

## Chapter 2

### 2.1 The Mole                      Moles, Density and Concentration

In the SI system a mole is composed of  $6.022 \times 10^{23}$  molecules (**Avogadro's number**). To convert the number of moles to mass and the mass to moles, we make use of the **molecular weight**

– the mass per mole:

$$\text{Molecular Weight (MW)} = \frac{\text{Mass}}{\text{Mole}}$$

Thus, the calculations you carry out are

$$\text{the g mol} = \frac{\text{mass in g}}{\text{molecular weight}}$$

$$\text{the lb mol} = \frac{\text{mass in lb}}{\text{molecular weight}}$$

and

$$\text{Mass in g} = (\text{MW}) (\text{g mol})$$

$$\text{Mass in lb} = (\text{MW}) (\text{lb mol})$$

For example

$$\frac{100.0 \text{ g H}_2\text{O}}{18.0 \text{ g H}_2\text{O}} \left| \frac{1 \text{ g mol H}_2\text{O}}{18.0 \text{ g H}_2\text{O}} \right. = 5.56 \text{ g mol H}_2\text{O}$$

$$\frac{6.0 \text{ lb mol O}_2}{1 \text{ lb mol O}_2} \left| \frac{32.0 \text{ lb O}_2}{1 \text{ lb mol O}_2} \right. = 192 \text{ lb O}_2$$

- ❖ **The atomic weight** of an element is the mass of an atom based on the scale that assigns a mass of exactly 12 to the carbon isotope  $^{12}\text{C}$ .
- ❖ A **compound** is composed of more than one atom, and the molecular weight of the compound is nothing more than the sum of the weights of atoms of which it is composed.

#### Example 2.1

What is the molecular weight of the following cell of a superconductor material? (The figure represents one cell of a larger structure.)

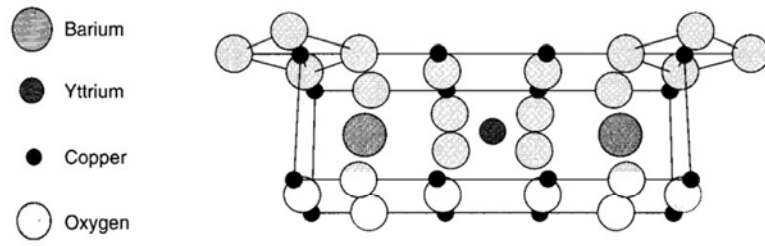


Figure E2.1

## Solution

Element	Number of atoms	Atomic weights	Mass (g)
Ba	2	137.34	2(137.34)
Cu	16	63.546	16(63.546)
O	24	16.00	24(16.00)
Y	1	88.905	<u>1(88.905)</u>
		Total	1764.3

The molecular weight of the cell for each mole is 1764.3 g/g mol.

### Example 2.2

If a bucket holds 2.00 lb of NaOH (MW=40), how many

- Pound moles of NaOH does it contain?
- Gram moles of NaOH does it contain?

### Solution

$$(a) \frac{2.00 \text{ lb NaOH}}{40.0 \text{ lb NaOH}} \left| \frac{1 \text{ lb mol NaOH}}{40.0 \text{ lb NaOH}} \right. = 0.050 \text{ lb mol NaOH}$$

$$(b_1) \frac{2.00 \text{ lb NaOH}}{40.0 \text{ lb NaOH}} \left| \frac{1 \text{ lb mol NaOH}}{40.0 \text{ lb NaOH}} \right| \frac{454 \text{ g mol}}{1 \text{ lb mol}} = 22.7 \text{ g mol}$$

$$(b_2) \frac{2.00 \text{ lb NaOH}}{1 \text{ lb}} \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \frac{1 \text{ g mol NaOH}}{40.0 \text{ g NaOH}} = 22.7 \text{ g mol}$$

### Example 2.3

How many pounds of NaOH (MW=40) are in 7.50 g mol of NaOH?

### Solution

$$\frac{7.50 \text{ g mol NaOH}}{454 \text{ g mol}} \left| \frac{1 \text{ lb mol}}{454 \text{ g mol}} \right| \frac{40.0 \text{ lb NaOH}}{1 \text{ lb mol NaOH}} = 0.661 \text{ lb NaOH}$$

## 2.2 Density

**Density** is the ratio of mass per unit volume, as for example, kg/m<sup>3</sup> or lb/ft<sup>3</sup>. Density has both a numerical value and units. **Specific volume** is the inverse of density, such as cm<sup>3</sup>/g or ft<sup>3</sup>/lb.

$$\rho = \text{density} = \frac{\text{mass}}{\text{volume}} = \frac{m}{V}$$

$$\hat{V} = \text{specific volume} = \frac{\text{volume}}{\text{mass}} = \frac{V}{m}$$

**For example**, given that the density of n-propyl alcohol is  $0.804 \text{ g/cm}^3$ , what would be the volume of 90.0 g of the alcohol? The calculation is

$$\frac{90.0 \text{ g}}{0.804 \text{ g}} \left| \frac{1 \text{ cm}^3}{1 \text{ g}} \right. = 112 \text{ cm}^3$$

- ❖ In a packed bed of solid particles containing void spaces, the bulk density is

$$\rho_B = \text{bulk density} = \frac{\text{total mass of solids}}{\text{total empty bed volume}}$$

- ❖ A homogeneous mixture of two or more components, whether solid, liquid, or gaseous, is called a **solution**.

