IB DP CHEMISTRY

Reactivity 2 · How Much, How Fast, and How Far?

MARK SCHEME

R2.1 How Much? The Amount of Chemical Change

R2.2 How Fast? The Rate of Chemical Change · R2.3 How Far? The Extent of Chemical Change

Standard and Higher Level · Syllabus 2025

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Original exam-style questions written for the IB Diploma Programme Chemistry course (first assessment 2025)

Section A — Multiple Choice: Answer Key (15 marks)

1. Answer: **B** — The limiting reagent is the reactant that is completely consumed first; it limits (determines) the maximum theoretical amount of product that can be formed.

2. Answer: **C** — From the mole ratio in the balanced equation, 1 mol N_2 reacts with 3 mol H_2, so 1.0 mol N_2 requires 3.0 mol H_2.

3. Answer: **A** — Percentage yield = (actual yield ÷ theoretical yield) × 100%, comparing the amount of product actually obtained with the maximum amount theoretically possible.

4. Answer: **C** — Percentage yield = (9.00 ÷ 12.0) × 100% = 75.0%.

5. Answer: **A** — Atom economy = (molar mass of desired product ÷ total molar mass of all reactants) × 100%, measuring the proportion of reactant atoms that are incorporated into the desired product, an important measure of a reaction's 'greenness'.

6. Answer: **B** — Reaction rate is defined as the change in concentration of a reactant (decreasing) or product (increasing) per unit time.

7. Answer: **D** — Reducing the pressure of a gaseous reactant decreases its concentration and the frequency of successful collisions, which would decrease (not increase) the rate.

8. Answer: **C** — The shaded area under the Maxwell-Boltzmann curve, to the right of E_a, represents the fraction of molecules that possess at least the activation energy and can therefore react upon a successful collision.

9. Answer: **B** — A catalyst provides an alternative reaction pathway with a lower activation energy, increasing the fraction of molecules with enough energy to react, without being used up itself and without changing ΔH or the equilibrium position.

10. Answer: **B** — The instantaneous rate of reaction at any time is given by the gradient of the tangent to the concentration-time curve at that point.

11. Answer: **B** — K_c is written as products over reactants, each raised to the power of its stoichiometric coefficient: $K_c = [SO_3]^2 \div ([SO_2]^2[O_2])$.

12. Answer: **B** — By Le Chatelier's principle, increasing pressure shifts the equilibrium towards the side with fewer moles of gas; here, 4 mol of gaseous reactants form 2 mol of gaseous product, so the equilibrium shifts towards the products (NH_3).

13. Answer: **B** — By Le Chatelier's principle, increasing temperature shifts an equilibrium in the endothermic direction (which absorbs the added heat); since the forward reaction is endothermic, the equilibrium shifts towards the products, increasing K_c.

14. Answer: **B** — At dynamic equilibrium, the forward and reverse reactions continue to occur, but at equal rates, so the macroscopic concentrations of reactants and products remain constant over time.

15. Answer: **C** — A catalyst speeds up both the forward and reverse reactions equally, so it has no effect on the position of equilibrium (or the value of K_c); it simply allows the system to reach equilibrium more quickly.

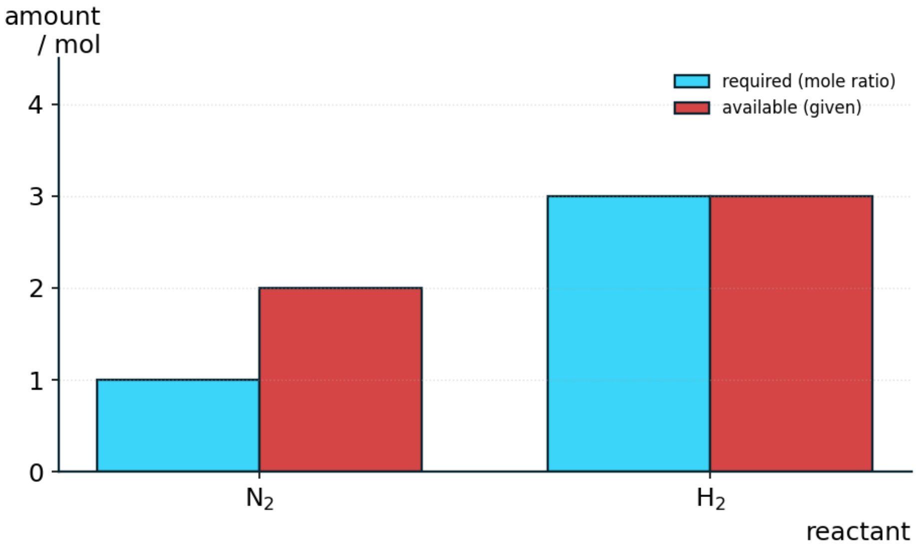
Section B — Structured Questions: Worked Solutions (65 marks)

Mark-scheme notation: M = method mark, A = accuracy mark (dependent on the preceding M mark), R = reasoning mark.

