Introduction

This is the first of hopefully two booklets written to teach the calculations for National 5 Chemistry as taught in Scotland. The first booklet will describe methods for these calculations and give a few 'Self-Check' problems. The 2nd booklet will be questions extracted from previous exam papers (Standard Grade & Intermediate 2) to show the questions in context.

It is assumed that you already know how to do the following:

- write formulae for any kind of compound
- write & balance equations
- be able to find relative atomic masses (RAM) in a data booklet

Contents

1. Formula Mass
2. Percentage Composition
3. Molar Mass (gfm)
4. Molar Calculations
5. Using Balanced Equations
6. Concentration of Solutions
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Answers

Test Yourself 10

Calculate the concentration (in \( \text{mol l}^{-1} \)) of the first named solution from the given results of a titration.

a) 25 cm\(^3\) of sodium hydroxide reacts with 21.0 cm\(^3\) of a 0.2 mol \( \text{l}^{-1} \) hydrochloric acid

\[
\text{NaOH} + \text{HCl} \rightarrow \text{NaCl} + \text{H}_2\text{O}
\]

b) 25 cm\(^3\) of sodium hydroxide reacts with 17.0 cm\(^3\) of a 0.1 mol \( \text{l}^{-1} \) sulphuric acid

\[
2\text{NaOH} + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O}
\]

c) 20 cm\(^3\) of hydrochloric acid reacts with 23.6 cm\(^3\) of a 0.1 mol \( \text{l}^{-1} \) sodium hydroxide

\[
\text{NaOH} + \text{HCl} \rightarrow \text{NaCl} + \text{H}_2\text{O}
\]

d) 25 cm\(^3\) of nitric acid reacts with 15.0 cm\(^3\) of a 0.2 mol \( \text{l}^{-1} \) ammonia (ammonium hydroxide)

\[
\text{NH}_4\text{OH} + \text{HNO}_3 \rightarrow \text{NH}_4\text{NO}_3 + \text{H}_2\text{O}
\]

e) 10 cm\(^3\) of calcium hydroxide reacts with 17.6 cm\(^3\) of a 0.02 mol \( \text{l}^{-1} \) sulphuric acid

\[
\text{Ca(OH)}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 + 2\text{H}_2\text{O}
\]

f) 25 cm\(^3\) of potassium hydroxide reacts with 21.0 cm\(^3\) of a 0.2 mol \( \text{l}^{-1} \) sulphuric acid

\[
2\text{KOH} + \text{H}_2\text{SO}_4 \rightarrow \text{K}_2\text{SO}_4 + 2\text{H}_2\text{O}
\]
Method 3: most suitable if
- equation is given
- question is not in parts

In general we titrate to balance the acidity and alkannity. Sometimes it is as simple as:

\[ \text{moles of acid} = \text{moles of alkali} \]

\[ \boxed{\frac{C_{\text{acid}} \times V_{\text{acid}}}{n_{\text{acid}}} = \frac{C_{\text{alk}} \times V_{\text{alk}}}{n_{\text{alk}}}} \]

but, as equations show, only sometimes are the moles of acid and moles of alkali equal.

\[ \text{HCl} + \text{NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 3\text{H}_2\text{O} \]

\(1 \text{ mole of acid} = 1 \text{ mole of alkali}\)

often, they are not

\[ \text{H}_2\text{SO}_4 + 2 \text{ NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 3\text{H}_2\text{O} \]

\(1 \text{ mole of acid (} n_{\text{acid}}\text{)} = 2 \text{ moles of alkali (} n_{\text{alk}}\text{)}\)

We can allow for this by including an extra term in our equation

\[ \boxed{\frac{C_{\text{acid}} \times V_{\text{acid}}}{n_{\text{acid}}} = \frac{C_{\text{alk}} \times V_{\text{alk}}}{n_{\text{alk}}}} \]

This is the 'preferred' method for N5 exams and this is the formula given in the Data Book.

**1. Formula Mass - all Units**

The Formula Mass of a substance is exactly what it says: it is the combined mass of all the atoms you can see in the formula for that substance. It can be done as follows:

- write formula (this is often done for you)
- determine number of atoms of each element
- use Data Book to find relative atomic masses (RAM)
- calculate total mass of substance

**Worked Example:** copper (II) carbonate \(\text{CuCO}_3\)

\[ 1 \times \text{Cu} = 1 \times 64 = 64 \]
\[ 1 \times \text{C} = 1 \times 12 = 12 \quad \text{formula mass} = 124 \text{ amu} \]
\[ 3 \times \text{O} = 3 \times 16 = 48 \]
\[ \frac{124}{124} \]

Notice the units are amu (atomic mass units)

where:

\[ 1 \text{ amu} = \text{mass of a proton} \]

**Test Yourself 1**

Calculate the Formula Mass of each of these substances.

