FACTFILE: GCSE CHEMISTRY: UNIT 1.7

Rewarding Learning

Quantitative chemistry

1.7.1 recall that the relative atomic mass (A_r) of an atom is the mass of the atom compared with that of the carbon-12 isotope, which has a mass of exactly 12, and demonstrate knowledge and understanding that it is a weighted mean of the mass numbers (linked to 1.1.12);

1.7.2 calculate relative formula mass (M_r) (relative molecular mass) of a compound and percentage of an element, by mass, in a compound;

1.7.3 demonstrate knowledge and understanding that chemical amounts are measured in moles and that the mass of one mole of a substance in grams is numerically equal to the relative formula mass;

1.7.4 convert the given mass of a substance to the amount of the substance in moles (and vice versa) by using the relative atomic or formula masses;

1.7.5 **demonstrate knowledge and understanding of the importance of scale in chemistry in terms of calculating moles from masses given in tonnes and kilograms, for example in industrial processes;**

1.7.6 **calculate the reacting masses of reactants or products, given a balanced symbol equation and using moles and simple ratio, including examples where there is a limiting reagent;**

1.7.7 calculate **the theoretical yield** and the percentage yield, of a chemical reaction given the actual yield;

1.7.8 recognise possible reasons why the percentage yield of a product is less than 100 %, including loss of product in separation from the reaction mixture, as a result of side reactions or because the reaction is reversible and may not go to completion;

1.7.9 demonstrate knowledge and understanding of the terms empirical formula, molecular formula, hydrated, anhydrous and water of crystallisation;

1.7.10 demonstrate knowledge and understanding that water of crystallisation can be removed by heating to constant mass and any thermal decomposition may be carried out to completion by heating to constant mass;

1.7.11 calculate the relative formula mass of compounds containing water of crystallisation;

1.7.12 calculate the percentage of water of crystallisation in a compound;

1.7.13 **determine the empirical formulae of simple compounds and determine the moles of water of crystallisation present in a hydrated salt from percentage composition, mass composition or experimental data.**

Relative atomic mass (A_r)

The relative atomic mass is a weighted mean mass of the isotopes of an element compared with that of the carbon-12 isotope, which has a mass of exactly 12.

Relative formula mass (M_r)

The **relative formula mass** (M_r) (**relative molecular mass** for covalent substances) is the sum of the relative atomic mass of all the atoms present in the formula of a substance.

Example

What is the relative formula mass of $Ca(NO_3)_2$?

$M_r = 1 \times A_r\,Ca + 2 \times A_r\,N + 6 \times A_r\,O$

$= 40 + 2 \times 14 + 6 \times 16 = 164$

Finding the percentage of an element by mass in a compound.

$$\textbf{\% of an element in a compound} = \frac{\text{mass of element in the compound}}{\text{relative formula mass } (M_r)} \times 100$$

Example

Calculate the percentage by mass of oxygen in Na_2SO_4

Answer

$M_r = 2 \times A_r\,(Na) + A_r\,(S) + 4 \times A_r\,(O)$
$= 2 \times 23 + 32 + 4 \times 16$
$= 142$

$$\text{\% of O in } Na_2SO_4 = \frac{\text{mass of element in the compound}}{\text{relative formula mass } (M_r)} \times 100 = \frac{64}{142} \times 100 = 45.1\%$$

The mole

Chemical amounts are measured in moles. The mass of one mole of a substance in grams is numerically equal to the relative formula mass

$$\text{moles} = \frac{\text{mass (g)}}{\text{relative formula mass } (M_r)}$$

Example

Calculate the number of moles in 100 g of $Ca(OH)_2$.

Answer

$M_r\ Ca(OH)_2 = 40 + 2 \times 16 + 2 \times 1 = 74$

$$\text{Number of moles} = \text{mass (g)} = \frac{\text{mass (g)}}{M_r} = \frac{100}{74} = 1.35 \text{ mol}$$

Mass in g = moles × M_r

Example

Calculate the mass, in grams of 20 moles of CO_2.

Answer

M_r CO_2 = 1 × 12 + 2 × 16 = 44

Mass = moles × M_r = 20 × 44 = 880 g

Converting units

To calculate number of moles the mass **must always be in grams**. You must be able to covert from other mass units such as kilograms (kg) and tonnes (t).