For some solutions, the density of the solution is

$$V = \sum_{i=1}^n V_i \quad \text{where } n = \text{number of components}$$

$$m = \sum_{i=1}^n m_i$$

$$\rho_{\text{solution}} = \frac{m}{V}$$

For others you cannot.

### 2.3 Specific Gravity الثقل النوعي

Specific gravity is commonly thought of as a dimensionless ratio.

$$\text{sp.gr. of } A = \text{specific gravity of } A = \frac{(\text{g/cm}^3)_A}{(\text{g/cm}^3)_{ref}} = \frac{(\text{kg/m}^3)_A}{(\text{kg/m}^3)_{ref}} = \frac{(\text{lb/ft}^3)_A}{(\text{lb/ft}^3)_{ref}}$$

- ◆ The reference substance for **liquids** and **solids** normally is **water**.
- ◆ The density of water is **1.000 g/cm<sup>3</sup>, 1000 kg/m<sup>3</sup>, or 62.43 lb/ft<sup>3</sup> at 4°C.**
- ◆ The specific gravity of **gases** frequently is referred to **air**, but may be referred to other gases.

**For Example** If dibromopentane (DBP) has a specific gravity of 1.57, what is the density in (a) g/cm<sup>3</sup>? (b) lb<sub>m</sub>/ft<sup>3</sup>? and (c) kg/m<sup>3</sup>?

$$(a) \frac{1.57 \frac{\text{g DBP}}{\text{cm}^3}}{1.00 \frac{\text{g H}_2\text{O}}{\text{cm}^3}} \left| \frac{1.00 \frac{\text{g H}_2\text{O}}{\text{cm}^3}}{\text{cm}^3} \right. = 1.57 \frac{\text{g DBP}}{\text{cm}^3}$$

$$(b) \frac{1.57 \frac{\text{lb DBP}}{\text{ft}^3}}{1.00 \frac{\text{lb H}_2\text{O}}{\text{ft}^3}} \left| \frac{62.4 \frac{\text{lb H}_2\text{O}}{\text{ft}^3}}{\text{ft}^3} \right. = 97.97 \frac{\text{lb DBP}}{\text{ft}^3}$$

$$(c) \frac{1.57 \frac{\text{g DBP}}{\text{cm}^3}}{\text{cm}^3} \left| \left( \frac{100 \text{ cm}}{1 \text{ m}} \right)^3 \right| \frac{1 \text{ kg}}{1000 \text{ g}} = 1.57 \times 10^3 \frac{\text{kg DBP}}{\text{m}^3}$$

or

$$\frac{1.57 \frac{\text{kg DBP}}{\text{m}^3}}{1.00 \frac{\text{kg H}_2\text{O}}{\text{m}^3}} \left| \frac{1.00 \times 10^3 \text{ kg H}_2\text{O}}{\text{m}^3} \right. = 1.57 \times 10^3 \frac{\text{kg DBP}}{\text{m}^3}$$

### Example 2.4

If a 70% (by weight) solution of glycerol has a specific gravity of 1.184 at 15°C, what is the density of the solution in (a) g/cm<sup>3</sup>? (b) lbm/ft<sup>3</sup>? and (c) kg/m<sup>3</sup>?

#### Solution

$$(a) (1.184 \text{ g glycerol/cm}^3)/(1 \text{ g water/cm}^3) * (1 \text{ g water/cm}^3) = 1.184 \text{ g solution/cm}^3.$$

$$(b) (1.184 \text{ lb glycerol/ft}^3)/(1 \text{ lb water/ft}^3) * (62.4 \text{ lb water/ft}^3) = 73.9 \text{ lb solution/ft}^3.$$

$$(c) (1.184 \text{ kg glycerol/m}^3)/(1 \text{ kg water/m}^3) * (1000 \text{ kg water/m}^3) = 1.184 * 10^3 \text{ kg solution/m}^3.$$

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The specific gravity of petroleum products is often reported in terms of a hydrometer scale called °API ([American Petroleum Institute](#)). The equation for the API scale is

$$^{\circ}\text{API} = \frac{141.5}{\text{sp.gr.} \frac{60^{\circ}\text{F}}{60^{\circ}\text{F}}} - 131.5 \quad (\text{API gravity}) \quad (2.1)$$

or

$$\text{sp.gr.} \frac{60^{\circ}}{60^{\circ}} = \frac{141.5}{^{\circ}\text{API} + 131.5} \quad (2.2)$$

$$60^{\circ}\text{F} = 15^{\circ}\text{C} \quad \text{Note: } T^{\circ}\text{F} = 1.8 T^{\circ}\text{C} + 32 \quad T^{\circ}\text{C} = (T^{\circ}\text{F} - 32)/1.8$$

The **volume** and therefore the **density** of petroleum products vary with **temperature**, and the petroleum industry has established 60 °F as the standard temperature for volume and API gravity.