- **a)** sodium sulphate \(\text{Na}_2\text{SO}_4\)
- **b)** magnesium nitrate \(\text{Mg(NO}_3\text{)}_2\)
- **c)** aluminium oxide \(\text{Al}_2\text{O}_3\)
- **d)** glucose \(\text{C}_6\text{H}_{12}\text{O}_6\)
- **e)** sulphuric acid \(\text{H}_2\text{SO}_4\)
- **f)** ammonium nitrate \(\text{NH}_4\text{NO}_3\)
- **g)** calcium hydroxide \(\text{Ca(OH)}_2\)
- **h)** marble \(\text{CaCO}_3\)
- **i)** water \(\text{H}_2\text{O}\)
- **j)** butane \(\text{C}_4\text{H}_{10}\)
- **k)** copper \(\text{Cu}\)
- **l)** salt \(\text{NaCl}\)
- **m)** ammonia \(\text{NH}_3\)
- **n)** ethanol \(\text{C}_2\text{H}_5\text{OH}\)
Very often we are only interested in one particular element within a compound. We may also want to compare different compounds. This is best done if we express the amount of an element as a percentage.

- write formula (this is often done for you)
- calculate total mass of the substance (Formula Mass)
- calculate (notice) what part is due to specific element
- express as a % using:

\[
\% \text{ Element} = \left( \frac{\text{mass of element}}{\text{formula mass}} \right) \times 100
\]

**Worked Example:** potassium sulphate \( \text{K}_2\text{SO}_4 \)

\[
\begin{align*}
2 \times \text{K} & = 2 \times 39 = 78 \quad \text{formula mass} = 174 \text{ amu} \\
1 \times \text{S} & = 1 \times 32 = 32 \\
4 \times \text{O} & = 4 \times 16 = 64 \quad \% \text{K} = \left( \frac{78}{174} \right) \times 100 \\
& = 44.8 \%
\end{align*}
\]

**Method 2:** most suitable if

- equation is **not** given / written
- question is **not** in parts

At the end-point, where the indicator changes colour, the solution is neutralised so:

\[
\begin{align*}
\text{moles of H}^+ \text{ ions} & = \text{moles of OH}^- \text{ ions} \\
\text{\textit{n}}_{\text{H}^+} & = \text{\textit{n}}_{\text{OH}^-}
\end{align*}
\]

\[
\begin{align*}
\text{\textit{n}}_{\text{ACID}} & = \text{\textit{C}}_{\text{ACID}} \times \text{\textit{V}}_{\text{ACID}} \\
\text{\textit{n}}_{\text{ALK}} & = \text{\textit{C}}_{\text{ALK}} \times \text{\textit{V}}_{\text{ALK}}
\end{align*}
\]

but, each acid has a different number of \( \text{H}^+ \) ions each alkali has a different number of \( \text{OH}^- \) ions

\[
\begin{align*}
\text{HCl,} & \quad \text{\textit{P}}_{\text{ACID}} = 1 \\
\text{H}_2\text{SO}_4, & \quad \text{\textit{P}}_{\text{ACID}} = 2 \\
\text{H}_3\text{PO}_4, & \quad \text{\textit{P}}_{\text{ACID}} = 3
\end{align*}
\]

\[
\begin{align*}
\text{\textit{n}}_{\text{H}^+} & = \text{\textit{C}}_{\text{ACID}} \times \text{\textit{V}}_{\text{ACID}} \times \frac{\text{\textit{P}}_{\text{ACID}}}{1} \\
\text{\textit{n}}_{\text{OH}^-} & = \text{\textit{C}}_{\text{ALK}} \times \text{\textit{V}}_{\text{ALK}} \times \frac{\text{\textit{P}}_{\text{ALK}}}{1}
\end{align*}
\]

\[
\begin{align*}
\text{\textit{C}}_{\text{ACID}} \times \text{\textit{V}}_{\text{ACID}} \times \text{\textit{P}}_{\text{ACID}} & = \text{\textit{C}}_{\text{ALK}} \times \text{\textit{V}}_{\text{ALK}} \times \frac{\text{\textit{P}}_{\text{ALK}}}{1}
\end{align*}
\]

