Further Quantitative Chemistry Mastery Booklet (triple only)

Part 1: Percentage Yield

In the first booklet we looked at how you could use a balanced chemical equation to calculate how much product you could expect from a reaction. This is called the **maximum theoretical amount.** In reality, we never actually obtain the maximum theoretical amount. The amount we actually obtain is called the **yield**, and we often work it out as a percentage of the maximum theoretical amount.

$$\%\ yield = \frac{yield}{maximum\ theoretical\ amount} \times 100$$

The % yield is never 100% for three main reasons:

- The reaction may be reversible
- Some of the product may be lost when separated from reaction mixture
- There may be unwanted side reactions among the reactants

1. Complete the table:

Yield	Theoretical maximum	% yield	Yield	Theoretical maximum	% yield
41g	55g	75	9.88	13g	76%
89kg	103kg	86	4.65	15kg	31%
0.8g	0.030kg	3	71g	77	92%
4.2kg	5350g	79	1300g	10833	12%

2. Copper oxide can be reduced by hydrogen. What mass of copper could be obtained from 79.5 g of copper oxide? $CuO + H_2 \rightarrow Cu + H_2O$

	CuO	Cu
Mass	79.5	?
Mr	79.5	63.5
Moles	1	

Mass of Cu = Moles x Mr = 1 x 63.5 = 63.5g

3. If only 12g is obtained what is the % yield? 12 / 63.5 = 18.8%

4. Calculate the mass of carbon dioxide you could obtain by adding hydrochloric acid to 15 g of calcium carbonate: $CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2O + CO_2$

	$CaCO_3$	CO_2
Mass	15	?
Mr	100	44
Moles	0.15	

Mass of CO_2 = Moles x Mr = 0.15 x 44 = 6.6g

5. If only 3g is obtained what is the % yield? 3 / 6.6 = 45%

6. Calculate the mass of sodium hydroxide that is needed to neutralise a solution containing 7.3 g of hydrochloric acid: $HCl + NaOH \rightarrow NaCl + H_2O$

	HCl	NaOH
Mass	7.3	?
Mr	36.5	40

Moles	0.2	

Mass of NaOH = Moles x Mr = 0.2 x 40 = <u>8g</u>

7. If only 1.7g is obtained what is the % yield? 1.7 / 8 = <u>21%</u>
8. What mass of calcium oxide could be made from 75 tonnes of limestone ($CaCO_3$)? $CaCO_3 \rightarrow CaO + CO_2$

	$CaCO_3$	CaO
Mass	75	?
Mr	100	56
Moles	0.75	

Mass of CaO = Moles x Mr = 0.75 x 56 = <u>42 tonnes</u>

9. If 17 tonnes are produced, what is the % yield? 17 / 42 = <u>40%</u>
10. 97.5 g of zinc was added to excess dilute hydrochloric acid: $Zn + 2HCl \rightarrow ZnCl_2 + H_2$ Calculate:
    a. the mass of zinc chloride that could be produced

	Zn	$ZnCl_2$	H_2
Mass	97.5	a	b
Mr	65	136	2
Moles	1.5		

Mass of $ZnCl_2$ = Moles x Mr = 1.5 x 136 = <u>204g</u>

    a. the mass of hydrogen that could be produced. Mass of H_2 = Moles x Mr = 1.5 x 2 = <u>3g</u>
    b. A yield of 53% was obtained. What mass of zinc chloride was this? 204 x 0.53 = <u>108g</u>

Part 2: Atom Economy

The atom economy of a reaction is the percentage of your reactant that is converted to **useful** product. This is important for sustainability and economics. We use the formula:

$$Atom\ economy = \frac{relative\ mass\ of\ useful\ product}{relative\ mass\ of\ all\ reactants} \times 100$$

Example: extraction of copper:

There are two possible ways to extract pure copper metal

$2CuO + C \rightarrow$ **2Cu** $+ CO_2$

$CuS + O_2 \rightarrow$ **Cu** $+ SO_2$

We can calculate the atom economy for the first reaction as below:

$$\frac{2 \times 63.5}{2(63.5 + 16) + 12} \times 100 = 74.4\%$$

For the second reaction:

$$\frac{63.5}{(63.5 + 32) + (2 \times 16)} \times 100 = 50\%$$

Showing that the second reaction has a lower atom economy. There are other factors to consider as well, including the usefulness of other products, the % yield of the reaction, the rate and the position of equilibrium.