### Example 2.5

In the production of a drug having a molecular weight of 192, the exit stream from the reactor flows at a rate of 10.5 L/min. The drug concentration is 41.2% (in water), and the specific gravity of the solution is 1.024. Calculate the concentration of the drug (in kg/L) in the exit stream, and the flow rate of the drug in kg mol/min.

#### Solution

Take 1 kg of the exit solution as a basis for convenience.

Basis: 1 kg solution

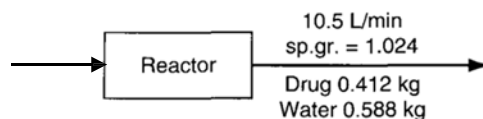


Figure E2.5

$$\text{density of solution} = \frac{1.024 \frac{\text{g soln}}{\text{cm}^3}}{1.000 \frac{\text{g H}_2\text{O}}{\text{cm}^3}} \left| \frac{1.000 \frac{\text{g H}_2\text{O}}{\text{cm}^3}}{1.000 \frac{\text{g H}_2\text{O}}{\text{cm}^3}} \right| = 1.024 \frac{\text{g soln}}{\text{cm}^3}$$

$$\frac{0.412 \text{ kg drug}}{1.000 \text{ kg soln}} \left| \frac{1.024 \text{ g soln}}{1 \text{ cm}^3} \right| \frac{1 \text{ kg}}{10^3 \text{ g}} \left| \frac{10^3 \text{ cm}^3}{1 \text{ L}} \right| = 0.422 \text{ kg drug/L soln}$$



To get the flow rate, take a different basis, namely 1 minute.

Basis: 1 min = 10.5 L solution

$$\frac{10.5 \text{ L soln}}{1 \text{ min}} \left| \frac{0.422 \text{ kg drug}}{1 \text{ L soln}} \right| \frac{1 \text{ kg mol drug}}{192 \text{ kg drug}} = 0.023 \text{ kg mol/min}$$

## 2.4 Flow Rate

For continuous processes the **flow rate** of a process stream is the rate at which material is transported through a pipe. The **mass flow rate** ( $\dot{m}$ ) of a process stream is the **mass (m)** transported through a line per unit **time (t)**.

$$\dot{m} = \frac{m}{t}$$

The **volumetric flow rate (F)** of a process stream is the **volume (V)** transported through a line per unit **time**.

$$F = \frac{V}{t}$$

The **molar flow (n) rate** of a process stream is the number of **moles (n)** of a substance transported through a line per unit **time**.

$$\dot{n} = \frac{n}{t}$$

## 2.5 Mole Fraction and Mass (Weight) Fraction

- ☒ **Mole fraction** is simply the number of moles of a particular compound in a mixture or solution divided by the total number of moles in the mixture or solution.
- ☒ This definition holds for **gases, liquids, and solids**.
- ☒ Similarly, the **mass (weight) fraction** is nothing more than the **mass (weight)** of the compound divided by the total mass (weight) of all of the compounds in the mixture or solution.

Mathematically, these ideas can be expressed as

$$\text{mole fraction of } A = \frac{\text{moles of } A}{\text{total moles}}$$

$$\text{mass (weight) fraction of } A = \frac{\text{mass of } A}{\text{total mass}}$$

**Mole percent** and **mass (weight) percent** are the respective fractions times **100**.

**Example 2.6**

An industrial-strength drain cleaner contains 5 kg of water and 5 kg of NaOH. What are the mass (weight) fractions and mole fractions of each component in the drain cleaner container?

## Solution

Basis: 10 kg of total solution

Component	kg	Weight fraction	Mol. Wt.	kg mol	Mole fraction
H <sub>2</sub> O	5.00	$\frac{5.00}{10.0} = 0.500$	18.0	0.278	$\frac{0.278}{0.403} = 0.69$
NaOH	5.00	$\frac{5.00}{10.00} = 0.500$	40.0	0.125	$\frac{0.125}{0.403} = 0.31$
Total	10.00	1.000		0.403	1.00

The kilogram moles are calculated as follows:

$$\frac{5.00 \text{ kg H}_2\text{O}}{18.0 \text{ kg H}_2\text{O}} \left| \frac{1 \text{ kg mol H}_2\text{O}}{18.0 \text{ kg H}_2\text{O}} \right. = 0.278 \text{ kg mol H}_2\text{O}$$

$$\frac{5.00 \text{ kg NaOH}}{40.0 \text{ kg NaOH}} \left| \frac{1 \text{ kg mol NaOH}}{40.0 \text{ kg NaOH}} \right. = 0.125 \text{ kg mol NaOH}$$

Adding these quantities together gives the total kilogram moles.

### **Example 2.7**

In normal living cells, the nitrogen requirement for the cells is provided from protein metabolism (i.e., consumption of the protein in the cells). When individual cells are commercially grown, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> is usually used as the source of nitrogen. Determine the amount of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> consumed in a fermentation medium in which the final cell concentration is 35 g/L in a 500 L volume of the fermentation medium. Assume that the cells contain 9 wt. % N, and that (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> is the only nitrogen source.

