**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.

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

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% |

1. Copper oxide can be reduced by hydrogen. What mass of copper could be obtained from 79.5 g of copper oxide? CuO + H2 → Cu + H2O

|  |  |  |
| --- | --- | --- |
|  | CuO | Cu |
| Mass | 79.5 | ? |
| Mr | 79.5 | 63.5 |
| Moles | 1 |  |

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

1. If only 12g is obtained what is the % yield? 12 / 63.5 = 18.8%
2. Calculate the mass of carbon dioxide you could obtain by adding hydrochloric acid to 15 g of calcium carbonate: CaCO3 + 2HCl → CaCl2 + H2O + CO2

|  |  |  |
| --- | --- | --- |
|  | CaCO3 | CO2 |
| Mass | 15 | ? |
| Mr | 100 | 44 |
| Moles | 0.15 |  |

Mass of CO2 = Moles x Mr = 0.15 x 44 = 6.6g

1. If only 3g is obtained what is the % yield? 3 / 6.6 = 45%
2. Calculate the mass of sodium hydroxide that is needed to neutralise a solution containing 7.3 g of hydrochloric acid: HCl + NaOH → NaCl + H2O

|  |  |  |
| --- | --- | --- |
|  | HCl | NaOH |
| Mass | 7.3 | ? |
| Mr | 36.5 | 40 |
| Moles | 0.2 |  |

Mass of NaOH = Moles x Mr = 0.2 x 40 = 8g

1. If only 1.7g is obtained what is the % yield? 1.7 / 8 = 21%
2. What mass of calcium oxide could be made from 75 tonnes of limestone (CaCO3)? CaCO3 → CaO + CO2

|  |  |  |
| --- | --- | --- |
|  | CaCO3 | CaO |
| Mass | 75 | ? |
| Mr | 100 | 56 |
| Moles | 0.75 |  |

Mass of CaO = Moles x Mr = 0.75 x 56 = 42 tonnes

1. If 17 tonnes are produced, what is the % yield? 17 / 42 = 40%
2. 97.5 g of zinc was added to excess dilute hydrochloric acid: Zn + 2HCl → ZnCl2 + H2 Calculate:
	1. the mass of zinc chloride that could be produced

|  |  |  |  |
| --- | --- | --- | --- |
|  | Zn | ZnCl2 | H2 |
| Mass | 97.5 | a | b |
| Mr | 65 | 136 | 2 |
| Moles | 1.5 |  |  |

Mass of ZnCl2 = Moles x Mr = 1.5 x 136 = 204g

1. the mass of hydrogen that could be produced. Mass of H2 = Moles x Mr = 1.5 x 2 = 3g
2. A yield of 53% was obtained. What mass of zinc chloride was this? 204 x 0.53 = 108g

**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:

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

Example: extraction of copper:

There are two possible ways to extract pure copper metal

2CuO + C → **2Cu** + CO2

CuS + O2 → **Cu** + SO2

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

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

For the second reaction:

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

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.

1. Iron is extracted from iron oxide in the Blast Furnace: Fe2O3 + 3 CO → 2 Fe + 3 CO2
	1. Calculate the maximum theoretical mass of iron that can be made from 100g of iron oxide.

|  |  |  |
| --- | --- | --- |
|  | Fe2O3 | 2 Fe |
| Mass | 100 | ? |
| Mr | 160 | 112 |
| Moles | 0.625 |  |

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

* 1. In the reaction, only 65 g of iron was made. Calculate the percentage yield.

65 / 70 = 93%

* 1. Calculate the atom economy of this reaction

Fe2O3 + 3 CO = 244 112/244 = 46%

1. Titanium can be extracted from titanium chloride by the following reaction: TiCl4 + 2Mg → Ti + 2MgCl2
	1. The reaction used 250kg of titanium chloride and produced 51kg of titanium. Calculate the percentage yield.

|  |  |  |
| --- | --- | --- |
|  | TiCl4 | 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%

* 1. Calculate the atom economy of this reaction

TiCl4 + 2Mg = 48/238 = 20.2%

* 1. 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/dm3. We must also be able to use the more common unit of mol/dm3.

Concentration (mol/dm3) = moles ÷ volume

Where volume is in dm3.