11. Iron is extracted from iron oxide in the Blast Furnace: $Fe_2O_3 + 3\ CO \rightarrow 2\ Fe + 3\ CO_2$
    a. Calculate the maximum theoretical mass of iron that can be made from 100g of iron oxide.

	Fe_2O_3	2 Fe
Mass	100	?
Mr	160	112
Moles	0.625	

Mass of Fe = Moles x Mr = 0.625 x 112 = 70g

    b. In the reaction, only 65 g of iron was made. Calculate the percentage yield.
    65 / 70 = 93%
    c. Calculate the atom economy of this reaction

$Fe_2O_3 + 3\ CO$ = 244   112/244 = 46%

12. Titanium can be extracted from titanium chloride by the following reaction: $TiCl_4 + 2Mg \rightarrow Ti + 2MgCl_2$
    a. The reaction used 250kg of titanium chloride and produced 51kg of titanium. Calculate the percentage yield.

	$TiCl_4$	Ti
Mass	250	
Mr	190	48
Moles	1.32	

    Mass of Ti – Moles x Mr = 1.32 x 48 = 63.2kg
    Percentage yield = 51 / 63.2 = 80.1%
    b. Calculate the atom economy of this reaction

$TiCl_4 + 2Mg$ = 48/238 = 20.2%

    c. Extension: The reaction was attempted again and a mass of 141kg was produced – a yield of 81%. How much titanium chloride was used?
    141 x 0.81 = 174kg – theoretical yield
    174 / 190 = 0.92 moles x 190 = 173.9kg

Part 3: Revisiting Concentrations

In the previous booklet we measured concentration in g/dm^3. We must also be able to use the more common unit of mol/dm^3.

Concentration (mol/dm^3) = moles ÷ volume

Where volume is in dm^3.

13. Express each of the below in mol/dm^3. You will have to deduce the formulae of the substances.
    a. 10.0 g of sodium chloride dissolved in 2.00 dm^3 of water 10/2 = 5 / 58.5 = $0.08mol/dm^3$
    b. 2.5 g of glucose dissolved in 0.5 dm^3 of water 2.5 / 0.5 = 5 / 180 = $0.027mol//dm^3$
    c. 3.8 g of copper (II) sulphate dissolved in 250 cm^3 of water 3.8 / 0.25 = 15.2 /159.5 = $0.095mol/dm^3$
    d. 3.8g of copper (I) sulphate dissolved in 250cm^3 of water 3.8 / 0.25 = 15.2 0.068moldm3
    e. 25.6 g of potassium chloride dissolved in 1500cm^3 of water. 25.6 / 1.5 = 17 / 74.5 = =$0.229mol.dm^3$
14. How many moles of sodium chloride are in:
    a. 250cm^3 of 3.2mol/dm^3 solution 0.250 x 3.2 = 0.8 46.8g
    b. 111cm^3 of 8.1mol/dm^3 solution 0.111 x 8.1 = 0.889 52g
    c. 2.1dm^3 of 0.1mol/dm^3 solution 2.1 x 0.1 = 0.21 12.29g
    d. 0.72dm^3 of 4.3mol/dm^3 solution 0.72 x 4.3 = 3.096 181g
15. For each of the solutions in question 14 calculate the mass of sodium chloride present. In blue above
16. What is the volume of:
    a. A 1.0mol/dm^3 solution with 6 moles of solute 6/1 = $6dm^3$
    b. A 1.7mol/dm^3 solution with 3.3 moles of solute 3.3 / 17 = $1.94dm^3$
    c. A 9.1mol/dm^3 solution with 0.91 moles of solute 0.91 / 9.1 = $0.1dm^3$
    d. A 0.08mol/dm^3 solution with 6 moles of solute 6 / 0.08 = $75dm^3$

Part 5: Titrations

Titration is a method used to find out the concentration of an unknown solution.

