net generation of gold! BUT, there is extraction of gold in reaction R2. per each ounce of gold extracted, we require 0.5 oz NaCN and 0.046 oz H_2O . These are the quantities that are actually consumed by reaction. There are 0.91 oz of waste byproducts generated per oz of gold.

The flow rate of the aqueous NaCN solution fed to Mixer 1 is set such that the slurry leaving the mixer is 50% solids. That means per ton of rock, there is one ton of solution. One ton of rock contains 0.00019 ton gold, or 6.08 oz gold. Thus, per oz of gold, we feed 0.165 tons rock, and 329 lb solution. At 0.05 wt% NaCN, this is 2.63 oz NaCN, of which only 0.5 oz are consumed by reaction. Thus, there is excess NaCN fed to the process, and therefore NaCN is in the liquid leaving the process. In other words, the liquid byproduct of gold extraction process contains a highly toxic material, and a significant quantity of water.

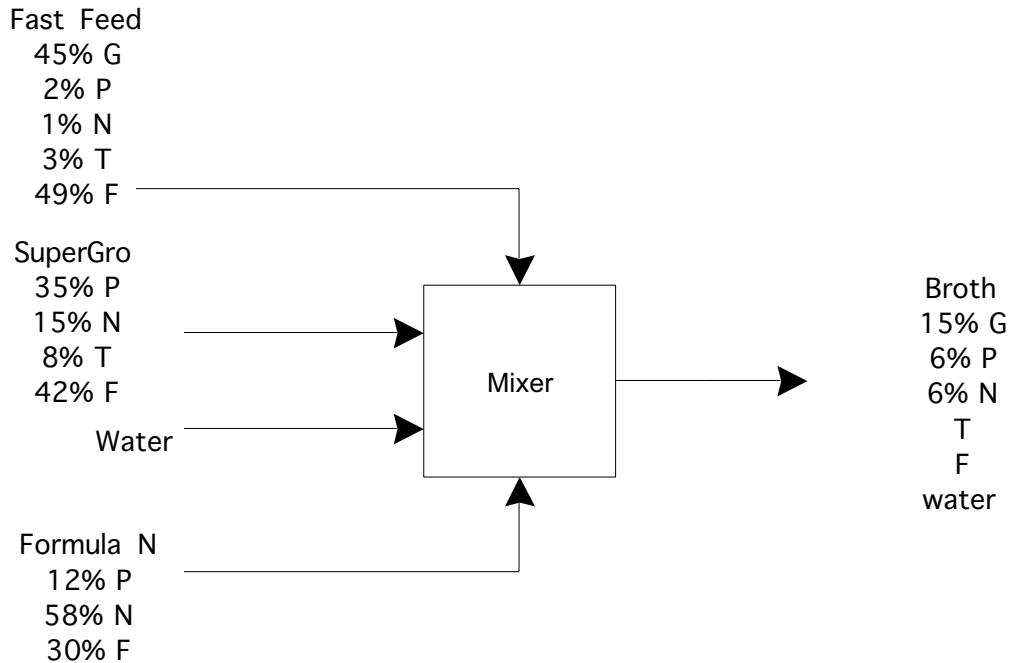
The block flow diagram is:



From 1 ton of rock, 6. oz. gold is extracted, or, 170 g. At a density of 19 g/cm^3 , the volume of gold nuggets obtained is about 9 cm^3 .

P2.58

The flow diagram, with the mixer as system, is



From a DOF analysis, we find that there are 19 stream variables, 12 specified stream compositions, 1 specified basis (1 kg broth), and 6 material balances. $DOF = 19 - (12+1+6) = 0$.

(a) Since we are given the compositions, but not the quantities, of each of the powders that go into the mix, it is easier to write the stream variables as the (known) mass fraction times the (unknown) total quantity of the powder. We will use “FF”, “SG”, and “FN” to indicate the quantities of the 3 powders. The material balance equations are:

Glucose: $0.45FF = 0.15(1) = 0.15 \text{ kg}$, so $FF = 0.333 \text{ kg}$

Phosphate: $0.02FF + 0.35SG + 0.12FN = 0.06(1) = 0.06 \text{ kg}$

Nitrate: $0.01FF + 0.15SG + 0.58FN = 0.06(1) = 0.06 \text{ kg}$

Substituting in the known value for FF and solving simultaneously, we find

$SG = 0.13 \text{ kg}$, and $FN = 0.064 \text{ kg}$

Each kg of broth should contain 0.333 kg Fast-Feed, 0.13 kg Super-Gro, and 0.064 kg Formula N, plus 0.473 kg water.

(b) The cost per kg of broth (excluding any operating costs such as labor or electricity) made from these ingredients is

$$(0.333 \times \$20) + (0.13 \times \$10) + (0.064 \times \$15) = \$8.92$$

Since the purchased broth costs \$15/kg, we can save \$6.08/kg (at most) by mixing our own. With a 20 kg batch, we save $(20 \times \$6.08)$ or \$121/batch. If the equipment costs \$2000, we need to make up $(\$2000/\$121/\text{batch})$, or 16 batches total, to pay for the equipment.

(c) The kg trace nutrients in the broth made according to the recipe in part (a) is

$$0.03(0.333) + 0.08(0.13) = 0.020 \text{ kg}$$

or, the wt% is 2.0. Requiring 3 wt% trace nutrients adds an additional constraint, (DOF = -1), and the problem is overspecified. We cannot make a broth that exactly matches all constraints.