R2.1 The Amount of Chemical Change

Question 1 [7 marks]

Ammonia is manufactured industrially by the reaction $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$. The graph compares the amount of each reactant required by the mole ratio with the amount actually available in a particular mixture.



Reacting amounts: required (mole ratio) vs available (given data).

(a) Using the graph, identify the limiting reagent in this mixture. **[2]**

H_2 is the limiting reagent. **A1 A1**

(b) Explain your answer to part (a), using the mole ratio of the equation. **[3]**

The equation requires 3 mol H_2 for every 1 mol N_2. With 2.0 mol N_2 available, 6.0 mol H_2 would be needed to react completely with all the N_2. Only 3.0 mol H_2 is available, which is **less than the 6.0 mol required**, so H_2 runs out first and is the limiting reagent (N_2 is in excess). **R1 R1 A1**

(c) Calculate the maximum amount, in moles, of NH_3 that can be produced from this mixture. **[2]**

Using the limiting reagent, H_2: $n(NH_3) = ⅔·n(H_2) = (2/3)·3.0 =$ **2.00 mol**. **M1 A1**

Question 2 [6 marks]

Continuing from the reaction in Question 1 ($N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$, $M(NH_3) = 17.03\ g\ mol^{-1}$), the maximum amount of NH_3 produced was 2.00 mol.

(a) Calculate the maximum mass of NH_3 that could be produced. **[2]**

$m(NH_3) = n \times M = 2.00·17.03 =$ **34.1 g**. **M1 A1**

(b) Define the term 'limiting reagent'. **[2]**

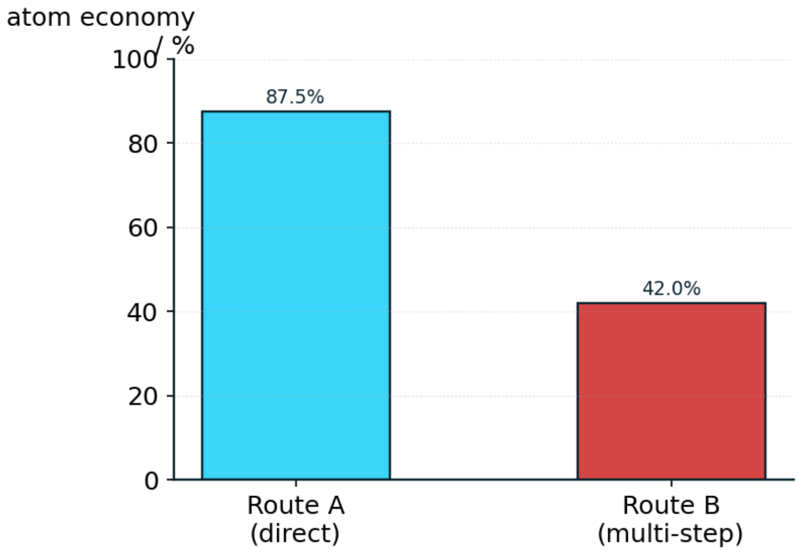
The limiting reagent is the reactant that is **completely used up first** in a reaction, and which therefore determines the **maximum theoretical amount** of product that can be formed. **A1 A1**

(c) Suggest why, in industrial processes such as the Haber process, one reactant is often deliberately used in excess. **[2]**

Using one reactant (often the cheaper or more readily available one, e.g. N_2 from air) in **excess** helps to ensure that the more valuable or expensive reactant (e.g. H_2) is converted as completely as possible, maximizing the yield based on that reactant and improving process efficiency. **R1 A1**

Question 3 [7 marks]

The graph compares the atom economy of two alternative synthesis routes for making the same desired product.



Atom economy of two synthesis routes (given data).