## Solution

Basis: 500 L solution containing 35 g/L

$$\frac{500 \text{ L}}{1} \left| \frac{35 \text{ g cell}}{\text{L}} \right| \left| \frac{0.09 \text{ g N}}{1 \text{ g cell}} \right| \left| \frac{1 \text{ g mol N}}{14 \text{ g N}} \right. \times \left. \left| \frac{1 \text{ g mol (NH}_4)_2\text{SO}_4}{2 \text{ g mol N}} \right| \left| \frac{132 \text{ g (NH}_4)_2\text{SO}_4}{1 \text{ g mol (NH}_4)_2\text{SO}_4} \right. = 7425 \text{ g (NH}_4)_2\text{SO}_4$$

## 2.6 Analyses of Multicomponent Solutions and Mixtures

The **composition of gases** will always be assumed to be given in **mole percent** or **fraction** unless specifically stated otherwise.

The **composition of liquids and solids** will be given by **mass (weight) percent** or **fraction** unless otherwise specifically stated.

**For Example** Table below lists the detailed composition of dry air (composition of air 21% O<sub>2</sub> and 79% N<sub>2</sub>). Calculate the average molecular weight of air?

Basis 100 mol of air

Component	Moles = percent	Mol. wt.	Lb or kg	Weight %
O <sub>2</sub>	21.0	32	672	23.17
N <sub>2</sub>	<u>79.0</u>	28.2	<u>2228</u>	<u>76.83</u>
Total	100		2900	100.00
The average molecular weight is 2900 lb/100 lb mol = 29.0, or 2900 kg/100 kg mol = 29				

## 2.7 Concentration

**Concentration** generally refers to the quantity of some substance per unit volume.

- Mass per unit volume (lb of solute/ft<sup>3</sup> of solution, g of solute/L, lb of solute/barrel, kg of solute/m<sup>3</sup>).
- Moles per unit volume (lb mol of solute/ft<sup>3</sup> of solution, g mol of solute/L, g mol of solute/cm<sup>3</sup>).
- Parts per million (**ppm**); parts per billion (**ppb**), a method of expressing the concentration of extremely dilute solutions; **ppm is equivalent to a mass (weight) fraction for solids and liquids** because the total amount of material is of a much higher order of magnitude than the amount of solute; it is a **mole fraction for gases**.
- Parts per million by volume (ppmv) and parts per billion by volume (ppbv)
- Other methods of expressing concentration with which you may be familiar are molarity (g mol/L), molality (mole solute/kg solvent), and normality (equivalents/L).

### Example 2.8

The current Occupational Safety and Health Administration (OSHA) 8-hour limit for Hydrogen cyanide (HCN) (boils at 25.6 °C) (MW = 27.03) in air is 10.0 ppm. A lethal dose of HCN in air is (from the Merck Index) 300 mg/kg of air at room temperature. How many mg HCN/kg air is 10 ppm? What fraction of the lethal dose is 10.0 ppm?

### **Solution**

Basis: 1 kg mol of the air/HCN mixture

$$\text{The 10.0 ppm is } \frac{10.0 \text{ g mol HCN}}{10^6(\text{air} + \text{HCN})\text{g mol}} = \frac{10.0 \text{ g mol HCN}}{10^6 \text{ g mol air}}$$

$$\text{a. } \frac{10.0 \text{ g mol HCN}}{10^6 \text{ g mol air}} \left| \frac{27.03 \text{ g HCN}}{1 \text{ g mol HCN}} \right| \frac{1 \text{ g mol air}}{29 \text{ g air}} \left| \frac{1000 \text{ mg HCN}}{1 \text{ g HCN}} \right| \times \frac{1000 \text{ g air}}{1 \text{ kg air}} = 9.32 \text{ mg HCN/kg air}$$

$$\text{b. } \frac{9.32}{300} = 0.031$$

### Example 2.9

A solution of  $\text{HNO}_3$  in water has a specific gravity of 1.10 at  $25^\circ\text{C}$ . The concentration of the  $\text{HNO}_3$  is 15 g/L of solution. What is the

- a. Mole fraction of  $\text{HNO}_3$  in the solution?

b. ppm of HNO<sub>3</sub> in the solution?

**Solution**

Basis: 1 L of solution  
 Density =  $1.1 \times 1 \text{ g/cm}^3 = 1.1 \text{ g/cm}^3$  (density of solution)

$$\frac{15 \text{ g HNO}_3}{1 \text{ L soln}} \left| \frac{1 \text{ L}}{1000 \text{ cm}^3} \right| \left| \frac{1 \text{ cm}^3}{1.10 \text{ g soln}} \right| = 0.01364 \frac{\text{g HNO}_3}{\text{g soln}}$$

Basis: 100 g solution

The mass of water in the solution is:  $100 - 1.364 = 98.636 \text{ g H}_2\text{O}$ .

	<b>g</b>	<b>MW</b>	<b>gmol</b>	<b>mol fraction</b>
HNO <sub>3</sub>	1.364	63.02	0.02164	0.00394
H <sub>2</sub> O	98.636	18.016	<u>5.475</u>	<u>0.99606</u>
Total			5.4966	1

b.  $\frac{0.01364}{1} = \frac{13,640}{10^6}$  or 13,640 ppm

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**Example 2.10**

Sulfur trioxide (SO<sub>3</sub>) can be absorbed in sulfuric acid solution to form more concentrated sulfuric acid. If the gas to be absorbed contains 55% SO<sub>3</sub>, 41% N<sub>2</sub>, 3% SO<sub>2</sub>, and 1% O<sub>2</sub>, how many parts per million of O<sub>2</sub> are there in the gas? What is the composition of the gas on a N<sub>2</sub> free basis?