To provide 3 wt% trace nutrients, we need to increase Super-Gro (it is cheaper than Fast Feed, and is the only powder with >3% trace nutrients).

$$0.03(0.333) + 0.08SG = 0.030 \text{ kg, so } SG = 0.25 \text{ kg.}$$

We cannot decrease the quantity of Fast-Feed, because that is our only source of glucose. We can, however, decrease the amount of Formula-N, which is attractive because it is more expensive than Super-Gro. From the balances on nitrates, we find that we can reduce Formula N to 0.033 kg. With this, the final mix would contain 15wt% glucose, 6 wt% nitrates, and 3 wt% trace nutrients, per the specifications, and would exceed phosphate requirement (9.8 wt%, vs 6 wt% required.) The quantity of water would decrease to 0.384 kg, and the price would increase to

$$(0.333 \times \$20) + (0.25 \times \$10) + (0.033 \times \$15) = \$9.66.$$

P2.59

The semi-batch unsteady-state process has an input but no output; accumulation (or depletion) and reaction occur within the system. The flow diagram is:



The material balances all take the form of In – Consumption = Accumulation. (We assume the density of the broth is that of water, 1 g/mL.)

$$(0.15 \text{ g glucose/g broth})(200 \text{ g broth/h}) - 35 \text{ g/h} = 30 - 35 = -5 \text{ g/h} = G_{acc}$$

$$(0.06 \text{ g phosphate/g broth})(200 \text{ g broth/h}) - 13 \text{ g/h} = -1 \text{ g/h} = P_{acc}$$

$$(0.06 \text{ g nitrate/g broth})(200 \text{ g broth/h}) - 12 \text{ g/h} = 0 \text{ g/h} = N_{acc}$$

Glucose and phosphate are both depleted over time, but not nitrates – the supply rate of nitrates from the fresh broth exactly matches the rate of consumption.

To determine whether glucose or phosphate runs out first, we calculate how long it will take for the quantity of nutrient in the system to decrease to zero. Initially, the fermentor contains $6000(0.15) = 900 \text{ g}$ glucose. Since $G_{acc} = -5 \text{ g/h}$, it will take 180 h to totally deplete the glucose. A similar calculation shows that it would take 360 h to deplete the phosphate, so glucose is depleted first. The initial mass of nitrates in the fermentor is $(6000)(0.06) = 360 \text{ g}$ nitrates, and does not change over the course of the fermentation, because $N_{acc} = 0$. The nitrate concentration decreases, however, because the total mass in the fermentor increases. At 180 h, the nitrate concentration is $360/(6000+200 \times 180) = 8.57 \text{ g/L}$ (at 1000 g = 1 L). The total quantity of phosphates at 180 h is

$$\left(\frac{0.06 \text{ g}}{\text{g broth}}\right)(6000 \text{ g broth}) + \left(\frac{0.06 \text{ g}}{\text{g broth}}\right)\left(\frac{200 \text{ g broth}}{\text{h}}\right)(180 \text{ h}) - \left(\frac{13 \text{ g}}{\text{h}}\right)(180 \text{ h}) = 180 \text{ g phosphate}$$

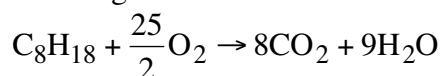
The total quantity of broth in the system at 180 h is $6000 + 200(180) = 42,000 \text{ g}$. Therefore, the concentration of phosphate in the fermentor at the end of 180 h is 4.3 g/L.

P2.60

If one-quarter of all CO_2 emissions are attributed to US, then the pounds of CO_2 produced per person in US is

$$\frac{\frac{0.25 \times 5.6 \times 10^9 \text{ metric tons}}{\text{yr}} \times \frac{2200 \text{ lb}}{\text{metric ton}}}{300 \times 10^6 \text{ persons}} = 10,266 \text{ lb CO}_2/\text{person}$$

Combustion of gasoline is modeled as



From this we calculate CO_2 emissions per g of gasoline:

$$\frac{8 \text{ gmol CO}_2}{\text{gmol C}_8\text{H}_{18}} \times \frac{44 \text{ g/gmol}}{114 \text{ g/gmol}} = \frac{3.1 \text{ g CO}_2}{\text{g C}_8\text{H}_{18}}$$

If average person drives 20 miles/day (7300 mi/year) and gets 27.5 miles/gallon, with gasoline at a specific gravity of 0.7, then each person is responsible for

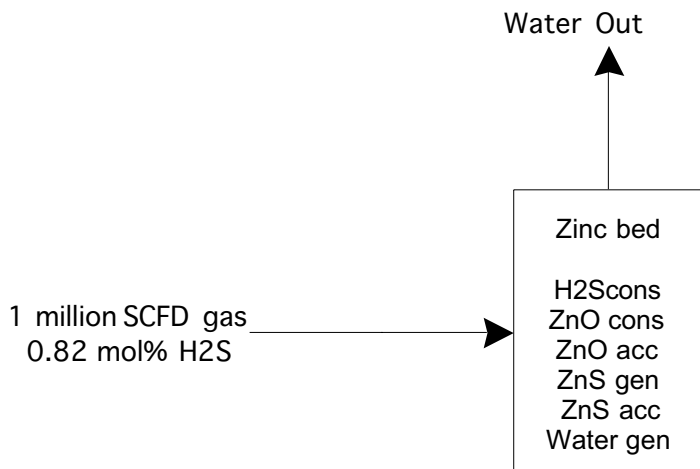
$$\frac{7300 \text{ mi}}{\text{y}} \times \frac{1 \text{ gal}}{27.5 \text{ mi}} \times \frac{1000 \text{ mL}}{0.26417 \text{ gal}} \times \frac{0.7 \text{ g C}_8\text{H}_{18}}{\text{mL}} \times \frac{3.1 \text{ g CO}_2}{\text{g C}_8\text{H}_{18}} \times \frac{\text{lb}}{454 \text{ g}} = 4800 \text{ lb CO}_2$$

(Estimates for average fleet mileage, miles driven per vehicle, and miles driven per person are somewhat variable depending on source; numbers seem to hover around 25 miles/gallon, about 15,000 miles/vehicle, and about 7000-8000 miles per person.)

This is just under half of the lb CO_2 /person calculated above. The estimate from the environmental group seems quite reasonable, because we have accounted for CO_2 generation only from automobiles, and not from electricity, home heating, public transportation, manufacturing, etc.

