

1.1 Formulae, equations and amount of substance

Name: _____ Class: _____ Date: _____

Total: 20 marks

KEY WORDS mole • atom economy • percentage yield
• empirical formula • molar volume

Objective

Practise Topic 1: mole arithmetic, reacting masses, gas volumes, solution amounts, empirical formulae, yield and atom economy – the skills every WCH11 question leans on.

1 Key knowledge and worked examples

■ The three doors to n

$$n = \frac{m}{M} \quad n = \frac{V}{24 \text{ dm}^3} \quad (\text{RTP}) \quad n = cV$$

Here M is molar mass and ν is the balanced product coefficient. For gases not at RTP, $pV = nRT$ with $R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$ and Pascals throughout.

■ Worked example: a full combustion chain

A 7.6 g hydrocarbon forms 26.4 g CO_2 and 3.6 g H_2O on complete combustion. The carbon in the sample becomes CO_2 , and pairs of H atoms become H_2O .

$$n(\text{C}) = n(\text{CO}_2) = \frac{m(\text{CO}_2)}{M(\text{CO}_2)} = \frac{26.4 \text{ g}}{44.0 \text{ g mol}^{-1}} = 0.600 \text{ mol}$$

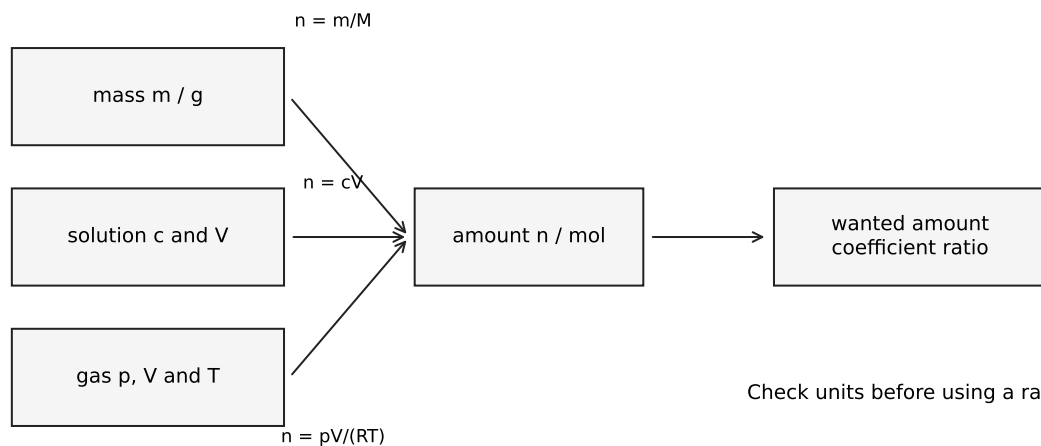
$$n(\text{H}) = 2n(\text{H}_2\text{O}) = \frac{2m(\text{H}_2\text{O})}{M(\text{H}_2\text{O})} = \frac{2 \times 3.6 \text{ g}}{18.0 \text{ g mol}^{-1}} = 0.400 \text{ mol}$$

Ratio C:H = 0.600:0.400 = 3:2, so the empirical formula is C_3H_2 . Check element masses: $m(\text{C}) = nM = 0.600 \times 12.0 = 7.20 \text{ g}$ and $m(\text{H}) = nM = 0.400 \times 1.00 = 0.400 \text{ g}$, adding to 7.60 g. A molecular formula also needs measured M_r .

Yield and atom economy

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

$$\text{atom economy} = \frac{\nu_{\text{wanted}} M_r(\text{wanted})}{\sum \nu_i M_r(\text{product } i)} \times 100$$



2 Practice

2.1 Calculate the number of atoms in 10 g of methane, CH_4 . (A_r : H = 1.0, C = 12.0; $L = 6.02 \times 10^{23}$) [2]

2.2 What volume of oxygen, measured at RTP, is needed for the complete combustion of 0.25 mol of butane? [2]

2.3 State what is meant by the term atom economy. [2]

3 Exam-style questions

3.1 A 2.50 g fertiliser sample contains ammonium sulfate, $(\text{NH}_4)_2\text{SO}_4$ ($M_r = 132$), and inert sand. Excess sodium hydroxide releases all the ammonia from the salt. The ammonia reacts exactly with 48.0 cm^3 of $0.250 \text{ mol dm}^{-3}$ sulfuric acid. No ammonia escapes. Use $(\text{NH}_4)_2\text{SO}_4 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{NH}_3 + 2\text{H}_2\text{O}$ and $\text{H}_2\text{SO}_4 + 2\text{NH}_3 \rightarrow (\text{NH}_4)_2\text{SO}_4$ to calculate the percentage by mass of ammonium sulfate. [5]