**Solution**

(a)  $\frac{1 \text{ mol O}_2}{100 \text{ mol gas}} \Rightarrow \frac{10^4 \text{ mol O}_2}{10^6 \text{ mol gas}}$  or 10<sup>4</sup> ppm

(b) Basis: 100 mol gas

answer

<u>Comp.</u>	<u>% = mol</u>	<u>mol fr.</u>	<u>or mol %</u>
SO <sub>3</sub>	55	0.932	93.2
SO <sub>2</sub>	3	0.051	5.1
O <sub>2</sub>	<u>1</u>	<u>0.017</u>	<u>1.7</u>
Total	59	1.000	100.0

**Example 2.11**

To avoid the possibility of explosion in a vessel containing gas having the composition of 40% N<sub>2</sub>, 45% O<sub>2</sub>, and 15% CH<sub>4</sub>, the recommendation is to dilute the gas mixture by adding an equal amount of pure N<sub>2</sub>. What is the final mole fraction of each gas?

**Solution**

The basis is 100 moles of initial gas



Composition	Original Mixture	After Addition	Final Mixture
	mol%	N <sub>2</sub>	Mole Fraction
N <sub>2</sub>	40 + 100	140	140/200 = 0.70
O <sub>2</sub>	45 $\xrightarrow{\quad}$	45	45/200 = 0.23
CH <sub>4</sub>	15	15	15/200 = 0.07
Total	100	200	1.00

### Example 2.12

Calculate the empirical formula of an organic compound with the following mass analysis: carbon, 26.9%; hydrogen, 2.2%; and oxygen as the only other element present.

### **Solution**

**Basis: 100 g of compound**

	<u>C</u>	<u>H</u>	<u>O</u>
Mass ( <i>m</i> ) combining / g	26.9	2.2	70.9
Molar mass ( <i>M</i> ) / g mol <sup>-1</sup>	12	1	16
Number of moles combining (mass ÷ molar mass)	26.9 / 12 = 2.24	2.2 / 1 = 2.20	70.9 / 16 = 4.43
Ratio of number of moles	2.24 / 2.20 = 1.02	2.20 / 2.20 = 1.00	4.43 / 2.20 = 2.01
Simplest ratio	1	1	2

**The empirical formula of this organic compound is C<sub>1</sub>H<sub>1</sub>O<sub>2</sub>.**

### Questions

- Answer the following questions true or false:
  - The pound mole is comprised of  $2.73 \times 10^{26}$  molecules
  - The kilogram mole is comprised of  $6.022 \times 10^{26}$  molecules.
  - Molecular weight is the mass of a compound or element per mole.
- What is the molecular weight of acetic acid (CH<sub>3</sub>COOH)?
- For numbers such as 2 mL of water + 2 mL of ethanol, does the sum equal to 4 mL of the solution?
- Answer the following questions true or false:
  - The inverse of the density is the specific volume.

- b. Density of a substance is the mass per unit volume.
- c. The density of water is less than the density of mercury.

5. A cubic centimeter of mercury has a mass of 13.6 g at Earth's surface. What is the density of mercury?
6. What is the approximate density of water at room temperature in  $\text{kg/m}^3$ ?
7. For liquid HCN, a handbook gives: sp. gr.  $10^\circ\text{C}/4^\circ\text{C} = 1.2675$ . What does this statement mean?
8. Answer the following questions true or false:
  - a. The density and specific gravity of mercury are the same.
  - b. Specific gravity is the ratio of two densities.
  - c. If you are given the value of a reference density, you can determine the density of a substance of interest by multiplying by the specific gravity.
  - d. The specific gravity is a dimensionless quantity.
9. A mixture is reported as 15% water and 85% ethanol. Should the percentages be deemed to be by mass, mole, or volume?
10. Answer the following questions true or false:
  - a) In engineering practice the compositions of liquids and solids are usually denoted in weight (mass) fraction or percent.
  - b) In engineering practice the composition of gases is usually denoted in mole fraction or percent.
  - c) e. A pseudo-average molecular weight can be calculated for a mixture of pure components whether solid, liquid, or gases.
11. Do parts per million denote a concentration that is a mole ratio?
12. Does the concentration of a component in a mixture depend on the amount of the mixture?
13. Pick the correct answer. How many ppm are there in 1 ppb? (a) 1000, (b) 100, (c) 1, (d) 0.1, (e) 0.01, (f) 0.001?
14. How many ppb are there in 1 ppm?
15. Does 50 ppm represent an increase of five times a value of 10 ppm?