1 tonne (1 t) = 1000 kg
1 kg = 1000 g

Example

Calculate the number of in moles, present in 9.8 kg of H_2SO_4

Answer

$$\text{moles} = \frac{\text{mass (g)}}{M_r}$$

First convert the mass from kg to g by multiplying by 1000

9.8 × 1000 = 9800 g

M_r = 2 × 1 + 32 + 4 × 16 = 98

$$\text{moles} = \frac{\text{mass (g)}}{M_r} = \frac{9800}{98} = 100 \text{ mol}$$

Molar ratios in equations

The balancing numbers in a chemical equation give the **ratio** of moles which react together.

For example 2 moles of calcium react with one mole of oxygen to produce 2 moles of calcium oxide.

$$2Ca + O_2 \longrightarrow 2CaO$$

The ratio is 2 moles Ca : 1 mole O_2 : 2 moles CaO

The ratio can be used to calculate the number of moles which would react, and be produced in any one equation.

Example

In the reaction
$2Cu(NO_3)_2 \longrightarrow 2CuO + 4NO_2 + O_2$

How many moles of copper(II) nitrate are needed to produce 0.4 moles of oxygen O_2?

Answer

$Cu(NO_3)_2$: O_2
Ratio 2 : 1
? : 0.4

There are twice as many moles of copper(II) nitrate as oxygen so multiply by 2.

$0.4 \times 2 = 0.8$ moles of $Cu(NO_3)_2$

Calculating reacting masses of reactant and products.

- Write the information (mass) given in the question, underneath the equation.
- Calculate the relative formula mass (M_r) of the substance you have information about and calculate the number of moles. (Remember that the balancing numbers in the equation are **not** part of the formulae).
- Use the ratio from the balanced equation to calculate the number of moles of the substance you need to find the mass of.
- Calculate the mass of the substance. (using mass = moles × M_r)

Example

What mass of magnesium oxide reacts with 3.65 g of HCl?

$\underline{MgO} + 2HCl \longrightarrow MgCl_2 + H_2O + CO_2$

3.65g

M_r HCl = 1 + 35.5 = 36.5

$$\text{moles HCl} = \frac{\text{Mass (g)}}{M_r} = \frac{3.65}{36.5} = 0.1 \text{ mol}$$

ratio 2 HCl : 1 MgO

$$0.1 : \frac{0.1}{2}$$

0.1 : 0.05

M_r MgO = 24 + 16 = 40

mass MgO = moles × M_r = 0.05 × 40 = 2 g

Limiting reactant

In a chemical reaction between two reactants if one reactant is in excess the other reactant is the **limiting reactant** and is completely used up.

Example

Iron(III) oxide reacts with carbon monoxide as shown below to produce iron. 10 moles of iron oxide (Fe_2O_3) is reacted with 40 moles of carbon monoxide (CO).

$Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2$

Which reactant is in excess? Calculate the number of moles of iron formed.

Answer

If there are 10 moles of iron(III) oxide, then according to the ratio (3 × 10) = 30 moles of CO are needed to completely react with it. There are 40 moles of CO present so there are 10 moles of CO in excess. The iron oxide is the limiting reactant and is completely used up. One mole of iron(III) oxide produces two moles of iron, so 10 moles of iron(III) oxide produces 20 moles of iron.

Percentage yield

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

There are many reasons why the percentage yield is less than 100%.

1. Some of the product may be lost when it is separated from the reaction mixture. It may be left on the apparatus. This is often called loss by mechanical transfer.
2. Side reactions may occur.
3. Some reactions are reversible and do not go to completion.

Example

In a reaction to produce a compound, the theoretical yield was 20 g, but the mass of compound produced was 5 g. Calculate the percentage yield of the compound.

Answer

$$\text{Percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100 = \frac{5}{20} \times 100 = 20\ \%$$

The **theoretical yield** can be worked out using the method of reacting mass calculations.

Example

Calculate the theoretical yield of calcium chloride when 5.6 g of calcium oxide reacts with excess hydrochloric acid. If 6 g of calcium chloride is produced calculate the percentage yield.