P2.61

This semi-batch process is sketched as:



First calculate mol/day H_2S , assuming the natural gas behaves as an ideal gas at STP:

$$\frac{10^6 \text{ ft}^3}{\text{day}} \times \frac{1 \text{ atm}}{(0.7302 \text{ ft}^3 \text{ atm/lbmol } ^\circ R)(492^\circ R)} \times \frac{0.0082 \text{ lbmol } H_2S}{\text{lbmol}} = 22.8 \text{ lbmol } H_2S/\text{day}$$

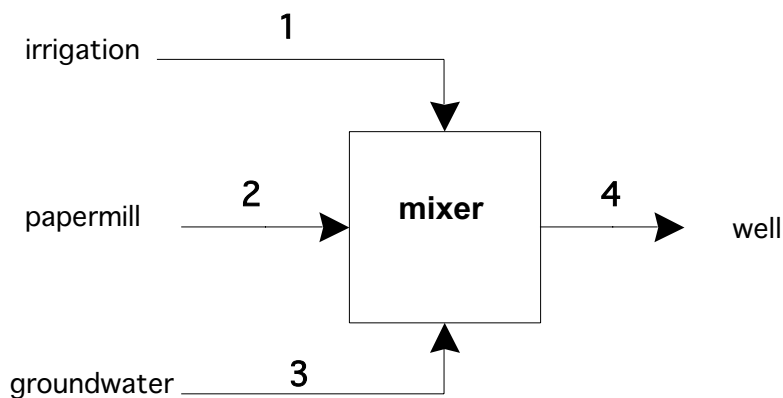
From the reaction stoichiometry, we need to load 22.8 lbmol ZnO to react with this much H_2S in one day. Since the molar mass of ZnO is 81 lb/lbmol, we need $22.8 \times 81 = 1850$ lb ZnO. The density of ZnO solid is $\sim 1.11 \text{ g/cm}^3$, therefore the volume of vessel required is approximately

$$1850 \text{ lb} \times \frac{454 \text{ g}}{\text{lb}} \times \frac{\text{cm}^3}{1.11 \text{ g}} \times \frac{L}{1000 \text{ cm}^3} = 755 \text{ L}$$

From reaction stoichiometry, $W_{gen} = H_2S_{cons} = 22.8 \text{ lbmol/day}$, and from the material balance on water, since no accumulation in the vessel is allowed, then $W_{out} = W_{gen} = 22.8 \text{ lbmol/day}$, or 187 kg/day water must be removed.

P2.62

Irrigation water, papermill wastewater, and/or local ground water could be feeding into municipal well water:



Each stream contains 6 components, and the composition of all streams are specified. Assuming a steady state operation with no reaction, we have 24 stream variables, with 6 material balance equations and 20 independent specifications on composition. If we choose as a basis 1 million grams of well water, then $\text{DOF} = 24 - (20 + 6 + 1) = -3$, and the system is overspecified.

When a problem is overspecified, data may be redundant, or inconsistent. An additional complication of this problem is that the data points have some error associated with them.

Our approach will be to first postulate that the municipal well water is identical to local groundwater. In other words, is it possible that $F_1 = F_2 = 0$, where F_1 and F_2 are the quantities of water from irrigation and the papermill sources that end up in the well? As we scan the data in the table, we see that TDS, Ca, Mg, SO_4 , and NO_3 in the groundwater are all within $\pm 15\%$ of the values in the well water. Thus, these data are all consistent with (but do not prove) our hypothesis that $F_1 = F_2 = 0$.

The only number that is out of line with this hypothesis is Cl. The chlorine level in the local ground water is lower than that in the well. It is not possible for the irrigation water to be the source of the Cl contamination, but the papermill could be.

We now hypothesize that the papermill wastewater and the local groundwater both contribute to the well water, but not the irrigation water. With this hypothesis, the balance around the system with Cl as the component is:

$$18F_2 + 3.5F_3 = 8.0$$

and the total mass balance equation is

$$F_2 + F_3 = 1$$

(where the basis is chosen as 1 million grams of well water, and the units are in million grams.

The solution to these equations is:

$$F_2 = 0.16, F_3 = 0.84$$

In other words, if 16% of the water supply to the well was from the papermill, this would account for the chlorine contamination. Would this be consistent with the other data? If we assume 0% water from irrigation, 16% from papermill, and 84% from local groundwater, and checked by material balances to see if this would give us well water consistent with the experiment, we'd find:

Hypothesis: well contaminated with 16% papermill waste	TDS	Ca	Mg	SO_4	Cl	NO_3
Calculated from material balance and hypothesis	238	24	15	13	8	13
Experimental data	245	22	15	13	8	15

The hypothesis is consistent with the data.

A similar analysis considering the irrigation water as the only source of contamination does not result in calculated values that agree with experimental data. For example, we could use a

material balance on the SO_4 data to support the contention that the municipal well is contaminated with irrigation water:

$$2F_1 + 14F_3 = 13$$

$$F_1 + F_3 = 1$$

$$F_1 = 0.08, F_2 = 0.92$$

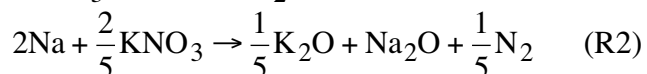
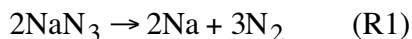
Hypothesis: well contaminated with 8% irrigation water	TDS	Ca	Mg	SO_4	Cl	NO_3
Calculated from material balance and hypothesis	232	27	18	13	3	11
Experimental data	245	22	15	13	8	15

The Cl and NO_3 data are not consistent with this hypothesis.

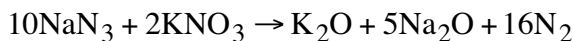
My letter would state that the data are inconsistent with contamination from irrigation waters, that one data point suggests the possibility of minor contamination from the papermill plant, and that 5 out of 6 indicators show that the well water is the same as the local groundwater.