**Answers:**

1. (a) T; (b) T; (c) T
2. 60.05
3. No
4. (a) T; (b) T; (c) T

5.  $13.6 \text{ g/cm}^3$

6.  $1000 \text{ kg/m}^3$

7. The statement means that the density at  $10^{\circ}\text{C}$  of liquid HCN is 1.2675 times the density of water at  $4^{\circ}\text{C}$ .
8. (a) F – the units differ; (b) T; (c) T; (d) F.
9. Mass
10. (a) T; (b) T; (c) T
11. For gases but not for liquids or solids.
12. No
13. 0.001
14. 1000
15. No (4 times)

### **Problems**

1. Convert the following:
  - a) 120 g mol of NaCl to g.
  - b) 120 g of NaCl to g mol.
  - c) 120 lb mol of NaCl to lb.
  - d) 120 lb of NaCl to lb mol.
2. Convert 39.8 kg of NaCl per 100 kg of water to kg mol of NaCl per kg mol of water.
3. How many lb mol of  $\text{NaNO}_3$  are there in 100 lb?
4. The density of a material is  $2\text{ kg/m}^3$ . What is its specific volume?
5. An empty 10 gal tank weighs 4.5 lb. What is the total weight of the tank plus the water when it is filled with 5 gal of water?
6. If you add 50 g of sugar to 500 mL of water, how do you calculate the density of the sugar solution?
7. For ethanol, a handbook gives: sp. gr.  $60^{\circ}\text{F} = 0.79389$ . What is the density of ethanol at  $60^{\circ}\text{F}$ ?
8. The specific gravity of steel is 7.9. What is the volume in cubic feet of a steel ingot weighing 4000 lb?
9. The specific gravity of a solution is 0.80 at  $70^{\circ}\text{F}$ . How many cubic feet will be occupied by 100 lb of the solution at  $70^{\circ}\text{F}$ ?
10. A solution in water contains 1.704 kg of  $\text{HNO}_3/\text{kg H}_2\text{O}$ , and the solution has a specific gravity of 1.382 at  $20^{\circ}\text{C}$ . What is the mass of  $\text{HNO}_3$  in kg per cubic meter of solution at

20°C?

11. Forty gal/min of a hydrocarbon fuel having a specific gravity of 0.91 flows into a tank truck with a load limit of 40,000 lb of fuel. How long will it take to fill the tank in the truck?
12. Pure chlorine enters a process. By measurement it is found that 2.4 kg of chlorine pass into the process every 3.1 minutes. Calculate the molar flow rate of the chlorine in kg mol/hr.
13. Commercial sulfuric acid is 98%  $\text{H}_2\text{SO}_4$  and 2%  $\text{H}_2\text{O}$ . What is the mole ratio of  $\text{H}_2\text{SO}_4$  to  $\text{H}_2\text{O}$ ?
14. A compound contains 50% sulfur and 50% oxygen by mass. Is the empirical formula of the compound (1)  $\text{SO}$ , (2)  $\text{SO}_2$ , (3)  $\text{SO}_3$ , or (4)  $\text{SO}_4$ ?
15. How many kg of activated carbon (a substance used in removing trace impurities) must be mixed with 38 kg of sand so that the final mixture is 28% activated carbon?
16. A gas mixture contains 40 lb of  $\text{O}_2$ , 25 lb of  $\text{SO}_2$ , and 30 lb of  $\text{SO}_3$ . What is the composition of the mixture in mole fractions?
17. Saccharin, an artificial sweetener that is 3000 times sweeter than sucrose, is composed of 45.90% carbon, 2.73% hydrogen, 26.23% oxygen, 7.65% nitrogen, and 17.49% sulfur. Is the molecular formula of saccharin (a)  $\text{C}_{14}\text{H}_{10}\text{O}_6\text{N}_2\text{S}_2$ , (b)  $\text{C}_5\text{H}_7\text{O}_3\text{NS}$ , (c)  $\text{C}_8\text{H}_9\text{O}_2\text{NS}$ , and (d)  $\text{C}_7\text{H}_5\text{O}_3\text{NS}$ ?
18. A mixture of gases is analyzed and found to have the following composition:  $\text{CO}_2$  12.0%,  $\text{CO}$  6.0%,  $\text{CH}_4$  27.3%,  $\text{H}_2$  9.9% and  $\text{N}_2$  44.8%. How much will 3 lb mol of this gas weigh?
19. A liquefied mixture of n-butane, n-pentane, and n-hexane has the following composition: n- $\text{C}_4\text{H}_{10}$  50%, n- $\text{C}_5\text{H}_{12}$  30%, and n- $\text{C}_6\text{H}_{14}$  20%. For this mixture, calculate:
  - a) The weight fraction of each component.
  - b) The mole fraction of each component.
  - c) The mole percent of each component.
  - d) The average molecular weight of the mixture.
20. How many mg/L is equivalent to a 1.2% solution of a substance in water?

**Answers:**

1. (a) 7010 g; (b) 2.05 g mol; (c) 7010 lb; (d) 2.05 lb mol
2. 0.123 kg mol NaCl/kg mol  $\text{H}_2\text{O}$
3. 1.177 lb mol
4.  $0.5 \text{ m}^3/\text{kg}$
5. 46.2 lb

6. Measure the mass of water (should be about 500g) and add it to 50 g. Measure the volume of the solution (will not be 450 mL). Divide the mass by the volume.