**Test Yourself 2** Calculate the following % compositions.

a) % sodium in sodium sulphate \( \text{Na}_2\text{SO}_4 \)

b) % magnesium in magnesium nitrate \( \text{Mg(NO}_3\text{)}_2 \)

c) % aluminium in aluminium oxide \( \text{Al}_2\text{O}_3 \)

d) % carbon in glucose \( \text{C}_6\text{H}_{12}\text{O}_6 \)

e) % sulphur in sulphuric acid \( \text{H}_2\text{SO}_4 \)

f) % nitrogen in ammonium nitrate \( \text{NH}_4\text{NO}_3 \)

g) % calcium in calcium hydroxide \( \text{Ca(OH)}_2 \)

**Worked Example:** it took 12.5 cm\(^3\) of 0.2 M NaOH to neutralise 10 cm\(^3\) of \( \text{H}_2\text{SO}_4 \). Calculate the concentration of the acid.

use

\[
\begin{align*}
\text{\textit{C}}_{\text{ACID}} \times \text{\textit{V}}_{\text{ACID}} \times \frac{\text{\textit{P}}_{\text{ACID}}}{1} & = \text{\textit{C}}_{\text{ALK}} \times \text{\textit{V}}_{\text{ALK}} \times \frac{\text{\textit{P}}_{\text{ALK}}}{1}
\end{align*}
\]

\[
\begin{align*}
\text{\textit{C}}_{\text{ACID}} \times 10 \times 2 & = 0.2 \times 12.5 \times 1 \\
\text{\textit{C}}_{\text{ACID}} \times \frac{20}{2} & = 2.5 \\
\text{\textit{C}}_{\text{ACID}} & = \frac{2.5}{20} = 0.125 \text{ M}
\end{align*}
\]
7. Titrations - Unit 1

A Titration is a practical method of using one chemical of known concentration to determine the unknown concentration of another. Usually the chemicals are acids (containing \( H^+ \) ions) and alkalis (containing \( OH^- \) ions).

At the end-point, where the indicator changes colour, the solution is neutralised so:

\[
\text{moles of } H^+ \text{ ions } = \text{moles of } OH^- \text{ ions}
\]

**Worked Example:** it took 12.5 cm\(^3\) of 0.2 M \( NaOH \) to neutralise 10 cm\(^3\) of sulphuric acid. Calculate the concentration of the acid.

**Method 1:** most suitable if
- equation is given / written
- question is broken into parts

**Step 1:** start with 'known' - know the concentration and the volume - calculate number of moles

\[
\begin{align*}
\text{n} &= \text{C} \times \text{V} \\
n &= 0.2 \times 0.0125 \ (12.5 \text{ cm}^3 \text{ in litres}) \\
n &= 0.0025 \text{ moles of } NaOH
\end{align*}
\]

**Step 2:** convert to 'unknown' - use balanced equation to convert to number of moles of other chemical.

\[
2 \text{NaOH} + H_2SO_4 \rightarrow Na_2SO_4 + 3H_2O
\]

2 mole \( \rightarrow \) 1 mole

0.0025 \( \rightarrow \) 0.00125 moles of \( H_2SO_4 \)

**Step 3:** calculate concentration of 'unknown'

\[
\begin{align*}
\text{C} &= \text{n} / \text{V} \\
\text{C} &= 0.00125 / 0.010 \ (10 \text{ cm}^3 \text{ in litres}) \\
\text{C} &= 0.125 \text{ moles} / l \ (0.125 \text{ M})
\end{align*}
\]

3. Molar Mass (gFM) - Unit 1

This is a very simple, but very significant, step in many calculations and should present no extra problems. Quite simply you

- calculate formula mass (in amu)
- convert to molar mass by converting to grammes

\[
\text{mass of 1 mole} = \text{formula mass in grammes} = \text{gFM}
\]

**Worked Example:** potassium sulphate \( K_2SO_4 \)

\[
\begin{align*}
2 \times K &= 2 \times 39 &= 78 \quad \text{formula mass} = 174 \text{ amu} \\
1 \times S &= 1 \times 32 &= 32 \\
4 \times O &= 4 \times 16 &= 64 \quad \text{Molar Mass} = 174 \text{ g} \\
& & 174 \quad 1 \text{ mole} = 174 \text{ g}
\end{align*}
\]

For the purposes of doing calculations it is enough to learn to perform this step. In the context of understanding Chemistry, it is important that you appreciate what 'a mole' actually is. Your teacher may explain further.