Answer

$CaO + 2HCl \rightarrow CaCl_2 + H_2O$

5.6g

M_r CaO = 40 + 16 = 56

$$\text{Moles CaO} = \text{moles} = \frac{\text{mass (g)}}{M_r} = \frac{5.6}{56} = 0.1\text{ mol}$$

Ratio 1 CaO : 1 $CaCl_2$

0.1 : 0.1

M_r $CaCl_2$ = 40 + 35.5 × 2 = 111

mass = moles × M_r = 0.1 × 111 = 11.1 g

Theoretical yield = 11.1 g

$$\text{Percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100 = \frac{6}{11.1} \times 100 = 54.1\ \%$$

Empirical formula and molecular formula

The empirical formula is the simplest whole number ratio of atoms of each element in a compound.

The molecular formula shows the actual number of atoms of each element present in a compound. It will be a simple multiple of the empirical formula.

For example:
molecular formula = C_4H_8 empirical formula = CH_2

molecular formula = CH_4 empirical formula = CH_4

To find the molecular formula from the empirical formula the relative formula mass is needed.

Example
A compound has relative formula mass 42 and empirical formula CH_2. What is the molecular formula of the compound?

Answer
A molecular formula is a multiple (n) of the empirical formula

$(CH_2)n = 42$

$(12 + 2 \times 1)n = 42$

$14n = 42$

$n = 3$

$(CH_2)n = (CH_2)3 = C_3H_6$

Finding empirical formula.

1. Find the number of moles of each element in the compound using moles = $\dfrac{\text{mass (g)}}{A_r}$
2. Find the simplest ratio of moles (divide all the moles values by the smallest number of moles)

Example
Find the empirical formula of a compound which contains 50.05 % sulfur, 49.95% oxygen

Answer
In a sample of 100g of this compound there is 50.05 g of sulfur and 49.95 g of oxygen.

	sulfur	oxygen
Mass in grams	50.05	49.95
Moles = mass/A_r	$\frac{50.05}{32} = 1.56$	$\frac{49.95}{16} = 3.12$
Simplest ratio – divide by smallest number of moles (1.56)	$\frac{1.56}{1.56} = 1$	$\frac{3.12}{1.56} = 2$
Ratio	1	2
Formula	SO_2	

Water of crystallisation

Water of crystallisation is water which is chemically bonded into the crystal structure. Hydrated means the crystals contains water of crystallisation, and anhydrous means the substance does not contain water of crystallisation.

For example hydrated copper(II) sulfate contains five molecules of water of crystallisation for every one of copper(II) sulfate, the degree of hydration is five and the empirical formula is written $CuSO_4.5H_2O$. When finding the relative formula mass of compounds containing water of crystallisation, the mass of the molecules of water of crystallisation must be included.

% water of crystallisation in compound $= \dfrac{\text{degree of hydration} \times M_r \text{ of water}}{M_r \text{ of the hydrated compound}} \times 100$

Example

Calculate the percentage of water of crystallisation in $CuSO_4.5H_2O$

Answer

M_r $CuSO_4.5H_2O = 64 + 32 + 4 \times 16 + 5 \times 18 = 250$

% water of crystallisation in compound $= \dfrac{\text{degree of hydration} \times M_r \text{ of water}}{M_r \text{ of the hydrated compound}} \times 100$

water of crystallisation in compound $= \dfrac{5 \times 18}{250} \times 100 = 36\ \%$

Experimental determination of mass of water of crystallization in hydrated crystals

Water of crystallisation can be removed by heating to constant mass.

hydrated copper(II) sulfate	→	anhydrous copper(II) sulfate	+	water
$CuSO_4.5H_2O$	→	$CuSO_4$	+	$5H_2O$

To heat to constant mass

- Weigh the solid and container
- Heat for a few minutes, cool then weigh
- Repeat this until the mass does not change (at this point all of the water of crystallisation has been removed)

Example. In an experiment to find the mass of water of crystallisation in hydrated magnesium chloride $MgCl_2.xH_2O$ the following results were obtained

Mass of empty crucible = 13.87g

Mass of crucible and hydrated magnesium chloride = 15.90g

Mass of crucible and anhydrous magnesium chloride = 14.82g

(i) Calculate the mass of the anhydrous magnesium chloride
(ii) Calculate the number of moles of anhydrous magnesium chloride

(iii) Calculate the mass of water of crystallisation removed

(iv) Calculate the number of moles of water of crystallisation removed

(v) Find x in the formula $MgCl_2.xH_2O$

Answer

(i) To calculate the mass of anhydrous magnesium chloride, subtract the mass of the crucible (13.87 g) from the mass of the crucible and the anhydrous magnesium chloride (14.82 g)