7. 0.79389 g/cm<sup>3</sup> (assuming the density of water is also at 60°F)
8. 8.11 ft<sup>3</sup>
9. 2 ft<sup>3</sup>
10. 870 kg HNO<sub>3</sub>/m<sup>3</sup> solution.
11. 132 min
12. 0.654 kg mol/hr
13. 9
14. SO<sub>2</sub>
15. 14.8 kg
16. O<sub>2</sub> 0.62; SO<sub>2</sub> 0.19; SO<sub>3</sub> 0.19
17. (d)
18. 72.17 lb
19. (a) C<sub>4</sub>: 0.50, C<sub>5</sub>: 0.30, C<sub>6</sub>: 0.20; (b) C<sub>4</sub>: 0.57, C<sub>5</sub>: 0.28, C<sub>6</sub>: 0.15; (c) C<sub>4</sub>: 57, C<sub>5</sub>: 28, C<sub>6</sub>: 15;  
(d) 66.4 kg/kg mol
20. 12000 mg/L

**Supplementary Problems (Chapter Two):**

**Problem 1**

Calcium carbonate is a naturally occurring white solid used in the manufacture of lime and cement. Calculate the number of lb mols of calcium carbonate in:

- a. 50 g mol of CaCO<sub>3</sub>.
- b. 150 kg of CaCO<sub>3</sub>.
- c. 100 lb of CaCO<sub>3</sub>.

**Solution**

$$\text{a. } \frac{50 \text{ g mol CaCO}_3}{1 \text{ g mol CaCO}_3} \left| \frac{100 \text{ g CaCO}_3}{454 \text{ g CaCO}_3} \right| \frac{1 \text{ lb mol CaCO}_3}{100 \text{ lb CaCO}_3} = 0.11 \text{ lb mol}$$

$$\text{b. } \frac{150 \text{ kg CaCO}_3}{1 \text{ kg CaCO}_3} \left| \frac{2.205 \text{ lb CaCO}_3}{1 \text{ kg CaCO}_3} \right| \frac{1 \text{ lb mol CaCO}_3}{100 \text{ lb CaCO}_3} = 3.30 \text{ lb mol}$$

$$\text{c. } \frac{100 \text{ lb CaCO}_3}{100 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{100 \text{ lb CaCO}_3} \right| = 1.00 \text{ lb mol CaCO}_3$$

**Problem 2**

Silver nitrate (lunar caustic) is a white crystalline salt, used in marking inks, medicine and chemical analysis. How many kilograms of silver nitrate ( $\text{AgNO}_3$ ) are there in :

- 13.0 lb mol  $\text{AgNO}_3$ .
- 55.0 g mol  $\text{AgNO}_3$

**Solution**

$$\begin{aligned} \text{a. } & \frac{13.0 \text{ lb mol AgNO}_3}{1 \text{ lb mol AgNO}_3} \left| \frac{170 \text{ lb AgNO}_3}{1 \text{ lb mol AgNO}_3} \right| \frac{1 \text{ kg}}{2.205 \text{ lb}} = 1002 \text{ kg or } 1000 \text{ kg} \\ \text{b. } & \frac{55.0 \text{ g mol AgNO}_3}{1 \text{ g mol AgNO}_3} \left| \frac{170 \text{ g AgNO}_3}{1 \text{ g mol AgNO}_3} \right| \frac{1 \text{ kg}}{1000 \text{ g}} = 9.35 \text{ kg} \end{aligned}$$

**Problem 3**

Phosphoric acid is a colorless deliquescent acid used in the manufacture of fertilizers and as a flavoring agent in drinks. For a given 10 wt % phosphoric acid solution of specific gravity 1.10 determine:

- the mol fraction composition of this mixture.
- the volume (in gallons) of this solution which would contain 1 g mol  $\text{H}_3\text{PO}_4$ .

**Solution**

- a. Basis: 100 g of 10 wt% solution

	g	MW	g mol	mol fr
$\text{H}_3\text{PO}_4$	10	97.97	0.102	0.020
$\text{H}_2\text{O}$	90	18.01	5.00	0.980

- b. Specific gravity =  $\frac{\rho_{\text{soln}}}{\rho_{\text{ref}}}$  The ref. liquid is water

The density of the solution is  $\frac{1.10 \text{ g soln/cm}^3 \text{ soln}}{1.00 \text{ g H}_2\text{O/cm}^3} \left| \frac{1.00 \text{ g H}_2\text{O/cm}^3}{1.00 \text{ g H}_2\text{O/cm}^3} \right| = 1.10 \frac{\text{g soln}}{\text{cm}^3}$

$$\frac{1 \text{ cm}^3 \text{ soln}}{1.10 \text{ g soln}} \left| \frac{1 \text{ g soln}}{0.1 \text{ g H}_3\text{PO}_4} \right| \left| \frac{97.97 \text{ g H}_3\text{PO}_4}{1 \text{ g mol H}_3\text{PO}_4} \right| \left| \frac{264.2 \text{ gal}}{10^6 \text{ cm}^3} \right| = 0.24 \text{ gal/g mol}$$

**Problem 4**

The density of a liquid is  $1500 \text{ kg/m}^3$  at  $20^\circ\text{C}$ .