1. Express each of the below in mol/dm3. You will have to deduce the formulae of the substances.
	1. 10.0 g of sodium chloride dissolved in 2.00 dm3 of water 10/2 = 5 / 58.5 = 0.08mol/dm3
	2. 2.5 g of glucose dissolved in 0.5 dm3 of water 2.5 / 0.5 = 5 / 180 = 0.027mol//dm3
	3. 3.8 g of copper (II) sulphate dissolved in 250 cm3 of water 3.8 / 0.25 = 15.2 /159.5 = 0.095mol/dm3
	4. 3.8g of copper (I) sulphate dissolved in 250cm3 of water 3.8 / 0.25 = 15.2 0.068moldm3
	5. 25.6 g of potassium chloride dissolved in 1500cm3 of water. 25.6 / 1.5 = 17 / 74.5 = =0.229mol.dm3
2. How many moles of sodium chloride are in:
	1. 250cm3 of 3.2mol/dm3 solution 0.250 x 3.2 = 0.8 46.8g
	2. 111cm3 of 8.1mol/dm3 solution 0.111 x 8.1 = 0.889 52g
	3. 2.1dm3 of 0.1mol/dm3 solution 2.1 x 0.1 = 0.21 12.29g
	4. 0.72dm3 of 4.3mol/dm3 solution 0.72 x 4.3 = 3.096 181g
3. For each of the solutions in question 14 calculate the mass of sodium chloride present. In blue above
4. What is the volume of:
	1. A 1.0mol/dm3 solution with 6 moles of solute 6/1 = 6dm3
	2. A 1.7mol/dm3 solution with 3.3 moles of solute 3.3 / 17 = 1.94dm3
	3. A 9.1mol/dm3 solution with 0.91 moles of solute 0.91 / 9.1 = 0.1dm3
	4. A 0.08mol/dm3 solution with 6 moles of solute 6 / 0.08 = 75dm3

**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/dm3 of hydrochloric acid. If we take exactly 25.0cm3 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 21.0cm3 of hydrochloric acid. We can now calculate the concentration of the unknown solution:

Step 1: write out and balance the equation

NaOH + HCl 🡪 NaCl + H2O

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

The known solution in this case was the HCl. We used 21.0cm3 (0.0210dm3) of 2.00mol/dm3 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

|  |  |
| --- | --- |
| HCl | NaOH |
| 1÷1x 0.042 | 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 25.0cm3 (0.0250dm3).

0.042 ÷ 0.0250 = 1.68mol/dm3

**Guided example**

25.0cm3 of an unknown concentration of sodium hydroxide is titrated against 31.0cm3 of a 1.30mol/dm3 solution of sulphuric acid. What is the concentration of the unknown solution?

Step 1: write out and balance the equation

\_\_\_NaOH + H2SO4 🡪 Na2SO4 + \_\_\_H2O

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

The known solution in this case was the H2SO4. We used 31.0cm3 (0.0310dm3) of 1.30mol/dm3 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

|  |  |
| --- | --- |
| H2SO4 | NaOH |
| 1÷1x \_\_\_\_ | \_\_\_\_ |
| 1 | \_\_\_\_ |
| 0.0403 | \_\_\_\_ |

Step 4: calculate concentration by moles/volume

We have \_\_\_\_\_\_\_\_\_ moles NaOH in a volume of 25.0cm3 (0.0250dm3).

\_\_\_\_\_\_\_ ÷ \_\_\_\_\_\_\_ = 3.224 mol/dm3

1. 20.0cm3 of an unknown concentration of sodium hydroxide is titrated against 26.3cm3 of a 2.50 mol/dm3 solution of sulphuric acid. What is the concentration of the unknown solution? 6.575
2. 25.0cm3 of an unknown concentration of sulphuric acid is titrated against 13.0cm3 of a 1.80 mol/dm3 solution of sodium hydroxide. What is the concentration of the unknown solution? 0.468
3. 22.0cm3 of an unknown concentration of potassium hydroxide is titrated against 17.5cm3 of a 1.15 mol/dm3 solution of sulphuric acid.
	1. What is the concentration of the unknown solution? 1.83
	2. What mass of potassium hydroxide was in 22.0cm3? (remember you can easily convert mass to moles) 2.254
	3. The potassium hydroxide solution was made by dissolving 45g of potassium hydroxide into water. How much water was used? 0.44dm3
4. 51g of sodium hydroxide is dissolved in 1500cm3 of water. 24.1cm3 of the resultant solution completely neutralises 13cm3 of a solution of nitric acid of unknown concentration.
	1. What is the concentration of the original sodium hydroxide? 0.85
	2. What is the concentration of the nitric acid? 1.58
5. 83g of lithium hydroxide is dissolved in 800cm3 of water. 17.8cm3 of the resultant solution completely neutralises 28cm3 of a solution of sulphuric acid of unknown concentration. What is the concentration of the sulphuric acid? 1.38
6. Challenge: 44g of potassium hydroxide is dissolved in 750cm3 of water. 12.3cm3 of the resultant solution completely neutralises 28cm3 of a solution of phosphoric acid (H3PO4) 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 0.1cm3 of each other. In the table of results below, titres 2 and 4 are concordant:

|  |  |  |  |
| --- | --- | --- | --- |
| Titre 1 (cm3) | Titre 2 (cm3) | Titre 3 (cm3) | Titre 4 (cm3) |
| 24.8 | 25.3 | 22.1 | 25.2 |

For the calculations, you would take the mean of titres 2 and 4 (25.25cm3).