(a) Using the graph, identify which route has the higher atom economy. **[2]**

Route A has the higher atom economy (87.5%, compared with 42.0% for Route B). **A1 A1**

(b) Define 'atom economy', and explain why a chemist would generally prefer Route A over Route B. **[3]**

Atom economy = (molar mass of desired product ÷ total molar mass of all reactants) × 100%. Route A has a much higher atom economy, meaning a **greater proportion of the reactant atoms end up in the desired product**, with less mass wasted as by-products. This makes Route A more resource-efficient, more environmentally sustainable, and generally more economical (less waste to dispose of). **A1 R1 R1**

(c) The reaction $CH_3Br + NaOH \rightarrow CH_3OH + NaBr$ produces methanol as the desired product ($M(CH_3Br) = 94.94$, $M(NaOH) = 40.00$, $M(CH_3OH) = 32.04\ g\ mol^{-1}$). Calculate the atom economy of this reaction. **[2]**

Atom economy = [32.04 ÷ (94.94+40.00)] × 100% = [32.04 ÷ 134.94] × 100% = **23.7%**. **M1 A1**

Question 4 [6 marks]

A student carries out a synthesis reaction with a theoretical yield of 8.50 g of product, but only obtains 6.80 g in practice.

(a) Define the term 'percentage yield'. **[2]**

Percentage yield = (actual yield ÷ theoretical yield) × 100%, comparing the mass of product actually obtained with the maximum mass theoretically possible from the limiting reagent. **A1 A1**

(b) Calculate the percentage yield for this reaction. **[2]**

Percentage yield = (6.80 ÷ 8.50) × 100% = **80.0%**. **M1 A1**

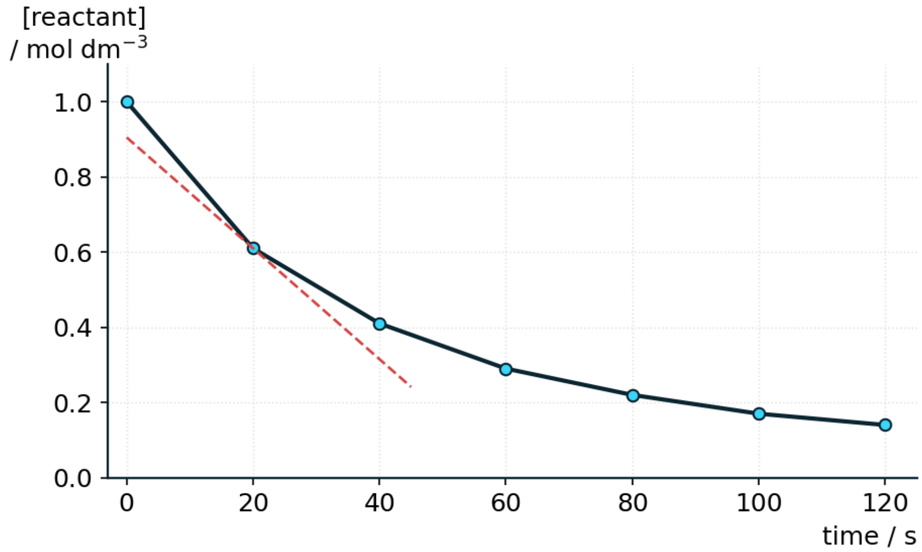
(c) Suggest one reason why the percentage yield of a reaction is often less than 100%. **[2]**

Any valid reason, e.g. the reaction may not go to completion (reaches equilibrium before all reactant is converted); some product may be **lost during purification/transfer** (e.g. filtration, recrystallization); **side reactions** may produce other products; or the reaction mixture may still contain impurities. **A1 R1**

R2.2 The Rate of Chemical Change

Question 5 [7 marks]

The graph shows how the concentration of a reactant changes with time during a reaction.



Concentration-time graph for a reaction (given data).

(a) Describe how the rate of reaction changes as the reaction proceeds, using the shape of the graph. **[2]**

The rate of reaction **decreases** over time (the curve becomes progressively less steep), as shown by the decreasing gradient of the curve. **A1 A1**

(b) Using the tangent drawn on the graph at t = 20 s, estimate the initial rate of reaction. **[3]**

Gradient of tangent at t = 20 s ≈ −0.0148 mol dm^{-3} s^{-1} (concentration decreasing). Rate of reaction = |gradient| ≈ **0.0148 mol dm^{-3} s^{-1}** (the negative sign of the concentration gradient indicates that the reactant is being consumed). **M1 M1 A1**

(c) Explain, using collision theory, why the rate of reaction decreases as the reaction proceeds. **[2]**

As the reaction proceeds, the **concentration of the reactant decreases**, so the particles become more spread out. This reduces the **frequency of collisions** between reactant particles, and therefore reduces the frequency of successful (effective) collisions, decreasing the rate of reaction. **R1 R1**

Question 6 [6 marks]

Several factors influence the rate of a chemical reaction.