P2.63

The balanced chemical reactions are:



giving an overall reaction (multiplying through by 5 to clear fractions):



Assuming the ideal gas law, 1 atm, and 70°F , we calculate

$$\frac{(6 \text{ ft}^3)(1 \text{ atm})}{(0.7302 \text{ ft}^3 \text{ atm/lbmol } ^\circ\text{R})(530^\circ\text{R})} = 0.0155 \text{ lbmol N}_2$$

From the reaction stoichiometry, 10 lbmol sodium azide are consumed for every 16 lbmol N_2 generated, or

$$\text{NaN}_3_{\text{cons}} = \frac{10}{16}(0.0155) = 0.0097 \text{ lbmol NaN}_3$$

At 65 lb/lbmol, this translates to 0.63 lb NaN_3 . The density of NaN_3 is 1.848 g/cm^3 (obtained from Knovel online engineering database). The volume of solid that must be packed into the cylinder (ignoring any void space) is

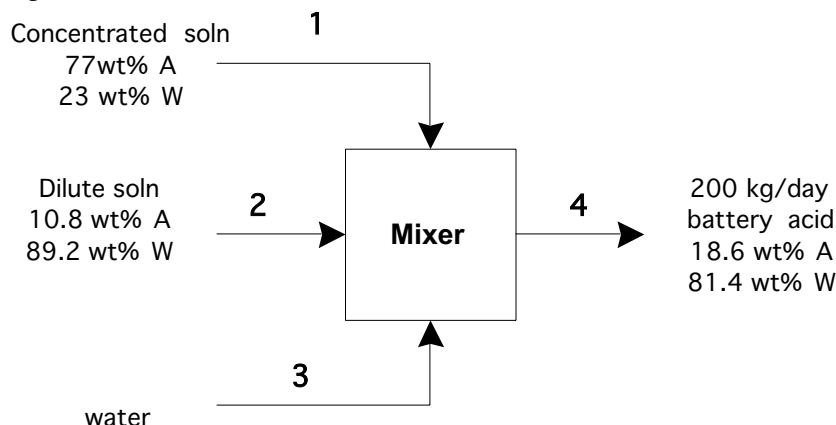
$$0.63 \text{ lb NaN}_3 \times \frac{454 \text{ g}}{\text{lb}} \times \frac{\text{cm}^3}{1.848 \text{ g}} \times \frac{\text{ft}^3}{28316 \text{ cm}^3} = 0.0055 \text{ ft}^3$$

The volume expands by a factor of 1100!

From the reaction stoichiometry and molar mass, we calculate that 0.091 lb K_2O and 0.30 lb Na_2O must be mixed with the NaN_3 . The total mass of the active ingredients is therefore $(0.63 + 0.09 + 0.30) = 1.02$ lb. If the solid is to be 50 wt% SiO_2 , then 1.02 lb SiO_2 must be added to the mix.

P2.64

The flow diagram is:



Components are sulfuric acid (A) and water (W).

DOF analysis:

	Variables	Constraints
Stream	7	
System	0	
Specified flows		1
Specified compositions		3 (% acid in streams 1, 2 and 4)
Specified system performance		0
Material balance		2

$$DOF = 7 - 6 = 1$$

The problem is underspecified. This is an opportunity for optimization – we want the “best” combination of flows into the mixer, with the best being defined as “minimum cost”.

Units are all in mass/day or wt%, no conversions needed.

With the compositions known and the flow rates unknown, it is easiest to work with variables defined as mass fractions and total mass flows, rather than mass flows of individual components.

Material balances:

$$\text{Acid: } 0.77F_1 + 0.108F_2 = 0.186(200) = 37.2 \text{ kg/day}$$

$$\text{Water: } 0.23F_1 + 0.892F_2 + F_3 = 0.814(200) = 162.8 \text{ kg/day}$$

There are 2 equations in 3 unknowns. We can add another equation (in another unknown) to describe the cost of the raw materials:

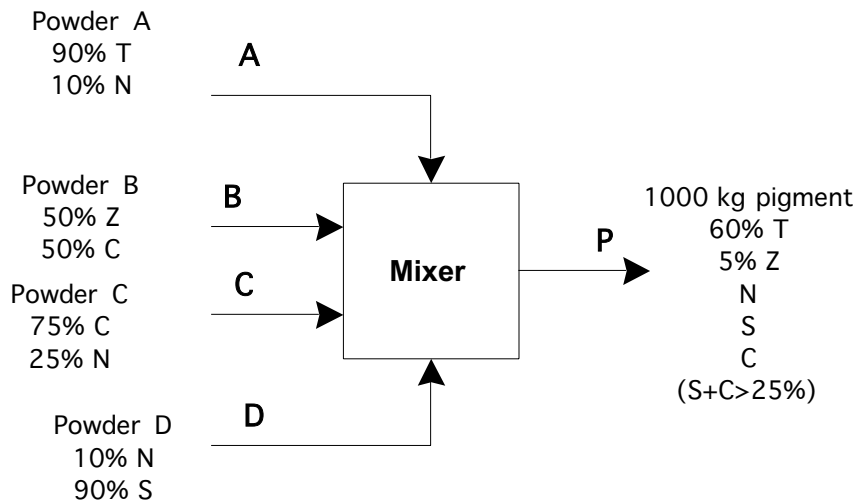
$$0.10F_1 + 0.02F_2 = \text{Cost}(\$/\text{day})$$

There are a couple of ways to solve this problem.

Method 1: Brute force: We set one of the unknowns (e.g., F_1) at a value between 0 and 200 kg/day, then calculate the flows of the remaining streams and the total cost. By varying F_1 , we can then find the cost as a function of F_1 , and pick the value of F_1 that minimizes the cost. These calculations are easily carried out in a spreadsheet. From these calculations, we first note that there is only a narrow range of possible values of F_1 , where F_2 and F_3 are also between 0-200 kg/day, from $F_1 = 23.6$ to $F_1 = 48.3$ kg/day. If we plot the cost vs F_1 , we note that the cost decreases linearly with increasing F_1 , so the minimum cost (within the other constraints) is achieved with $F_1 = 48.3$ kg/day (and $F_2 = 0$, $F_3 = 151.7$ kg/day).

