Reactivity 2.1 Answers

IB CHEMISTRY SL

25	16		6	2	25
Mn	S	J	C	He	Mn
Manganese	Sulfur		Carbon	Helium	Manganese
54.938045	32.065		12.0107	4.002602	54.938045

Reactivity 2.1.1 and 2.1.2

Understandings:

- Chemical equations show the ratio of reactants and products in a reaction (2.1.1).
- The mole ratio of an equation can be used to determine:
  the masses and/or volumes of reactants and products
  the concentrations of reactants and products for reactions occurring in solution (2.1.2).

Learning outcomes:

- Deduce chemical equations when reactants and products are specified (2.1.1).
- Calculate reacting masses and/or volumes and concentrations of reactants and products (2.1.2).

Additional notes:

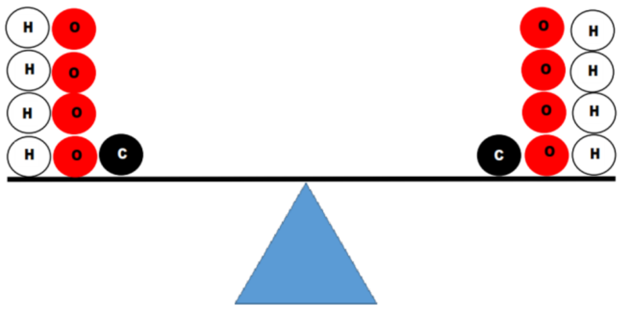
- Include the use of state symbols in chemical equations.
- Avogadro's law and definitions of molar concentration are covered in Structure 1.4.
- The values for A_r given in the data booklet to two decimal places should be used in calculations.

Linking questions:

- Reactivity 3.2 When is it useful to use half- equations?
- Structure 1.5 How does the molar volume of a gas vary with changes in temperature and pressure?

Balancing chemical equations

- The law of the conservation of mass states that mass is conserved in a chemical reaction.
- Therefore, there must be the same number of each type of atom in the reactants and products, as shown in the diagram below.



$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

- To balance a chemical equation, we can only change the numbers in front of the reactants or products which are called coefficients.

Example 1:

- Sodium reacts with chlorine to produce sodium chloride. The unbalanced equation is shown.

  …..Na(s) + …..Cl_2(g) → …..NaCl(s)

  There is one Na atom in the reactants and one in the products. However, there are two Cl atoms in the reactants but only one in the products. Write the balanced equation for the reaction.

  $2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$

Example 2:

- Calcium carbonate reacts with hydrochloric acid to produce calcium chloride, water and carbon dioxide. The unbalanced equation is shown.

  …..$CaCO_3$(s) + …..HCl(aq) → …..$CaCl_2$(aq) + …..H_2O(l) + …..CO_2(g)

Write the balanced equation for the reaction.

$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$

Exercises: Balance the following chemical equations using whole number coefficients. When each equation is balanced, determine the sum of coefficients in the equations.

1) $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$ sum of coefficients 6

2) $C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$ sum of coefficients 13

3) $2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$ sum of coefficients 11

4) $Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + 2H_2(g)$ sum of coefficients 5

5) $MgCO_3(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2O(l) + CO_2(g)$

sum of coefficients 5

6) $2NaCl(s) + CaO(aq) \rightarrow CaCl_2(aq) + Na_2O(s)$ sum of coefficients 5

7) $8Al(s) + 3Fe_3O_4(s) \rightarrow 4Al_2O_3(s) + 9Fe(s)$ sum of coefficients 24

8) $Mg_3N_2(s) + 4H_2SO_4(aq) \rightarrow 3MgSO_4(aq) + (NH_4)_2SO_4(aq)$

sum of coefficients 9

9) $Fe_2O_3(s) + 3C(s) \rightarrow 2Fe(s) + 3CO(g)$ sum of coefficients 9

10) $2Al(OH)_3(s) + 3H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + 6H_2O(l)$

sum of coefficients 12

Mole ratios

- The coefficients in a balanced chemical equation tell us the mole ratios (or molar ratio) of reactants and products.
- In the equation below we can determine that 2 mol of A react with 3 mol of B to form 1 mol of C and 2 mol of D.

$$2A + 3B \rightarrow C + 2D$$

Exercises:

1) State the mole ratios in the following chemical equations.