3.2 Copper(II) nitrate, $\text{Cu}(\text{NO}_3)_2$ ($M_r = 188$), can be made by reacting copper(II) oxide with nitric acid. Calculate the maximum mass of copper(II) nitrate that can be produced from 4.0 g of copper(II) oxide with excess nitric acid ($M_r = 80$), and the atom economy of the reaction if water is the only other product. [5]

3.3 A 0.050 cm^3 drop of water is analysed. Calculate the number of molecules in the drop and the number of oxygen atoms. (density of water = 1.0 g cm^{-3}) [4]

Solutions

Original-task marking: M1 method, A1 accuracy, B1 reasoning.

2.1 Methane has five atoms per molecule. Its molar mass is 16 g mol^{-1} .

$$n = \frac{m}{M} = \frac{10 \text{ g}}{16 \text{ g mol}^{-1}} = 0.625 \text{ mol}$$

$$N_{\text{atoms}} = 5nL = 5 \times 0.625 \text{ mol} \times 6.02 \times 10^{23} \text{ mol}^{-1} = 1.88 \times 10^{24}$$

Molecule count alone does not answer this question.

2.2 $\text{C}_4\text{H}_{10} + 6.5\text{O}_2 \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O}$. Oxygen amount follows the 1:6.5 coefficient ratio.

$$n(\text{O}_2) = 6.5n(\text{C}_4\text{H}_{10}) = 6.5 \times 0.25 \text{ mol} = 1.625 \text{ mol}$$

$$V(\text{O}_2) = nV_m = 1.625 \text{ mol} \times 24 \text{ dm}^3 \text{ mol}^{-1} = 39 \text{ dm}^3$$

2.3 The balanced desired-product mass contribution divided by the sum of balanced mass contributions of all products, $\times 100 \%$.

3.1 $\text{H}_2\text{SO}_4 + 2\text{NH}_3 \rightarrow (\text{NH}_4)_2\text{SO}_4$. One mole of ammonium sulfate releases two moles of ammonia, which consume one mole of sulfuric acid.

$$n(\text{H}_2\text{SO}_4) = cV = 0.250 \text{ mol dm}^{-3} \times 0.0480 \text{ dm}^3 = 0.0120 \text{ mol}$$

Thus $n((\text{NH}_4)_2\text{SO}_4) = 0.0120 \text{ mol}$.

$$m = nM = 0.0120 \text{ mol} \times 132 \text{ g mol}^{-1} = 1.584 \text{ g}$$

$$\text{mass percentage} = \frac{m(\text{salt})}{m(\text{sample})} \times 100\% = \frac{1.584 \text{ g}}{2.50 \text{ g}} \times 100\% = 63.4\%$$

The salt mass is smaller than the sample mass, as required.

3.2 $\text{CuO} + 2\text{HNO}_3 \rightarrow \text{Cu}(\text{NO}_3)_2 + \text{H}_2\text{O}$. Nitric acid is assumed in excess. The oxide and salt have a 1:1 mole ratio.

$$n(\text{CuO}) = \frac{m}{M} = \frac{4.0 \text{ g}}{80 \text{ g mol}^{-1}} = 0.050 \text{ mol}$$

Hence $n(\text{Cu}(\text{NO}_3)_2) = 0.050 \text{ mol}$.

$$m(\text{Cu}(\text{NO}_3)_2) = nM = 0.050 \text{ mol} \times 188 \text{ g mol}^{-1} = 9.4 \text{ g}$$

Both product coefficients are one.

$$\text{atom economy} = \frac{M(\text{salt})}{M(\text{salt}) + M(\text{water})} \times 100\% = \frac{188}{188 + 18} \times 100\% = 91.3\%$$

3.3 The volume and density give the mass; the water formula then identifies the number of oxygen atoms per molecule.

$$m = \rho V = 1.0 \text{ g cm}^{-3} \times 0.050 \text{ cm}^3 = 0.050 \text{ g}$$

$$n = \frac{m}{M} = \frac{0.050 \text{ g}}{18.0 \text{ g mol}^{-1}} = 2.78 \times 10^{-3} \text{ mol}$$

$$N = nL = 2.78 \times 10^{-3} \text{ mol} \times 6.02 \times 10^{23} \text{ mol}^{-1} = 1.7 \times 10^{21} \text{ molecules}$$

There is one oxygen atom per molecule, so $N(\text{O}) = N(\text{H}_2\text{O}) = 1.7 \times 10^{21}$.