Method 2: Thinking: we note that per kg of sulfuric acid, we are paying $(\$0.10/(0.77))$ or $\$0.13/\text{kg}$ sulfuric acid in the concentrated form, and $(\$0.02/0.108)$ or $\$0.185/\text{kg}$ sulfuric acid in the dilute form. Obviously, we want to use as much of the “cheaper” sulfuric acid as possible, so we want to use as much of the concentrated solution as possible. We want to set F_2 as low as possible – indeed, we can set $F_2 = 0$ and satisfy all constraints. We get the same answer as in Method 1: the minimum cost is obtained with $F_1 = 48.3$ kg/day, $F_2 = 0$, $F_3 = 151.7$ kg/day, and the cost is $\$4.83/\text{day}$.

P2.65



DOF analysis:

	Variables	Constraints
Stream	13	
System	0	

Specified flows		1
Specified compositions		4 (1 each for powders A, B, C and D)
Specified system performance		0
Material balance		5

$$\text{DOF} = 13 - 10 = 3.$$

We have 3 additional “soft” constraints – that the pigment must be “at least” 60% TiO_2 , at least 5% ZnO , and at least 25% filler. Since these are minimum values but not absolute constraints, our solution is not completely constrained, and there are multiple recipes that would meet the requirements.

The material balances are (using F_A , F_B , F_C and F_D to indicate total mass quantities of powders A, B, C, and D):

$$\text{TiO}_2: 0.90F_A \geq 0.60(1000) = 600 \text{ kg}, F_A \geq 667 \text{ kg}$$

$$\text{ZnO}: 0.5F_B \geq 0.05(1000) = 50 \text{ kg}, F_B \geq 100 \text{ kg}$$

Also, minimum filler content is 25%. Filler can be SiO_2 , CaCO_3 or NaCl , so we combine balances:

$$\text{Filler}: 0.10F_A + 0.50F_B + F_C + F_D \geq 0.25(1000) = 250 \text{ kg}$$

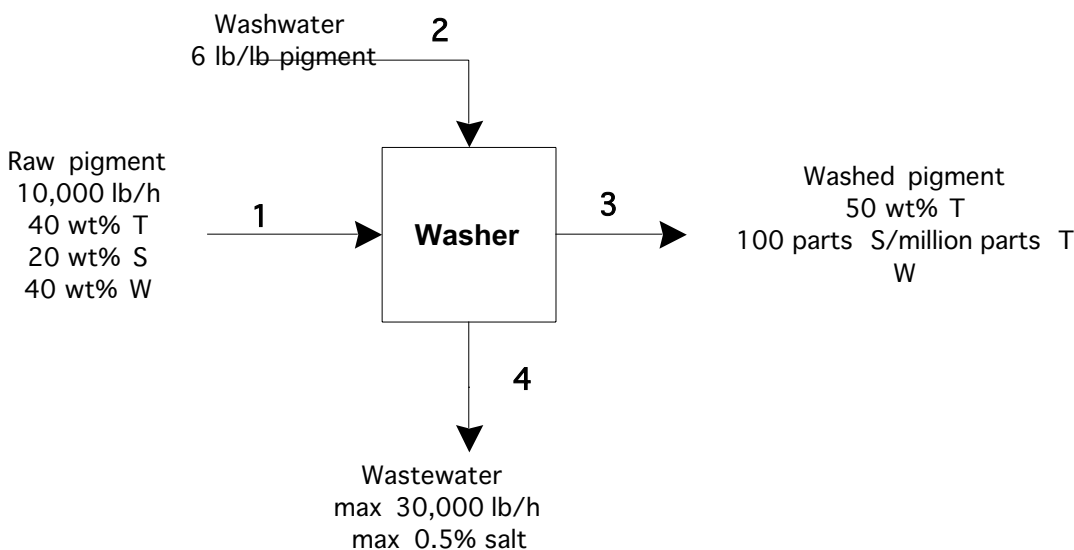
Finally, we know that the total quantity of pigment powder must be 1000 kg, or

$$F_A + F_B + F_C + F_D = 1000 \text{ kg}$$

The minimum NaCl content is obtained by maximizing Powder B, while the maximum NaCl content is obtained by maximizing Powder C. Here are some recipes that meet all our constraints (other answers are possible):

	Recipe 1	Recipe 2	Recipe 3	Recipe 4
Powder A (kg)	667	667	667	667
Powder B (kg)	100	100	300	100
Powder C (kg)	233	0	0	66.7
Powder D (kg)	0	233	33	167
% TiO_2	60	60	60	60
% ZnO	5	5	15	5
% CaCO_3	22.5	5	15	10
% NaCl	12.5	9	7	10
% SiO_2	0	21	3	15
comments	Highest NaCl		Lowest NaCl	Exactly 25% $\text{SiO}_2 + \text{CaCO}_3$

P2.66



There are 3 components: T (titanium dioxide), S (salt) and W (water). All units are in lb/h or wt%, so no conversions needed.

DOF analysis:

	Variables	Constraints
Stream	9	
System	0	
Specified flows		2 (raw pigment, wastewater)
Specified compositions		7 (2 for raw pigment, 1 for wastewater, 2 for washed pigment, 1 for ratio of washwater to raw pigment)
Specified system performance		0
Material balance		3

$$\text{DOF} = 9 - 12 = -3.$$

The problem is overspecified, but this conclusion does depend on what we count as constraints. Several of the constraints are “soft” – that is, they are maximums or optimums, not absolute requirements.

One way to attack an overspecified problem such as this is to ignore the soft constraints (at first), complete the process flow calculations in the absence of these constraints, and then check to insure that you have not violated any of the soft constraints.

