FACTFILE: GCSE CHEMISTRY: UNIT 2.6

Rewarding Learning

Quantitative Chemistry

Learning outcomes

Students should be able to:

2.6.1 **calculate the concentration of a solution in mol/dm³ given the mass of solute and volume of solution;**

2.6.2 **calculate the number of moles or mass of solute in a given volume of solution of known concentration;**

2.6.3 demonstrate knowledge and understanding that the volumes of acid and alkali solutions that react together can be measured by titration using phenolphthalein or methyl orange;

2.6.4 carry out acid-base titrations using an indicator and record results to one decimal place, repeating for reliability and calculating the average titre from accurate titrations (details of the practical procedure and apparatus preparation are required);

2.6.5 **collect data from primary and secondary sources for acid-base titration and use this data to calculate the concentrations of solutions in mol/dm³ and g/dm³;**

2.6.6 **calculate concentrations of solutions and solution volumes in an acid-base titration and identify unknown compounds and determine the degree of hydration;**

2.6.7 **recall that the volume of one mole of any gas at room temperature and pressure (20 °C and 1 atmosphere pressure) is 24 dm³;**

2.6.8 **recall and use Avogadro's Law as equal volumes of gases at the same temperature and pressure contains the same number of particles/molecules;**

2.6.9 **calculate the volumes of gaseous reactants and products from the balanced equation for a reaction;**

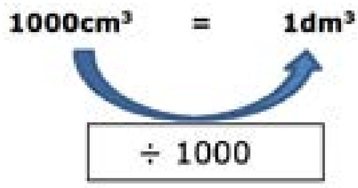
2.6.10 calculate the atom economy of a reaction to form a desired product from the balanced equation:

$$\text{Atom economy} = \frac{\text{mass of desired product}}{\text{total mass of products}} \times 100$$

2.6.11 **demonstrate knowledge and understanding that a high atom economy is important for sustainable development and economic reasons**;

Concentration of solutions

The concentration of a solution is a measure of how much of a substance is dissolved in a given volume of water. Concentration is usually quoted in the units mol/dm^3 or g/dm^3.

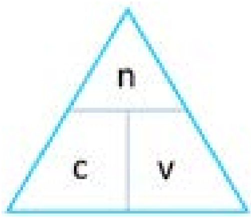


A concentrated solution will have a large number of particles of the solute in the solvent. A dilute solution will have a small number of particles of the solute in the solvent.

Concentration can be calculated using the following equation:

$$\text{concentration} = \frac{\text{number of moles}}{\text{volume (dm}^3\text{)}} \qquad c = \frac{n}{v}$$

This equation can be easily remembered using a triangle:



concentration = number of moles ÷ volume
number of moles = concentration × volume
volume = number of moles ÷ concentration

The units of concentration can be converted from mol/dm^3 to g/dm^3 using the following equation:

$$\textbf{mol/dm}^3 \times \textbf{RFM} = \textbf{g/dm}^3$$

Example

What is the concentration in mol/dm^3 of a solution containing 11.1 g of $CaCl_2$ dissolved in 500 cm^3 of water?

Step 1: calculate the number of moles of solute (from unit 1 moles = $\frac{\text{mass (g)}}{M_r}$)

$$\text{moles of } CaCl_2 = \frac{\text{mass (g)}}{M_r} = \frac{11.1}{111} = 0.1 \text{ mol}$$

Step 2: convert the volume into dm^3

$$\text{Volume} = \frac{500}{1000} = 0.5 \text{ dm}^3$$

Step 3: substitute the values into the equation

$$\text{concentration} = \frac{\text{number of moles}}{\text{volume (dm}^3\text{)}} = \frac{0.1}{0.5} = 0.2 \text{ mol/dm}^3$$

Titrations

A titration is a technique used to find the volume of one solution which will react with a known volume of a different solution (usually acid and base). It can also be used to find the concentration of an unknown solution. In a titration methyl orange or phenolphthalein indicator are used to determine the end point of the titration.

Indicator	Colour in acid	Colour in alkali
methyl orange	red	yellow
phenolphthalein	colourless	pink

Preparing the apparatus for a titration

Preparing a burette

- Rinse the burette with deionised water ensuring the water flows through the jet.
- This water should be discarded from the burette.
- Rinse the burette with the solution being measured out from the burette, again ensure this flows through the jet.
- This solution should be discarded from the burette.
- Fill the burette with the required solution to approximately 3 cm^3 above the zero mark. Open the tap and allow the solution to drain until the bottom of the meniscus is on the zero mark (this ensures the jet is filled).