Worked example:

We have a solution of sodium hydroxide, but we do not know the concentration. We also have a solution of 2.00mol/dm^3 of hydrochloric acid. If we take exactly 25.0cm^3 of the sodium hydroxide we can add an indicator then add hydrochloric acid drop by drop until the reaction is just finished (known as the end point). We find that we used 21.0cm^3 of hydrochloric acid. We can now calculate the concentration of the unknown solution:

Step 1: write out and balance the equation

$NaOH + HCl \rightarrow NaCl + H_2O$

Step 2: work out the number of moles from known solution

The known solution in this case was the HCl. We used 21.0cm^3 (0.0210dm^3) of 2.00mol/dm^3 solution

Moles = concentration x volume

Moles = 2 x 0.021 = 0.042

Step 2: manipulate the ratio

As we have done many times before, we need to look at the ratio in the equation to work out how many moles of NaOH were present

÷1

x 0.042

HCl	NaOH
1	1
1	1
0.042	0.042

In this case the ratio is 1:1 so we know we have 0.042 moles NaOH present

Step 4: calculate concentration by moles/volume

We have 0.042 moles NaOH in a volume of 25.0cm^3 (0.0250dm^3).

0.042 ÷ 0.0250 = 1.68mol/dm^3

Guided example

25.0cm^3 of an unknown concentration of sodium hydroxide is titrated against 31.0cm^3 of a 1.30mol/dm^3 solution of sulphuric acid. What is the concentration of the unknown solution?

Step 1: write out and balance the equation

___$NaOH + H_2SO_4 \rightarrow Na_2SO_4 +$ ___H_2O

Step 2: work out the number of moles from known solution

The known solution in this case was the H_2SO_4. We used 31.0cm^3 (0.0310dm^3) of 1.30mol/dm^3 solution

Moles = concentration x volume

Moles = ______ x _______ = 0.0403

Step 2: manipulate the ratio

As we have done many times before, we need to look at the ratio in the equation to work out how many moles of NaOH were present

÷1

x ____

H_2SO_4	NaOH
1	____

1	____
0.0403	____

Step 4: calculate concentration by moles/volume

We have _________ moles NaOH in a volume of 25.0cm^3 (0.0250dm^3).

_______ ÷ _______ = 3.224 mol/dm^3

17. 20.0cm^3 of an unknown concentration of sodium hydroxide is titrated against 26.3cm^3 of a 2.50 mol/dm^3 solution of sulphuric acid. What is the concentration of the unknown solution? 6.575
18. 25.0cm^3 of an unknown concentration of sulphuric acid is titrated against 13.0cm^3 of a 1.80 mol/dm^3 solution of sodium hydroxide. What is the concentration of the unknown solution? 0.468
19. 22.0cm^3 of an unknown concentration of potassium hydroxide is titrated against 17.5cm^3 of a 1.15 mol/dm^3 solution of sulphuric acid.
    a. What is the concentration of the unknown solution? 1.83
    b. What mass of potassium hydroxide was in 22.0cm^3? (remember you can easily convert mass to moles) 2.254
    c. The potassium hydroxide solution was made by dissolving 45g of potassium hydroxide into water. How much water was used? 0.44dm^3
20. 51g of sodium hydroxide is dissolved in 1500cm^3 of water. 24.1cm^3 of the resultant solution completely neutralises 13cm^3 of a solution of nitric acid of unknown concentration.
    a. What is the concentration of the original sodium hydroxide? 0.85
    b. What is the concentration of the nitric acid? 1.58
21. 83g of lithium hydroxide is dissolved in 800cm^3 of water. 17.8cm^3 of the resultant solution completely neutralises 28cm^3 of a solution of sulphuric acid of unknown concentration. What is the concentration of the sulphuric acid? 1.38
22. Challenge: 44g of potassium hydroxide is dissolved in 750cm^3 of water. 12.3cm^3 of the resultant solution completely neutralises 28cm^3 of a solution of phosphoric acid (H_3PO_4) of unknown concentration. What is the concentration of the sulphuric acid?