Here, we will (for now) ignore the constraints imposed on wastewater quantity and quality. We'll keep the constraint on salt concentration in the washed pigment, and on the optimum washwater feed rate. The material balance equations become:

$$\text{TiO}_2: T_1 = 0.4(10,000) = 4000 \text{ lb/h} = T_3$$

$$\text{Salt: } S_1 = 0.2(10,000) = 2000 \text{ lb/h} = S_3 + S_4$$

$$\text{Water: } W_1 + W_2 = 0.4(10,000) + 6(10,000) = 64,000 \text{ lb/h} = W_3 + W_4$$

From stream composition specifications on the washed pigment:

$$\frac{S_3}{T_3} = \frac{100}{1,000,000}, S_3 = \frac{100}{1,000,000}(4000) = 0.4 \text{ lb/h}$$

$$\frac{T_3}{T_3 + S_3 + W_3} = 0.5 = \frac{4000}{4000 + 0.4 + W_3}, W_3 = 3999.6 \text{ lb/h (close enough)}$$

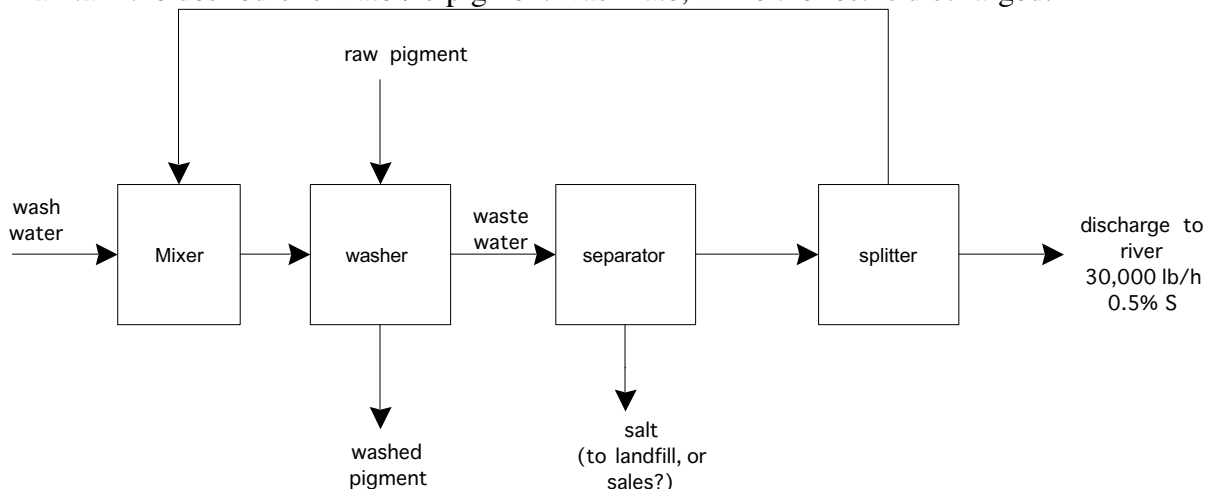
Returning to the material balances:

$$S_4 = 2000 - 0.4 = 1999.6 \text{ lb/h}$$

$$W_4 = 64000 - 3999.6 = 60,000 \text{ lb/h}$$

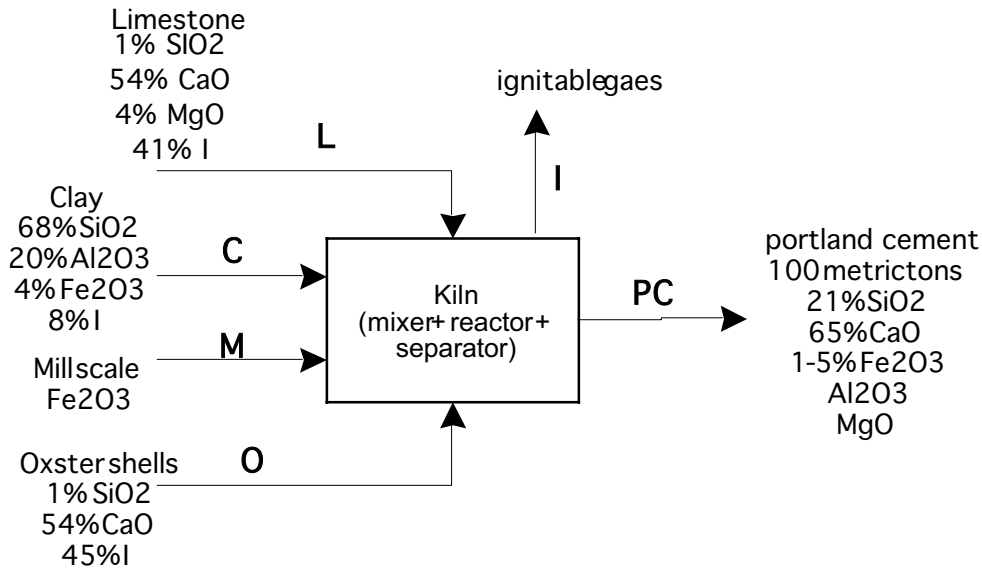
The salt concentration in the wastewater is 3.2 wt%. Neither the total wastewater discharge rate of 30,000 lb/h, or the maximum wastewater salt concentration of 0.5% is met with this design.

The only solution is to modify the design. A separation unit is required, that removes most of the salt from the wastewater and recycles part (or all) of the water. A reverse osmosis unit might work. One idea is sketched below. Excess salt is removed in the separator, to reduce the salt content of the water to 0.5 wt%. Then, part of the water is recycled and mixed with fresh water, to maintain the desired 6 lb water/lb pigment wash rate, while the rest is discharged.



P2.67

We'll combine mixing and heating to drive off gases in a single flow diagram:



The streams are labeled as L, C, M and O for limestone, clay, mill scale and oyster shells, respectively. There are 6 components. All units are in tons or wt%, so no conversions are needed.

DOF analysis:

	Variables	Constraints
Stream	18	
System	0	
Specified flows		1
Specified compositions		10
Specified system performance		0
Material balance		6

DOF = 18 – 17 = 1. We have an underspecified problem, but we did not count the constraint that Fe_2O_3 must be between 1-5%. Within these limits, our objective is to minimize the total cost.