Preparing a pipette

- Using a pipette filler, rinse the pipette using deionised water.
- This water should then be discarded from the pipette.
- Rinse the pipette with the solution being measured out from the pipette.
- This should then be discarded from the pipette.
- Fill the pipette with the required solution until the bottom of the meniscus lies on the fill line.

Carrying out the titration

- Prepare a burette by rinsing with deionised water and with its solution.
- Fill the burette with its solution, ensure the jet is full and record the initial reading from the burette, reading at the bottom of the meniscus.
- Prepare a pipette by rinsing with deionised water and the solution to be measured.
- Fill the pipette until the bottom of the meniscus is on the line and transfer the solution to a conical flask.
- Add a few drops of indicator to the solution in the conical flask.
- Add the solution from the burette to the conical flask with swirling until a permanent colour change is observed.
- Record the final reading on the burette and calculate the volume added – this will be the rough titre value.
- A further two titrations should be completed but the burette solution should be added drop-wise when

within 1 cm^3 of the rough titre value. These accurate titre values should be concordant – within 0.1 cm^3 of each other. If necessary continue to repeat the titration until concordant results are obtained.

Collecting results from a titration

A table of results must be completed during the titration. There are a number of key points to note when completing the table:

- Headings should include units;
- Values should be recorded to at least one decimal place;
- The rough titre value should be greater than the accurate titre values (no greater than 1 cm^3);
- Accurate titre values should be within 0.1 cm^3 of each other;
- The average titre value should be calculated using **only** the accurate titre values and stated to at least one decimal place.

	Rough	Accurate 1	Accurate 2
Initial burette reading (cm^3)			
Final burette reading (cm^3)			
Titre (cm^3)			

$$\text{Average titre} = \frac{\text{Accurate 1} + \text{Accurate 2}}{2}$$

Acid-Base titration calculation

The following results were obtained when 25.0 cm^3 of sodium hydroxide solution were titrated against 0.1 mol/dm^3 sulfuric acid.

	Rough	Accurate 1	Accurate 2
Initial burette reading (cm^3)	0.0	0.0	0.0
Final burette reading (cm^3)	22.5	21.7	21.6
Titre (cm^3)	22.5	21.7	21.6

$$\text{Average titre} = \frac{21.7 + 21.6}{2} = 21.65\ cm^3$$

The number of moles can be calculated from the volume in cm^3 and the concentration in mol/dm^3 using the expression:

$$\text{moles} = \frac{\text{volume } (cm^3) \times \text{concentration } (mol/dm^3)}{1000}$$

The data can be used to calculate the concentration of sodium hydroxide in g dm^{-3} using the following method:

1. Write an equation for the reaction:

$$H_2SO_4 + 2NaOH \longrightarrow Na_2SO_4 + 2H_2O$$

2. Use the average titre to find the number of moles of sulfuric acid used in the titration:

	H_2SO_4	2NaOH	Na_2SO_4	$2H_2O$
Ratio	1	2	1	2
Concentration (mol dm^{-3})	0.1			
Volume (cm^3)	21.65	25.0		
Moles	0.002165			

3. Use the ratio to find the number of moles of sodium hydroxide.

	H_2SO_4	2NaOH	Na_2SO_4	$2H_2O$
Ratio	1	2	1	2
Concentration (mol dm^{-3})	0.1			
Volume (cm^3)	21.65	25.0		
Moles	**0.002165**	0.00433		

4. Find the concentration of sodium hydroxide in mol dm^{-3} and then g dm^{-3}.

$$\text{concentration} = \frac{\text{number of moles} \times 1000}{\text{volume (cm}^3\text{)}}$$

$$c = \frac{n \times 1000}{v} = \frac{0.00433 \times 1000}{25.0} = 0.1732 \text{ mol/dm}^3$$

M_r of NaOH = 40.

Concentration in g/dm^3 = 0.01732 × 40 = 6.93 g/dm^3

Degree of hydration calculation

A 250 cm^3 solution contains 0.715 g of hydrated sodium carbonate ($Na_2CO_3.xH_2O$). 25.0 cm^3 of this solution was titrated against 0.05 mol/dm^3 hydrochloric acid and the average titre was determined to be 12.3 cm^3. Determine the value of x in $Na_2CO_3.xH_2O$.