Concordance

When we do a titration it is important to obtain accurate results. We take one measurement and then repeat it until we have two results that are **concordant**; within 0.1cm^3 of each other. In the table of results below, titres 2 and 4 are concordant:

Titre 1 (cm^3)	Titre 2 (cm^3)	Titre 3 (cm^3)	Titre 4 (cm^3)
24.8	25.3	22.1	25.2

For the calculations, you would take the mean of titres 2 and 4 (25.25cm^3).

GCSE questions:

23. A student used a pipette to add 25.0 cm^3 of sodium hydroxide of unknown concentration to a conical flask. The student carried out a titration to find out the volume of 0.100 mol / dm^3 sulfuric acid needed to neutralise the sodium hydroxide.
   a. The student carried out five titrations. Her results are shown in the table below.

	Titration 1	Titration 2	Titration 3	Titration 4	Titration 5
Volume of 0.100 mol / dm^3 sulfuric acid in cm^3	27.40	28.15	27.05	27.15	27.15

Use the student's concordant results to work out the mean volume of 0.100 mol / dm^3 sulfuric acid added. 27.1167

   b. The equation for the reaction is: $2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$
   Calculate the concentration of the sodium hydroxide. Give your answer to three significant figures. 0.217
   c. The student did another experiment using 20 cm^3 of sodium hydroxide solution with a concentration of 0.18 mol / dm^3. Calculate the mass of sodium hydroxide in 20 cm^3 of this solution. 0.144

24. Ethanoic acid is a *weak* acid.

a. Which ion is present in aqueous solutions of all acids?
b. What is the difference between the pH of a *weak* acid compared to the pH of a strong acid of the same concentration? Give a reason for your answer.
c. 25.00 cm^3 of vinegar was neutralised by 30.50 cm^3 of a solution of sodium hydroxide with a concentration of 0.50mol/dm^3. The equation for this reaction is:

$$CH_3COOH(aq) \quad + \quad NaOH(aq) \quad \rightarrow \quad CH_3COONa(aq) \quad + \quad H_2O(l)$$

Calculate the concentration of ethanoic acid in this vinegar. 0.61

d. The concentration of ethanoic acid in a different bottle of vinegar was 0.80 mol/dm^3. Calculate the mass in grams of ethanoic acid (CH_3COOH) in 250 cm^3 of this vinegar. 12

Part 6: Volumes of Gases

In the same way that we can calculate moles of solute in solution from the volumes, we can calculate the number of moles of a gas by the amount of space it takes up (its volume). We can use the formula:

Moles of a gas = volume of gas (dm^3) ÷ 24

This equation only works at room temperature and pressure (20°C and 1 atmosphere). This is because 1 mole of **any** gas will occupy 24dm^3 at room temperature and pressure.

Worked example

A gas occupies 3200cm^3 at room temperature and pressure. How many moles of gas are present?

First, we convert 3200cm^3 to 3.2dm^3.