It is most convenient to work in mass fractions and total quantities of each stream, because the compositions are known but the quantities are unknown. Combining stream composition specifications with material balance equations, we find:

$$\text{SiO}_2: 0.01F_L + 0.68F_C + 0.01F_O = 0.21(100) = 21 \text{ tons}$$

$$\text{CaO}: 0.54F_L + 0.54F_O = 0.65(100) = 65 \text{ tons}$$

Although there are only 2 equations and 3 unknowns, we can partially solve for some useful information:

$$F_L + F_O = 120.4 \text{ tons}$$

$$F_C = 29.1 \text{ tons}$$

We have an additional relationship from the Fe_2O_3 balance:

$$1 \leq 0.04F_L + F_M \leq 5 \text{ tons}$$

and, from the total mass balance:

$$0.59F_L + 0.92F_C + F_M + 0.55F_O = 100 \text{ tons}$$

Finally, we want to find the quantities that provide the minimum cost,

$$\text{Cost}(\$) = 88F_L + 35F_C + 60F_O$$

Although the limestone is more expensive than the oyster shells, it also has more MgO in it, which reduces the amount of (free) mill scale we might be able to blend in. Thus, the cheapest combination is not immediately obvious. We set up a spreadsheet to analyze the problem.

Iron content	F_C	F_M (from Fe_2O_3 balance)	F_L (from total balance)	F_O (from CaO balance)	cost (\$)	
1	29.1	-0.164	179.3	-58.9	--	--
2	29.1	0.836	154.3	-33.9	--	--
3	29.1	1.836	129.3	-8.9	--	--
4	29.1	2.836	104.3	16.1	11163	
5	29.1	3.836	79.3	41.1	10463	

Values below 3% iron are not physically possible. The cheapest combination gives 5% iron, with 29.1 tons clay, 3.8 tons mill scale, 79.3 tons limestone, and 41.1 tons oyster shells.

P2.68

Let's use 10,000 cups as a basis for comparison. We'll start with the Hocking report. The total mass of raw materials required for 10,000 paper cups is $38.9 \text{ g} \times 10,000$ or 389 kg. With the 10.1 g/cup finished weight, the final mass of 10,000 paper cups is 101 kg, or about 0.1 metric tons. From the emissions data, we sum to find that the water emissions are 7.1 – 13.7 kg and air emissions are 1.77 – 2.77 kg per 10,000 cups (0.1 metric tons). Therefore the solid wastes must be $389 - 101 - (9 \text{ to } 16) \text{ kg}$, or about 275 kg.

The Franklin report states that 10,000 paper cups weigh about 104 kg (LDPE coated) to 130 kg (wax coated). Water emissions are 1.3 to 2.05 kg, and air emissions are 8.2 to 9.9 kg. Solid wastes total to 124 to 153 kg, with about 25-32 as industrial and 99-121 kg postconsumer solid waste. These numbers are summarized in table form:

	Hocking	Franklin
Cups	101 kg	104 to 130 kg
Water emissions	7 – 14 kg	1 – 3 kg
Air emissions	2 – 3 kg	8 – 10 kg
Solid wastes	275 kg	124 – 153 kg

Franklin's report indicates only about 1/2 the solid waste of Hocking. The difference is attributable to the different accounting methods chosen: Hocking included in his estimates the solid wastes generated in converting wood chips to bleached pulp, whereas Franklin did not.

For 10,000 polystyrene cups, we convert the data to a comparable bases and find:

	Hocking	Franklin
Cups	15 kg	44 kg
Water emissions	0.3 kg	1 kg
Air emissions	0.7 – 0.9 kg	5 - 6 kg
Solid wastes	16 - 17 kg	63 kg

Per cup, Franklin estimates much higher emissions, but per kg of cup, the numbers from the two different reports are quite comparable. (The difference is an indication that polystyrene cups can be made in different sizes and thicknesses.)

These reports show that solid wastes and water emissions are much lower per cup (but not per kg) for polystyrene vs paper. (Is the “per cup” or “per kg” basis more appropriate?) However, there are other arguments for paper vs polystyrene that derive primarily from the nature of the raw materials – renewable (wood) vs non-renewable (fossil fuel).

P 2.69

DOF analysis:

	Variables	Explanation	Constraints	Explanation
Stream	25	3 in stream 1 3 in stream 2 5 in stream 3 3 in stream 4 2 in stream 5 1 in stream 6 1 in stream 7 1 in stream 8 2 in stream 9 2 in stream 10 2 in stream 11		
System	2	2 chemical reactions; steady-state, so no accumulation		
Specified flows			1	Cumene production rate
Specified compositions			4	95/5 P:I in stream 1 1.2:1 P:B in stream 1 10% P in stream 2 1 splitter restriction
Specified system performance			2	80% conversion of P 72% conversion of B

Material balance			20	3 for mixer 5 for reactor 5 for V/L separator 2 for splitter 3 for dist col 1 2 for dist col 2
total	27		27	

$$\text{DOF} = 27 - 27 = 0$$

The set of equations includes 25 stream variables. There are 2 reactions, each of which involve 3 compounds, so we will write 4 equations relating 6 generation and consumption variables and their stoichiometric coefficients.