**Test Yourself 3** Calculate the mass of 1 mole for each substance below.

a) copper sulphate \( \text{CuSO}_4 \)

b) potassium nitrate \( \text{KNO}_3 \)

c) nickel(III) sulphide \( \text{Ni}_2\text{S}_3 \)

d) sucrose \( \text{C}_{12}\text{H}_{22}\text{O}_{11} \)

e) nitric acid \( \text{HNO}_3 \)

f) ammonium sulphate \( (\text{NH}_4)_2\text{SO}_4 \)

g) pearl ash \( \text{K}_2\text{O} \)

h) carbon dioxide \( \text{CO}_2 \)

i) ethane \( \text{C}_2\text{H}_6 \)

j) oxygen \( \text{O}_2 \)

k) methanol \( \text{CH}_3\text{OH} \)

l) iron (III) nitrate \( \text{Fe(NO}_3)_3 \)
4. Molar Calculations - Unit 1

Typically, we start by weighing out chemicals but to allow us to compare the amounts of chemicals present we need to convert from masses to moles. Again, we start by

- calculating formula mass (in amu)
- converting to molar mass by converting to grammes

\[ \text{number of moles} = \frac{\text{mass of chemical}}{\text{gfm}} \]

Worked Example: 148g of \( \text{Ca(OH)}_2 \)

\[
\begin{align*}
1 \times \text{Ca} & = 1 \times 40 = 40 \\
2 \times \text{O} & = 2 \times 16 = 32 \\
2 \times \text{H} & = 2 \times 1 = 2 \\
\text{formula mass} & = 74 \text{ amu} \\
\text{Molar Mass} & = 74 \text{ g} \\
1 \text{ mole} & = 74 \text{ g} \\
\end{align*}
\]

\[ n = \frac{m}{\text{gfm}} \]

\[ = \frac{148}{74} \]

\[ = 2 \text{ moles} \]

There are 2 moles of \( \text{Ca(OH)}_2 \) in 148g

Test Yourself 7 Calculate the number of moles of chemical in each of the following solutions.

a) 25 cm\(^3\) of a 1.0 mol l\(^{-1}\) solution
b) 50 cm\(^3\) of a 0.5 mol l\(^{-1}\) solution
c) 250 cm\(^3\) of a 0.25 mol l\(^{-1}\) solution
d) 500 cm\(^3\) of a 0.01 mol l\(^{-1}\) solution
e) 25 cm\(^3\) of a 0.1 mol l\(^{-1}\) solution
f) 100 cm\(^3\) of a 0.2 mol l\(^{-1}\) solution

Test Yourself 8 Calculate the mass of chemical present in each of the following solutions. (Use your answers to TY 7).

a) 25 cm\(^3\) of a 1.0 mol l\(^{-1}\) solution of hydrochloric acid \( \text{HCl} \)
b) 50 cm\(^3\) of a 0.5 mol l\(^{-1}\) solution of sodium hydroxide \( \text{NaOH} \)
c) 250 cm\(^3\) of a 0.25 mol l\(^{-1}\) solution of sulphuric acid \( \text{H}_2\text{SO}_4 \)
d) 500 cm\(^3\) of a 0.01 mol l\(^{-1}\) solution of calcium hydroxide \( \text{Ca(OH)}_2 \)
e) 25 cm\(^3\) of a 0.1 mol l\(^{-1}\) solution of nitric acid \( \text{HNO}_3 \)
f) 100 cm\(^3\) of a 0.2 mol l\(^{-1}\) solution of ammonia \( \text{NH}_3 \)

Test Yourself 9 Calculate the concentration (in mol l\(^{-1}\)) of each of the following solutions.

a) 3.65 g of \( \text{HCl} \) in 1000 cm\(^3\) of a hydrochloric acid solution
b) 3.65 g of \( \text{HCl} \) in 100 cm\(^3\) of a hydrochloric acid solution
c) 6.62 g of \( \text{Pb(NO}_3\text{)}_2 \) in 250 cm\(^3\) of a lead(II) nitrate solution
d) 1.00 g of \( \text{NaOH} \) in 250 cm\(^3\) of a sodium hydroxide solution
e) 1.96 g of \( \text{H}_2\text{SO}_4 \) in 250 cm\(^3\) of a sulphuric acid solution
f) 1.58 g of \( \text{KMnO}_4 \) in 250 cm\(^3\) of a potassium manganate solution
With solutions we need to know how much chemical is dissolved in a given amount of solution. Typical units can be grammes per litre (g/l) or even milligrammes per millilitre (mg/ml).

However, to make comparisons between different chemicals easier, it is better to convert from weights into number of moles and express the concentration in moles per litre (moles / l or mol l⁻¹).

\[
\text{no. of moles} = \frac{\text{mass}}{\text{gfm}} \quad \text{then} \quad \text{conc.} = \frac{\text{moles}}{\text{volume}}
\]

\[n = \frac{m}{gfm} \quad \text{then} \quad C = \frac{n}{V}\]

Volumes must always be in litres.