Moles of a gas = 3.2 ÷ 24 = 1.33 moles

23. Calculate the number of moles in the volumes below (assume room temperature and pressure)
    a. 1000cm^3 1 / 24 = 0.04
    b. 2000cm^3 2 / 24 = 0.083
    c. 2000dm^3 2000 / 24 = 83.3
    d. 17500cm^3 17.5 / 24 = 0.729
    e. 1.2dm^3 1.2 / 24 = 0.05
    f. 25cm^3 0.025 / 24 = 0.001
24. Calculate the volumes occupied at room temperature and pressure by the amount of gas below:
    a. 5 moles 5 x 24 = 120dm^3
    b. 2.3 moles 2.3 x 24 = 55.2dm^3
    c. 0.08 moles 0.08 x 24 = 1.92dm^3
    d. 21 moles = 21 x 24 = 504dm^3
25. A reaction generates 45g of carbon dioxide at room temperature and pressure.
    a. How many moles of carbon dioxide are formed? 45 / 44 = 1.023
    b. What volume of carbon dioxide is therefore produced? 1.023 x 24 = 24.55dm^3
26. A different reaction produces 32g of nitrogen gas. What volume does the gas occupy at room temperature and pressure? 32 / 28 = 1.14 mole x 24 = 27.4dm^3
27. A reaction generates 3.2kg of hydrogen gas at room temperature and pressure.
    a. What volume does this gas occupy? 3200g / 2 = 1600moles 1600 x 24 = 38400 dm^3
    b. The same reaction produces the same mass of oxygen gas. What is the combined volume of the two gases? 3200 / 32 = 100moles x 24 = 2400 + 38400 = 40800dm^3

We can use this knowledge as well as manipulation of ratios to use equations to establish reacting volumes. For example, hydrogen reacts with nitrogen to form ammonia as below:

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

This means that 3 moles of hydrogen reacts with 1 mole of nitrogen to make 2 moles of ammonia. If we want to know what volumes are involved we can manipulate the ratios very easily.

What volume of ammonia is formed from 300cm^3 of hydrogen?

	H_2	N_2	NH_3
	3	1	2
÷3	1		0.67
x 300			

300		200

So 200cm^3 of ammonia would be formed. We could then work out how many moles of ammonia this is (at room temperature and pressure) by converting to cm^3 and dividing by 24

0.2 ÷ 24 = 0.0083moles

28. In the reaction above, calculate the volume of ammonia formed from:
    a. 200cm^3 of hydrogen
    b. 2.6dm^3 of hydrogen
    c. 13.5dm^3 of hydrogen
    d. 17000cm^3 of nitrogen
29. For each answer to question 30, calculate the number of moles of ammonia present
30. For each answer to question 30, calculate the mass of ammonia present

	28 - volume NH_3	29 – moles NH_3	30 – mass NH_3
A - 200cm^3 of hydrogen			
B - 2.6dm^3 of hydrogen			
C - 13.5dm^3 of hydrogen			
D - 17000cm^3 of nitrogen			

A Level Brainteasers:

31. 1 mole of a hydrocarbon of formula C_nH_{2n} was burned completely in oxygen producing carbon dioxide and water vapour only. It required 192 g of oxygen. Work out the formula of the hydrocarbon.
32. Using Carbon-12, calculate the mass of one proton.
33. The actual mass of a proton is 1.6726×10^{-24}. Why do you think your answer is different?
34. 0.8500 g of hexanone, $C_6H_{12}O$, is converted into its 2,4-dinitrophenylhyrazone during its analysis. After isolation and purification, 2.1180 g of product $C_{12}H_{18}N_4O_4$ are obtained. Calculate the percentage yield.
35. When 100 cm^3 of hydrogen bromide reacts with 80 cm^3 of ammonia, a white solid is formed and some gas is left over. What gas and how much of it is left over? $NH_3(g) + HBr(g) \rightarrow NH_4Br(s)$
36. 100 cm^3 of methane was reacted with 500 cm^3 of oxygen (complete combustion). What is the total volume of all gases at the end, and indicate how much there is of each gas
37. When 15 cm^3 of a gaseous hydrocarbon was exploded with 60 cm^3 of oxygen (an excess), the final volume was 45cm^3. This decreased to 15 cm^3 on treatment with NaOH solution (removes CO_2). What was the formula of the hydrocarbon? (all measurements were made at room temperature and pressure, ∴ the water produced is a liquid).