1. Write an equation for the reaction:

$$2HCl + Na_2CO_3 \longrightarrow 2NaCl + H_2O + CO_2$$

2. Use the average titre to find the number of moles of hydrochloric acid used in the titration:

	2HCl	Na_2CO_3	2NaCl	H_2O	CO_2
Ratio	2	1	2	1	1
Concentration (mol dm^{-3})	0.05				
Volume (cm^3)	12.3	25.0			
Moles	**0.000615**				

3. Find the number of moles of hydrated sodium carbonate in the 25cm3 portion used in the titration.

	2HCl	Na_2CO_3	2NaCl	H_2O	CO_2
Ratio	2	1	2	1	1
Concentration (mol dm^{-3})	0.05				
Volume (cm^3)	12.3	25.0			
Moles	**0.000615**	**0.0003075**			

4. Use the moles value for 25.0 cm^3 and scale for a solution of 250 cm^3.

   25.0 cm^3 contained **0.0003075** moles of $Na_2CO_3.xH_2O$

   so 250 cm^3 will contain **0.0003075 × 10** = **0.003075** moles of $Na_2CO_3.xH_2O$

5. Using the moles in 250 cm^3 and the mass of hydrated sodium carbonate (from question) calculate the M_r of the hydrated salt.

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

$$M_r = \frac{0.715}{0.003075} = 232$$

   Therefore $Na_2CO_3.xH_2O$ has a total M_r of 232.

6. Subtract the M_r of Na_2CO_3 to the find the total M_r contributed by the water.

$$Na_2CO_3 = 106$$

$$232 – 106 = 126$$

   Therefore xH_2O = 126

7. Divide this M_r by 18 to find the number of water of crystallisation molecules present in the sample.

$$\frac{126}{18} = 7$$

Therefore x = 7 Formula = $Na_2CO_3.7H_2O$

Identifying an unknown compound calculation

The formula for an insoluble unknown metal hydroxide can be written as $M(OH)_2$. 3 g of solid $M(OH)_2$ is added to 50 cm^3 of 1 mol/dm^3 hydrochloric acid with stirring. Some solid $M(OH)_2$ is observed lying at the bottom. The solution was filtered and the residue washed with some water and dried. The mass of unreacted $M(OH)_2$ is 0.55 g.

(a) What mass of $M(OH)_2$ reacted with the hydrochloric acid?

Original mass = 3 g
Unreacted mass = 0.55 g
Reacted mass = 2.45 g

(b) Calculate the number of moles of hydrochloric acid used.

$$\text{moles} = \frac{\text{volume (cm}^3) \times \text{concentration (mol/dm}^3)}{1000} = \frac{50 \times 1}{1000} = 0.05 \text{ mol}$$

(c) Using the balanced symbol equation calculate the number of moles of $M(OH)_2$ required to react with the hydrochloric acid.

	$2HCl$	$M(OH)_2$	MCl_2	$2H_2O$
Ratio	2	1	1	2
Concentration (mol dm^{-3})	1			
Volume (cm^3)	50			
Moles	**0.05**	**0.025**		

Moles of $M(OH)_2$ = 0.025

(d) Calculate the RFM of $M(OH)_2$.

$$M_r = \frac{\text{mass (g)}}{\text{moles}} = \frac{2.45}{0.025} = 98$$

(e) Determine the relative atomic mass (A_r) of M.

$M(OH)_2$ = 98

$(OH)_2$ = 34

Therefore A_r of M = 98 – 34 = 64

A_r of M = 64

(f) Identify element M.

A_r of 64 indicates copper (Cu)

Gas volume calculations

Provided that the pressure and temperature are the same, equal volumes of gases contain the same number of molecules.

At room temperature and pressure (20 °C and 1 atm), 1 mole of any gas occupies a volume of 24 dm³ or 24000 cm³

$$\text{moles} = \frac{\text{gas volume (cm}^3\text{)}}{24000}$$

$$\text{moles} = \frac{\text{gas volume (dm}^3\text{)}}{24}$$

volume of gas (cm³) = moles × 24000

volume of gas (dm³) = moles × 24

Example

What volume of oxygen is required for the complete combustion of 11.5 g of sodium?

$$4Na + O_2 \rightarrow 2Na_2O$$

	4Na	O_2	$2Na_2O$
Ratio	4	1	2
mass	11.5		
M_r	23		
Moles	**0.5**	**0.125**	

4:1

number of moles of O_2 = 0.125

volume of gas = n × 24 V = 0.125 × 24 = 3 dm³

Volume of oxygen = 3 dm³

Reacting gas volumes

Avogadro's Law states that equal volumes of gas under the same condition of temperature and pressure contain the same number of molecules/particles/moles.