(a) $2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$

$CH_3OH : H_2O$ 2:4 or 1:2

$CH_3OH : CO_2$ 2:2 or 1:1

$CH_3OH : O_2$ 2:3

(b) $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$

$N_2 : H_2$ 1:3

$H_2 : NH_3$ 3:2

$N_2 : NH_3$ 1:2

2) Determine the amount of the following.

(a) $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

The amount of CO_2 produced from 0.10 mol of CH_4 0.10 mol (1:1 ratio)

The amount of O_2 required to react with 0.75 mol of CH_4 1.5 mol (1:2 ratio)

(b) $Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

The amount of H_2 produced from 1.50 mol of Mg 1.50 mol (1:1 ratio)

The amount of H_2 produced from 0.80 mol of HCl 0.40 mol (2:1 ratio)

The amount of HCl required to react with 3.00 mol of Mg 6.00 mol (1:2 ratio)

Reactivity 2.1.3

Understandings:

- The limiting reactant determines the theoretical yield.

Learning outcomes:

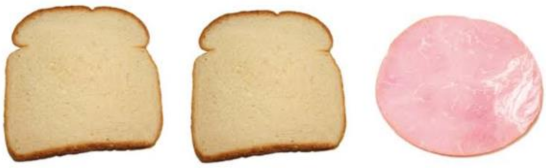
- Identify the limiting and excess reactants from given data.

Additional notes:

- Distinguish between the theoretical yield and the experimental yield.

Limiting reactant and excess reactant

- The limiting reactant (reagent) is the reactant that limits the amount of product(s) that can be formed.
- The excess reactant is the reactant that remains when the limiting reactant is consumed.



- How many sandwiches can be made with 12 pieces of bread and 7 slices of ham? 6 sandwiches
- Which is the limiting reactant? The bread
- Which is the excess reactant? The ham

How to determine the limiting and excess reactant.

1. Determine the amount (in mol) of each reactant.
2. Divide the amount of each reactant by its coefficient in the balanced equation.
3. The lowest value is the limiting reactant and the highest is the excess reactant.

Exercises:

1) 50.0 g of N_2H_4 is reacted with 75.0 g of N_2O_4 according to the following equation.

$$2N_2H_4(l) + N_2O_4(l) \rightarrow 3N_2(g) + 4H_2O(g)$$

(a) Determine the limiting and excess reactants.

$n(N_2H_4) = \frac{50.0 \text{ g}}{32.06 \text{ g mol}^{-1}} = 1.56 \text{ mol}$ $n(N_2O_4) = \frac{75.0 \text{ g}}{92.02 \text{ g mol}^{-1}} = 0.815 \text{ mol}$

$N_2H_4 = \frac{1.56}{2} = 0.780$ $N_2O_4 = \frac{0.815}{1} = 0.815$

N_2H_4 is the limiting reactant and N_2O_4 is the excess reactant.

(b) Determine the amount of excess reactant that remains at the end of the reaction.

Molar ratio of N_2H_4 to N_2O_4 is 2:1

$1.56 \text{ mol } N_2H_4 \times \frac{1 \text{ mol } N_2O_4}{2 \text{ mol } N_2H_4} = 0.780 \text{ mol } N_2O_4$

$n(N_2O_4)$ remaining = 0.815 – 0.780 = 0.0350 mol

2) 3.00 g of Zn is reacted with 50.0 cm^3 of 1.00 mol dm^{-3} HCl according to the following equation.

$$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$$

(a) Determine the limiting and excess reactants.

$n(Zn) = \frac{3.00 \text{ g}}{65.38 \text{ g mol}^{-1}}$ = 0.0459 mol $n(HCl) = 1.00 \text{ mol dm}^{-3} \times 0.0500 \text{ dm}^3 =$ 0.0500 mol

Zn = $\frac{0.0459}{1}$ = 0.0459 HCl = $\frac{0.0500}{2}$ = 0.0250

HCl is the limiting reactant and Zn is the excess reactant.

(b) Determine the amount of excess reactant that remains at the end of the reaction.