Here are the equations:

Basis:	$C_6 = 25$
Reaction stoichiometry:	$\frac{C_{gen1}}{B_{cons1}} = \frac{1}{1}, \frac{P_{cons1}}{B_{cons1}} = \frac{1}{1}$ $\frac{D_{gen2}}{C_{cons2}} = \frac{1}{1}, \frac{P_{cons2}}{C_{cons2}} = \frac{1}{1}$
Stream composition:	$\frac{P_1}{I_1} = \frac{95}{5}$ $\frac{P_1}{B_1} = \frac{1.2}{1}$ $\frac{I_2}{I_2 + P_2 + B_2} = 0.1$
Splitter:	$\frac{P_9}{I_9} = \frac{P_{10}}{I_{10}}$
System performance:	$P_{cons1} + P_{cons2} = 0.8P_2$ $B_{cons1} = 0.72B_2$
Material balances:	
mixer	$P_2 = P_1 + P_{10}$ $I_2 = I_1 + I_{10}$ $B_2 = B_1 + B_8$
reactor	$P_3 = P_2 - P_{cons1} - P_{cons2}$ $I_3 = I_2$ $B_3 = B_2 - B_{cons1}$ $C_3 = C_{gen1} - C_{cons2}$ $D_3 = D_{gen2}$
V/L separator:	$P_9 = P_3$ $I_9 = I_3$ $B_4 = B_3$

	$C_4 = C_3$
	$D_4 = D_3$
splitter	$P_{10} + P_{11} = P_9$
	$I_{10} + I_{11} = I_9$
dist col 1	$B_8 = B_4$
	$C_5 = C_4$
	$D_5 = D_4$
dist col 2	$C_6 = C_5$
	$D_7 = D_5$

P2.70

DOF analysis:

	Variables	Explanation	Constraints	Explanation
Stream	32	5 in stream 1 3 in stream 2 3 in stream 3 1 in stream 4 3 in stream 5 2 in stream 6 3 in stream 7 3 in stream 8 2 in stream 9 3 in stream 10 2 in stream 11 2 in stream 12		
System	0	no chemical reactions; steady-state, so no accumulation		
Specified flows			4	Streams 1, 4, 6 and 11
Specified compositions			8	4 in stream 1 1 in stream 6 1 in stream 8 1 in stream 9 1 in stream 12
Specified system performance			0	
Material balance			20	5 for 1 st separator 3 for 2 nd separator 3 for mixer 3 for 3 rd separator 3 for 4 th separator 3 for 5 th separator

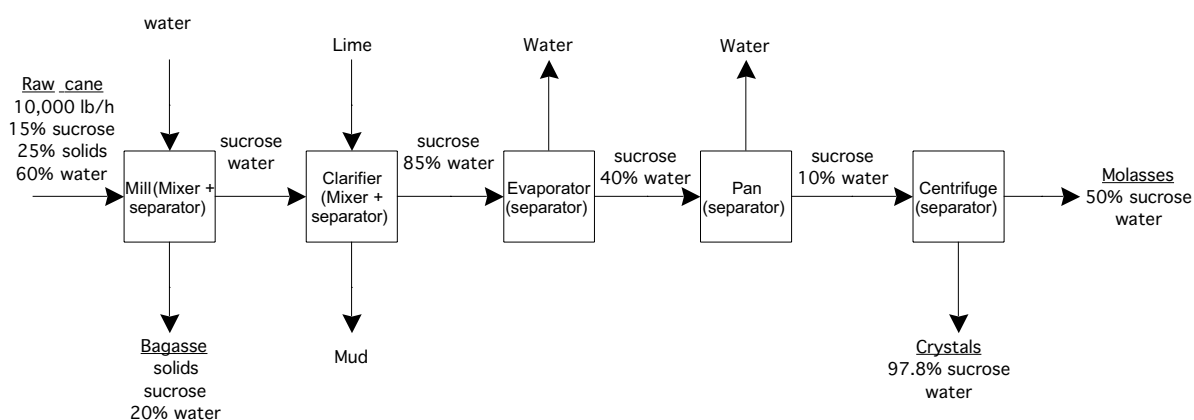
total	32		32	
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$$\text{DOF} = 32 - 32 = 0$$

Calculations proceed by hand or by equation solver. Results are summarized in table form. All flows are given in units of kgmol/h.

	1	2	3	4	5	6	7	8	9	10	11	12
methane	100	100	---	---	100	99.5	0.5	0.5	---	---	---	---
ethane	300	300	---	---	300	0.5	299.5	298	1.42			
propane	150	106.94	43.06	40	146.94	---	146.94	6.1	140.65	3.06	3.06	
butane	300	---	300	---	---	---	---	---	---	300	296.94	3.06
pentane	150	---	150	---	---	---	---	---	---	150		150
total	1000	506.94	493	40	546.9	100	446.9	304.6	142	453.1	300	153.06

P2.71



We solve this problem by combining material balance, stream composition specifications, and system performance specifications. We will work from one unit to the next.

Mill: 93% of sucrose in raw cane is recovered in the mill, therefore the flow rate of sucrose to the clarifier is $0.93 \times 0.15 \times 10000 = 1395$ lb/h. The bagasse contains all the solids (2500 lb/h), the remaining sucrose (105 lb/h) and water. Since the bagasse is 20 wt% water, the water in the bagasse must be 650 lb/h.

Clarifier: Assuming no loss of sucrose or water, the sucrose flow out of the clarifier equals the flow in, or 1395 lb/h. The solution leaving the clarifier is 85wt% water; we combine these numbers to calculate that the water flow rate in the stream leaving the clarifier is 7905 lb/h. Since 6000 lb/h water entered in the raw cane, and 650 lb/h water left in the bagasse, there must have been $(7905 + 650 - 6000)$ or **2555 lb/h water added to the mill.**

Evaporator: The sucrose content increases from 15% to 60% in the evaporator. The flow rate of sucrose in the solution leaving the evaporator is 1395 lb/h, so the water flow rate must be 930 lb/h. By material balance, the **water removed by evaporation is $7905 - 930 = 6975$ lb/h.**

Pan: The stream leaving the pan is a mix of crystals and solution and contains only 10% water. The sucrose flow rate is still 1395 lb/h, so we calculate that the stream leaving the pan must be 155 lb/h water and another 775 lb/h water is removed by evaporation in this step.

Centrifuge: The compositions of the molasses and the crystals are specified. We write 2 material balance equations in 2 unknowns: the flow rate of molasses F_m and the flow rate of crystals F_c :

$$1395 = 0.5F_m + 0.978F_c$$

$$155 = 0.5F_m + 0.022F_c$$

Solving by substitution, we find that the molasses flow rate is 253 lb/h and the crystals flow rate is 1297 lb/h.