**Worked Example:** calculate the concentration of NaOH solution containing 12g of NaOH in 500 cm³ of solution.

\[
\text{NaOH} \quad \text{Formula Mass} = 40 \text{ amu} \quad \text{molar mass, gfm} = 40 \text{ g}
\]

\[
\text{moles of NaOH, } n = \frac{\text{mass}}{\text{gfm}} = \frac{12}{40} = 0.3 \text{ moles}
\]

\[
\text{Concentration of NaOH, } C = \frac{n}{V} = \frac{0.3}{0.5} (500 \text{ cm}^3 \text{ in litres}) = 0.6 \text{ moles / l } (0.6 \text{ M})
\]

At other times we will know the quantity of chemical needed (in moles) but will need to express this as a mass in grammes.

- calculating formula mass (in amu)
- converting to molar mass by converting to grammes

\[
\text{mass of chemical} = \text{number of moles} \times \text{gfm}
\]

**Worked Example:** mass of 2.5 moles of CaCO₃

\[
\begin{align*}
1 \times \text{Ca} &= 1 \times 40 = 40 \quad \text{formula mass} = 100 \text{ amu} \\
1 \times \text{C} &= 1 \times 12 = 12 \\
3 \times \text{O} &= 3 \times 16 = \frac{48}{100} \quad \text{Molar Mass} = 100 \text{ g} \\
&\quad \text{1 mole} = 100 \text{ g}
\end{align*}
\]

\[
m = n \times \text{gfm} = 2.5 \times 100 = 250 \text{ g}
\]

2.5 moles of CaCO₃ weighs 250g

**Test Yourself 5** Calculate the mass of each of the following.

- **a)** 1.5 moles of sucrose \(\text{C}_{12}\text{H}_{22}\text{O}_{11}\)
- **b)** 2 moles of oxygen \(\text{O}_2\)
- **c)** 0.2 moles of nitric acid \(\text{HNO}_3\)
- **d)** 0.6 moles of methanol \(\text{CH}_3\text{OH}\)
- **e)** 0.01 moles of ammonium sulphate \((\text{NH}_4)_2\text{SO}_4\)
- **f)** 0.3 moles of iron (III) nitrate \(\text{Fe(NO}_3\text{)}_3\)
A balanced equation tells us the number of moles of each reactant and product in a given reaction.

A calculation based on a balanced equation can be broken down into stages:

- write the balanced equation (usually given)
- underline the substances involved in the calculation
- extract from the equation the number of moles of each substance
- replace number of moles with calculated molar masses (if necessary, change grams to other units eg kg, tonnes)
- use simple proportion to complete calculation

**Worked Example:** what mass of iron would be produced by reacting 300 tonnes of iron(III) oxide with carbon monoxide in a blast furnace.

\[
\text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2
\]

| 1 mole | 2 moles |
| 160 g  | 112 g (2 x 56g) |
| 160 tonnes | 112 tonnes |
| 1 tonne | 112 / 160 = 0.7 tonnes |
| 300 tonnes | 300 x 0.7 = 210 tonnes |

There are a variety of methods available for the final proportion calculation. The one shown is often referred to as the unitary method. Other methods include the ratio method and scaling factor method. Your teacher will help you find the best method for you.

**Test Yourself 6**

a) What mass of carbon dioxide is produced when 160 g of methane burns completely in air?

\[
\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}
\]

b) Calculate the mass of magnesium oxide produced when 100 g of magnesium carbonate decomposes completely on heating.

\[
\text{MgCO}_3 \rightarrow \text{CO}_2 + \text{MgO}
\]

c) Silicon carbide, SiC, which is used as an abrasive on sandpaper, is prepared using the chemical reaction.

\[
3\text{C} + \text{SiO}_2 \rightarrow 2\text{CO} + \text{SiC}
\]

How many grams of SiC can be produced from 15.0 g of C?

d) The chemical equation for the photosynthesis reaction in plants is

\[
6\text{H}_2\text{O} + 6\text{CO}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2
\]

How many grams of H$_2$O reacts with 20.0 g of CO$_2$?

e) Decomposition of KClO$_3$ serves as a convenient laboratory source of small amounts of oxygen gas. The reaction is

\[
2\text{KClO}_3 \rightarrow 2\text{KCl} + 3\text{O}_2
\]

What mass of KClO$_3$ must be heated to produce 8 g of O$_2$?