- What is the specific gravity  $20^\circ\text{C}/4^\circ\text{C}$  of this material.
- What volume ( $\text{ft}^3$ ) does  $140 \text{ lb}_m$  of this material occupy at  $20^\circ\text{C}$ .

**Solution**

Assume the reference substance is water which has a density of  $1000 \text{ kg/m}^3$  at  $4^\circ\text{C}$ .

$$\text{a. Specific gravity} = \frac{\rho_{\text{soln}}}{\rho_{\text{ref}}} = \frac{(\text{kg/m}^3)_{\text{soln}}}{(\text{kg/m}^3)_{\text{ref}}} = \frac{1500 \text{ kg/m}^3}{1000 \text{ kg/m}^3} = 1.50$$

$$\text{b. } \frac{1 \text{ m}^3 \text{ liquid}}{1500 \text{ kg}} \left| \frac{1 \text{ kg}}{2.20 \text{ lb}} \right| \frac{35.31 \text{ ft}^3}{1 \text{ m}^3} \left| \frac{140 \text{ lb}_m}{140 \text{ lb}_m} \right| = 1.50 \text{ ft}^3$$

The 1993 Environmental Protection Agency (EPA) regulation contains standards for 84 chemicals and minerals in drinking water. According to the EPA one of the most prevalent of the listed contaminants is naturally occurring antimony. The maximum contaminant level for antimony and nickel has been set at  $0.006 \text{ mg/L}$  and  $0.1 \text{ mg/L}$  respectively.

A laboratory analysis of your household drinking water shows the antimony concentration to be  $4 \text{ ppb}$  (parts per billion) and that of nickel to be  $60 \text{ ppb}$ . Determine if the drinking water is safe with respect to the antimony and nickel levels.

Assume density of water to be  $1.00 \text{ g/cm}^3$

**Solution**

Antimony

$$\frac{0.006 \text{ mg Sb}}{1 \text{ L soln}} \left| \frac{1 \text{ L soln}}{1000 \text{ cm}^3 \text{ soln}} \right| \frac{1 \text{ cm}^3 \text{ soln}}{1.00 \text{ g H}_2\text{O}} \left| \frac{1 \text{ g}}{1000 \text{ mg}} \right| = \frac{6 \text{ g Sb}}{10^9 \text{ g soln}} = 6 \text{ ppb}$$

Nickel

**Problem 5**

$$\frac{0.1 \text{ mg Ni}}{1 \text{ L soln}} \left| \frac{1 \text{ L soln}}{1000 \text{ cm}^3 \text{ soln}} \right| \frac{1 \text{ cm}^3 \text{ soln}}{1.0 \text{ g H}_2\text{O}} \left| \frac{1 \text{ g}}{1000 \text{ mg}} \right| = \frac{9 \text{ g Ni}}{10^9 \text{ g soln}} = 100 \text{ ppb}$$

House hold drinking water contains less than the EPA mandated tolerance levels of antimony and nickel. Drinking water is therefore safe.

**Problem 6**

Wine making involves a series of very complex reactions most of which are performed by microorganisms. The starting concentration of sugars determines the final alcohol content and sweetness of the wine. The specific gravity of the starting stock is therefore adjusted to achieve desired quality of wine.

A starting stock solution has a specific gravity of 1.075 and contains 12.7 wt% sugar. If all the sugar is assumed to be  $C_{12}H_{22}O_{11}$ , determine

- kg sugar/kg  $H_2O$
- lb solution/ft<sup>3</sup> solution
- g sugar/L solution

**Solution**

Basis: 100 kg starting stock solution

$$a. \frac{12.7 \text{ kg sugar}}{100 \text{ kg soln}} \left| \frac{100 \text{ kg solution}}{87.3 \text{ kg } H_2O} \right. = .145 \frac{\text{kg sugar}}{\text{kg } H_2O}$$

$$b. \frac{1.075 \text{ g soln/cm}^3}{1.0 \text{ g } H_2O/\text{cm}^3} \left| \frac{1.00 \text{ g } H_2O/\text{cm}^3}{1.00 \text{ g } H_2O/\text{cm}^3} \right| \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| \left| \frac{2.832 \times 10^4 \text{ cm}^3}{\text{ft}^3} \right. = 67.1 \frac{\text{lb soln}}{\text{ft}^3 \text{ soln}}$$

$$c. \frac{1.075 \text{ g soln/cm}^3}{1.0 \text{ g } H_2O/\text{cm}^3} \left| \frac{1.0 \text{ g } H_2O/\text{cm}^3}{1.0 \text{ g } H_2O/\text{cm}^3} \right| \left| \frac{12.7 \text{ g sugar}}{100 \text{ g soln}} \right| \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right. = 136 \frac{\text{g sugar}}{\text{L soln}}$$

**Problem 7**

How many ppb are there in 1 ppm? Does the system of units affect your answer? Does it make any difference if the material for which the ppb are measured is a gas, liquid, or solid?

**Solution**

a) **1000**

b) **No**

c) **Yes, because for solids and liquids the ratio in ppb is mass whereas for gases the ratio is in moles.**