Molar ratio of Zn to HCl is 1:2

0.0500 mol HCl × $\frac{1 \text{ mol Zn}}{2 \text{ mol HCl}}$ = 0.0250 mol Zn

n(Zn) remaining = 0.0459 – 0.0250 = 0.0209 mol

(c) 30.0 g of ammonium nitrate (NH_4NO_3) and 50.0 g of sodium phosphate (Na_3PO_4) are reacted together. Determine the limiting and excess reactants.

$$3NH_4NO_3 + Na_3PO_4 \rightarrow (NH_4)_3PO_4 + 3NaNO_3$$

M (NH_4NO_3) = 80.04 g mol^{-1}
M (Na_3PO_4) = 163.94 g mol^{-1}

$n(NH_4NO_3) = \frac{30.0}{80.04}$ = 0.375 mol 0.375 ÷ 3 = 0.125

$n(Na_3PO_4) = \frac{50.0}{163.94}$ = 0.305 mol 0.305 ÷ 1 = 0.305

NH_4NO_3 is the limiting reactant, Na_3PO_4 is the excess reagent

Reactivity 2.1.4

Understandings:

- The percentage yield is calculated from the ratio of experimental yield to theoretical yield.

Learning outcomes:

- Solve problems involving reacting quantities, limiting and excess reactants, theoretical, experimental and percentage yields.

Theoretical yield and percentage yield

- The theoretical yield is the maximum amount of product that can be formed in a chemical reaction (based on the stoichiometry of the reaction and amount of the limiting reactant).
- The actual yield is the actual amount of product that is formed in a chemical reaction.
- The percentage yield is the actual yield divided by the theoretical yield.

$$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\ \%$$

Exercises:

1) A 15.0 g sample of pure K_2O produces 7.62 g of K_2CO_3. Determine the percentage yield of K_2CO_3 in the reaction.

$$4K_2O(s) + 2CO_2(g) \rightarrow 2K_2CO_3(s) + 3O_2(g)$$

$n(K_2O) = \frac{15.0}{94.20} = 0.159$ mol

$0.159 \div 2 = 0.0796$ mol K_2CO_3

$0.0796 \times 138.19 = 11.0$ g K_2CO_3

$\%\ \text{yield} = \frac{7.62}{11.0} = 69.3\%$

2) Aluminium reacts with excess oxygen according to the following equation. Determine the percentage yield if 20.0 g of Al reacts with oxygen to produce 32.7 g of Al_2O_3.

$$4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$$

$n(Al) = \frac{20.0}{26.98} = 0.741$ mol

$0.741 \div 2 = 0.371$ mol Al_2O_3

$0.371 \times 101.96 = 37.8$ g Al_2O_3

$\%\ \text{yield} = \frac{32.7}{37.8} \times 100 = 86.5\%$

3) A 20.0 g sample of pure Fe_3O_4 produces 5.98 g of Fe. Determine the percentage yield of Fe in the reaction.

$$Fe_3O_4(s) + 4H_2(g) \rightarrow 3Fe(s) + 4H_2O(l)$$

$n(Fe_3O_4) = \frac{20.0}{231.54} = 0.0864$ mol

$0.0864 \times 3 = 0.259$ mol Fe

$0.259 \times 55.85 = 14.5$ g Fe

$\%\ \text{yield} = \frac{5.98}{14.5} = 41.2\%$

4) 100.0 g of iron(II) oxide is reacted with 100.0 g of carbon. 46.73 g of iron is produced. Calculate the % yield of Fe.

$$2Fe_2O_3(s) + 3C(s) \rightarrow 4Fe(s) + CO_2(g)$$

$n(Fe_2O_3) = \frac{100.0\ \text{g}}{159.70\ \text{g mol}^{-1}} = 0.6262$ mol

$n(C) = \frac{100.0\ \text{g}}{12.01\ \text{g mol}^{-1}} = 8.326$ mol

$Fe_2O_3 = \frac{0.6262}{2} = 0.3131$

$C = \frac{8.326}{3} = 2.775$

Fe_2O_3 is the limiting reactant and C is the excess reactant.

Molar ratio of Fe_2O_3 to Fe is 2:4

0.6262 mol $Fe_2O_3 \times \frac{4\ \text{mol Fe}}{2\ \text{mol}\ Fe_2O_3} = 1.252$ mol Fe

$m(Fe) = 1.252\ \text{mol} \times 55.85\ \text{g mol}^{-1} = 69.92$ g

Theoretical yield of Fe = 69.92 g

$$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\ \%$$

$$\text{Percent yield} = \frac{46.73\ \text{g}}{69.92\ \text{g}} \times 100\ \%$$

$$\text{Percent yield} = 66.8\ \%$$

5) 15.0 g of $CaCO_3$ is reacted with 50.0 cm^3 of 2.00 mol dm^{-3} HCl. 1.85 g of CO_2 is produced. Calculate the % yield of CO_2.