14.82 – 13.87 = 0.95 g

(ii) M_r of anhydrous magnesium chloride = 24 + 2 × 35.5 = 95

$$\text{moles of anhydrous magnesium chloride} = \frac{\text{mass (g)}}{M_r} = \frac{0.95}{95} = 0.01 \text{ mol}$$

(iii) To calculate the mass of water, subtract the mass of the crucible and anhydrous magnesium chloride (14.82 g) from the mass of the crucible and hydrated magnesium chloride (15.90 g)

15.90 – 14.82 = 1.08 g

(iv) M_r of water = 18

$$\text{moles} = \frac{\text{mass (g)}}{M_r} = \frac{1.08}{18} = 0.06 \text{ mol}$$

(v)

	$MgCl_2$	H_2O
moles	0.01	0.06
ratio	1	6
formula	$MgCl_2.6H_2O$	

The value of x is 6

Thermal decomposition by heating to constant mass

Thermal decomposition is the breakdown of a solid using heat.

Sometimes a substance such as carbonates thermally decompose by the action of heat to produce a solid and a gas, which is released to the air and the mass decreases. To ensure the thermal decomposition goes to completion the solid is heated to constant mass. This means the solid is weighed, heated, cooled and reweighed until the mass no longer changes.

Revision Questions

2016 C1 Q 5

1. Magnesium compounds have many important and wide-ranging uses. Magnesium nitrate is used as a fertiliser and is also present in many cosmetics including hair conditioner.

(a) On heating, magnesium nitrate breaks down according to the equation below:

$$2Mg(NO_3)_2(s) \rightarrow 2MgO(s) + 4NO_2(g) + O_2(g)$$

(i) What term is used to describe a reaction in which a substance breaks down when heated?

____ [2]

(ii) Calculate the mass of nitrogen dioxide, NO_2, produced when 4.44 g of magnesium nitrate are heated.

[5]

(b) To find out the number of moles of water of crystallisation, a student heated some hydrated magnesium sulfate in a crucible and recorded the results in the table below.

mass of empty crucible	12.73 g
mass of crucible + hydrated magnesium sulfate	13.96 g
mass of crucible after heating for 5 minutes	13.56 g
mass of crucible after heating for 10 minutes	13.33 g
mass of crucible after heating for 15 minutes	13.33 g

(i) Explain why the student weighed the crucible and its contents several times during the heating process.

____

____ [1]

(ii) Calculate the mass of water of crystallisation lost.

_______________ g [1]

(iii) Calculate the number of moles of water of crystallisation lost.

_______________ [1]

(iv) Calculate the mass of the anhydrous magnesium sulfate.

_______________ g [1]

(v) Calculate the number of moles of anhydrous magnesium sulfate.

_______________ [1]

(vi) Using your answers to parts **(iii)** and **(v)**, calculate the number of moles of water of crystallisation contained in one mole of hydrated magnesium sulfate.

_______________ [2]

(iv) Hydrated aluminium oxide, $Al_2O_3.nH_2O$, may be used as an alternative abrasive.

To determine the degree of hydration in hydrated aluminium oxide 3.12 g of hydrated aluminium oxide were heated to constant mass. 2.04 g of anhydrous aluminium oxide remained.

Find the value of n in $Al_2O_3.nH_2O$.

[6]

2.

Tooth whitening is not a modern invention. Ancient Romans used urine and goats' milk to whiten their teeth. A chemical called urea which is present in the urine bleaches teeth.

(a) Urea contains 20.00 % carbon, 6.66 % hydrogen, 46.67 % nitrogen and 26.67 % oxygen. Determine the empirical formula of urea.

[5]

(b) Today, most teeth whitening kits contain the chemical carbamide peroxide which breaks down in the mouth into urea and hydrogen peroxide. During the bleaching process the hydrogen peroxide decomposes to produce water and oxygen.

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

Calculate the mass of oxygen produced from 5.1 g of hydrogen peroxide.

[5]

(c) Some whitening toothpastes contain hydrated silica, $SiO_2.2H_2O$, which acts as an abrasive to remove stains and polish teeth.

(i) Hydrated silica contains water of crystallisation. What is meant by the term water of crystallisation?

____

____

____ [2]

(ii) Calculate the percentage of water of crystallisation present in hydrated silica.

Percentage of water = ____________ % [3]