**GCSE questions:**

1. A student used a pipette to add 25.0 cm3 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 / dm3 sulfuric acid needed to neutralise the sodium hydroxide.
	1. 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 / dm3 sulfuric acid in cm3 | 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 / dm3 sulfuric acid added. 27.1167

* 1. The equation for the reaction is: 2NaOH + H2SO4  →  Na2SO4 + 2H2O
	Calculate the concentration of the sodium hydroxide. Give your answer to three significant figures. 0.217
	2. The student did another experiment using 20 cm3 of sodium hydroxide solution with a concentration of 0.18 mol / dm3. Calculate the mass of sodium hydroxide in 20 cm3 of this solution. 0.144
1. Ethanoic acid is a *weak* acid.
	1. Which ion is present in aqueous solutions of all acids?
	2. 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.
	3. 25.00 cm3 of vinegar was neutralised by 30.50 cm3 of a solution of sodium hydroxide with a concentration of 0.50mol/dm3. The equation for this reaction is:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  CH3COOH(aq) | + | NaOH(aq) | → | CH3COONa(aq) | + | H2O(l) |

Calculate the concentration of ethanoic acid in this vinegar. 0.61

* 1. The concentration of ethanoic acid in a different bottle of vinegar was 0.80 mol/dm3. Calculate the mass in grams of ethanoic acid (CH3COOH) in 250 cm3 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 (dm3) ÷ 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 24dm3 at room temperature and pressure.

Worked example

A gas occupies 3200cm3 at room temperature and pressure. How many moles of gas are present?

First, we convert 3200cm3 to 3.2dm3.

Moles of a gas = 3.2 ÷ 24 = 1.33 moles

1. Calculate the number of moles in the volumes below (assume room temperature and pressure)
	1. 1000cm3 1 / 24 = 0.04
	2. 2000cm3  2 / 24 = 0.083
	3. 2000dm3 2000 / 24 = 83.3
	4. 17500cm3  17.5 / 24 = 0.729
	5. 1.2dm3  1.2 / 24 = 0.05
	6. 25cm3 0.025 / 24 = 0.001
2. Calculate the volumes occupied at room temperature and pressure by the amount of gas below:
	1. 5 moles 5 x 24 = 120dm3
	2. 2.3 moles 2.3 x 24 = 55.2dm3
	3. 0.08 moles 0.08 x 24 = 1.92dm3
	4. 21 moles = 21 x 24 = 504dm3
3. A reaction generates 45g of carbon dioxide at room temperature and pressure.
	1. How many moles of carbon dioxide are formed? 45 / 44 = 1.023
	2. What volume of carbon dioxide is therefore produced? 1.023 x 24 = 24.55dm3
4. 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 = 27.4dm3
5. A reaction generates 3.2kg of hydrogen gas at room temperature and pressure.
	1. What volume does this gas occupy? 3200g / 2 = 1600moles 1600 x 24 = 38400 dm3
	2. 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 = 40800dm3

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:

3H2(g) + N2(g) 🡪 2NH3(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 300cm3 of hydrogen?

|  |  |  |
| --- | --- | --- |
| H2 | N2 | NH3 |
| 3÷3x 300 | 1 | 2 |
| 1 |  | 0.67 |
| 300 |  | 200 |

So 200cm3 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 cm3 and dividing by 24

0.2 ÷ 24 = 0.0083moles

1. In the reaction above, calculate the volume of ammonia formed from:
	1. 200cm3 of hydrogen
	2. 2.6dm3 of hydrogen
	3. 13.5dm3 of hydrogen
	4. 17000cm3 of nitrogen
2. For each answer to question 30, calculate the number of moles of ammonia present
3. For each answer to question 30, calculate the mass of ammonia present

|  |  |  |  |
| --- | --- | --- | --- |
|  | 28 - volume NH3 | 29 – moles NH3 | 30 – mass NH3 |
| A - 200cm3 of hydrogen |  |  |  |
| B - 2.6dm3 of hydrogen |  |  |  |
| C - 13.5dm3 of hydrogen |  |  |  |
| D - 17000cm3 of nitrogen |  |  |  |

**A Level Brainteasers:**

1. 1 mole of a hydrocarbon of formula CnH2n 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.
2. Using Carbon-12, calculate the mass of one proton.
3. The actual mass of a proton is 1.6726x10-24. Why do you think your answer is different?
4. 0.8500 g of hexanone, C6H12O, is converted into its 2,4-dinitrophenylhyrazone during its analysis. After isolation and purification, 2.1180 g of product C12H18N4O4 are obtained. Calculate the percentage yield.
5. When 100 cm3 of hydrogen bromide reacts with 80 cm3 of ammonia, a white solid is formed and some gas is left over. What gas and how much of it is left over? NH3(g) + HBr(g) → NH4Br(s)
6. 100 cm3 of methane was reacted with 500 cm3 of oxygen (complete combustion). What is the total volume of all gases at the end, and indicate how much there is of each gas
7. When 15 cm3 of a gaseous hydrocarbon was exploded with 60 cm3 of oxygen (an excess), the final volume was 45cm3. This decreased to 15 cm3 on treatment with NaOH solution (removes CO2). What was the formula of the hydrocarbon? (all measurements were made at room temperature and pressure, ∴ the water produced is a liquid).