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

$n(CaCO_3) = \frac{15.0\ \text{g}}{100.09\ \text{g mol}^{-1}} = 0.150$ mol

$n(HCl) = 2.00\ \text{mol dm}^{-3} \times 0.0500\ \text{dm}^3 = 0.100$ mol

$CaCO_3 = \frac{0.150}{1} = 0.150$

$HCl = \frac{0.100}{2} = 0.0500$

HCl is the limiting reactant and $CaCO_3$ is the excess reactant.

Molar ratio of HCl to CO_2 is 2:1

$0.100\ \text{mol HCl} \times \frac{1\ \text{mol CO}_2}{2\ \text{mol HCl}} = 0.0500\ \text{mol CO}_2$

$m(CO_2) = 0.0500\ \text{mol} \times 44.01\ \text{g mol}^{-1} = 2.20$ g

Theoretical yield of CO_2 = 2.20 g

$$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\ \%$$

$$\text{Percent yield} = \frac{1.85\ \text{g}}{2.20\ \text{g}} \times 100\ \%$$

$$\text{Percent yield} = 84.1\ \%$$

Reactivity 2.1.5

Understandings:

- The atom economy is a measure of efficiency in green chemistry.

Learning outcomes:

- Calculate the atom economy from the stoichiometry of a reaction.

Additional notes:

- Include discussion of the inverse relationship between atom economy and wastage in industrial processes.
- The equation for calculation of the atom economy is given in the data booklet.

Linking questions:

- Structure 2.4, Reactivity 2.2 The atom economy and the percentage yield both give important information about the "efficiency" of a chemical process. What other factors should be considered in this assessment?

Atom economy

- The atom economy of a chemical reaction is a measure of the amount of starting materials that become useful products.
- A high % atom economy means that the reaction has a high efficiency.

$$\%\text{ atom economy} = \frac{\text{molar mass of desired product}}{\text{molar mass of all reactants}} \times 100$$

How to calculate the atom economy for a reaction:

1) Calculate the sum of the molar masses of the reactants.
2) Calculate the molar mass of the desired product and multiply by the coefficient.
3) Calculate the % atom economy.

Example: Calculate the atom economy for the following reaction in which ethanol (C_2H_4O) is the desired product.

$$2C_2H_5OCl + Ca(OH)_2 \rightarrow 2C_2H_4O + CaCl_2 + 2H_2O$$

1) Calculate the sum of the molar masses of the reactants.
   $M(C_2H_5OCl) = 80.52\text{ g mol}^{-1}$ $M(Ca(OH)_2) = 74.10\text{ g mol}^{-1}$
   Sum of molar masses = $(2 \times 80.52) + 74.10 = 235.14\text{ g mol}^{-1}$
2) Calculate the molar mass of the desired product and multiply by the coefficient.
   $M(C_2H_4O) = 44.06\text{ g mol}^{-1}$ $2 \times 44.06 = 88.12$
3) Calculate the % atom economy.

$$\%\text{ atom economy} = \frac{88.12}{235.14} \times 100 = 37.5\%$$

Exercises:

1) Calculate the atom economy for the following reaction for making hydrogen (H_2) by reacting coal with steam. Comment on the efficiency of the reaction.

$$C(s) + 2H_2O(g) \rightarrow CO_2(g) + 2H_2(g)$$

$$\%\ \text{atom economy} = \frac{4.04}{48.05} \times 100 = 8.41\%$$

The reaction has a low atom economy which means it has a low efficiency and produces a high amount of waste.

2) Titanium is manufactured by reacting titanium(IV) chloride with magnesium. Calculate the atom economy for this method of producing titanium. Comment on the efficiency of the reaction.

$$TiCl_4(s) + 2Mg(s) \rightarrow Ti(s) + 2MgCl_2(s)$$

$$\%\ \text{atom economy} = \frac{47.87}{238.29} \times 100 = 20.1\%$$

The reaction has a low atom economy which means it has a low efficiency and produces a high amount of waste.