This means that gases will react in simple volume ratios.

Example

What volume of oxygen is required to react with 10 dm³ of methane to form carbon dioxide and water?

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

The ratio of methane to oxygen is 1:2. As volumes of gases can be used directly in this ratio as it is a gaseous reaction the volume of oxygen required is simply 10 × 2 = 20 dm³.

Atom Economy

Atom economy is essentially an efficiency calculation for a chemical reaction. It provides an indication of how much product is desired from the reaction and how much product is waste. The higher the atom economy of a reaction the 'greener' the process. Industrial processes need as high an atom economy as possible because it makes the process more sustainable and reduces the production of unwanted products – this saves on costs of disposal of these waste products.

Atom economy can be calculated using the following equation:

$$\text{Atom economy} = \frac{\text{mass of desired product}}{\text{total mass of products}} \times 100$$

Example

Iron is extracted from its ore using carbon. Find the atom economy of this reaction.

$$2Fe_2O_3 + 3C \longrightarrow 4Fe + 3CO_2$$

Step 1 – find the total M_r of iron atoms $4Fe = 4 \times 56 = 224$

Step 2 – find the total M_r of all products $4Fe = 224;\ 3CO_2 = 3 \times 44 = 132;$

$224 + 132 = 356$

Step 3 – use the equation to calculate the atom economy

$$\frac{224}{356} \times 100 = 62.9\%$$

REVISION QUESTIONS

1. 10.0 cm^3 of a solution of potassium hydroxide was titrated with a 0.10 mol/dm^3 solution of hydrochloric acid. 13.5 cm^3 of the acid was required for neutralisation. Calculate the concentration of the potassium hydroxide solution in g/dm^3.

$$KOH + HCl \rightarrow KCl + H_2O$$

[5]

2. To prepare aqueous calcium chloride, a student added the exact amount of calcium so that all the hydrochloric acid had reacted. They used 50 cm^3 of 2.0 mol/dm^3 hydrochloric acid. Write an equation to show the reaction of calcium with hydrochloric acid to make aqueous calcium chloride and calculate the mass of calcium that was required.

[5]

3. A student reacted 0.438 g of strontium with 200 cm^3 of water.

$$Sr(s) + 2H_2O(l) \longrightarrow Sr(OH)_2(aq) + H_2(g)$$

(i) Calculate how many moles of Sr were reacted.

[2]

(ii) Calculate the volume, in dm^3, of $H_2(g)$ produced.

[2]

(iii) Calculate the concentration, in mol/dm^3, of the $Sr(OH)_2$ produced.

[2]

4. 3.686 g of an acid HX were dissolved in water and made up to 250 cm^3. 25.0 cm^3 of this solution was titrated against a solution of 0.0614 mol/dm^3 sodium carbonate solution, Na_2CO_3, and 23.45 cm^3 were required to reach the end point. Calculate the relative formula mass (M_r) of the acid.

$$Na_2CO_3 + 2HX \longrightarrow 2NaX + CO_2 + H_2O$$

[5]

5. 1.22 g of hydrated sodium carbonate ($Na_2CO_3.xH_2O$) were dissolved in 100 cm^3 of water. 25.0 cm^3 of this solution were titrated against 0.10 mol/dm^3 HCl and the following results were obtained:

	Rough	Accurate 1	Accurate 2
Initial burette reading (cm^3)	0.0	0.0	0.2
Final burette reading (cm^3)	22.0	21.3	21.6
Titre (cm^3)	22.0	21.3	21.4

The equation for this reaction is:

$$Na_2CO_3 + 2HCl \longrightarrow 2NaCl + CO_2 + H_2O$$

Calculate x in $Na_2CO_3.xH_2O$.

[6]

6. Calculate the atom economy when sodium is made from sodium chloride.

$$2NaCl \rightarrow 2Na + Cl_2$$

[3]

7. Calculate the atom economy when hydrogen is produced from the reaction of zinc and hydrochloric acid.

$$Zn + 2HCl \rightarrow ZnCl_2 + H_2$$

[3]

8. Magnesium reacts with hydrochloric acid according to the equation:

$$Mg + 2HCl \rightarrow MgCl_2 + H_2$$

Calculate the mass of magnesium required to produce 100 cm^3 of hydrogen gas, assuming the acid is in excess.

[3]