(a) State two factors (other than temperature) that can increase the rate of a reaction. **[2]**

Any two of: **increasing the concentration** of a reactant in solution (or pressure of a gas); **increasing the surface area** of a solid reactant; **adding a suitable catalyst**. **A1 A1**

(b) Explain, using collision theory, why increasing the temperature increases the rate of a reaction. **[2]**

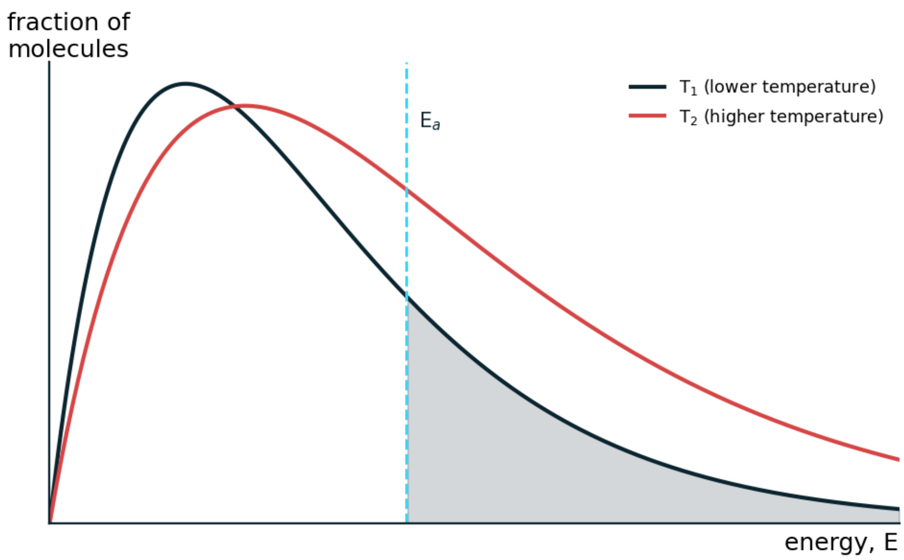
Increasing temperature increases the **average kinetic energy** of the particles, so they move faster. This increases both the **frequency of collisions** and, more significantly, the **proportion of collisions with energy ≥ the activation energy**, greatly increasing the frequency of successful (effective) collisions and hence the rate. **R1 R1**

(c) Explain why increasing the surface area of a solid reactant increases the rate of reaction. **[2]**

Increasing surface area (e.g. using a powder instead of a lump) exposes **more particles of the solid to collisions** with the other reactant, increasing the frequency of collisions (and hence successful collisions) per unit time, increasing the rate. **R1 A1**

Question 7 [7 marks]

The graph shows Maxwell-Boltzmann energy distribution curves for the same sample of gas at two different temperatures, T_1 and T_2, with the activation energy, E_a, marked.



Maxwell-Boltzmann energy distribution at two temperatures (schematic).

(a) Identify which curve, T_1 or T_2, represents the higher temperature, and justify your answer. **[2]**

T_2 represents the higher temperature: its curve is flatter, broader, and shifted to the right (towards higher energies), showing a wider spread of particle energies with a higher average energy, characteristic of a higher temperature. **A1 R1**

(b) Using the graph, explain why increasing the temperature increases the rate of reaction. **[3]**

At the higher temperature (T_2), a **greater proportion (area under the curve) of molecules have energy ≥ E_a**, the minimum energy needed to react. This means a greater fraction of collisions between particles will be successful (effective) collisions, so the rate of reaction increases. **R1 R1 A1**

(c) Explain, with reference to the graph, how a catalyst could increase the rate of reaction without any change in temperature. **[2]**

A catalyst provides an alternative reaction pathway with a **lower activation energy**, $E_a' < E_a$. This shifts the energy threshold on the graph to the left, so a **greater proportion of molecules (at the same temperature) now have enough energy** to react, increasing the rate without any change in temperature or the energy distribution curve itself. **R1 R1**

R2.3 The Extent of Chemical Change

Question 8 [6 marks]

Hydrogen and iodine react according to the equilibrium $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$. At a certain temperature, the equilibrium concentrations were found to be $[H_2] = 0.220$ mol dm^{-3}, $[I_2] = 0.220$ mol dm^{-3}, and $[HI] = 1.560$ mol dm^{-3}.

(a) Write the expression for K_c for this equilibrium. **[2]**

K_c = $\mathbf{[HI]^2 \div ([H_2][I_2])}$. **A1 A1**

(b) Calculate the value of K_c at this temperature. **[2]**

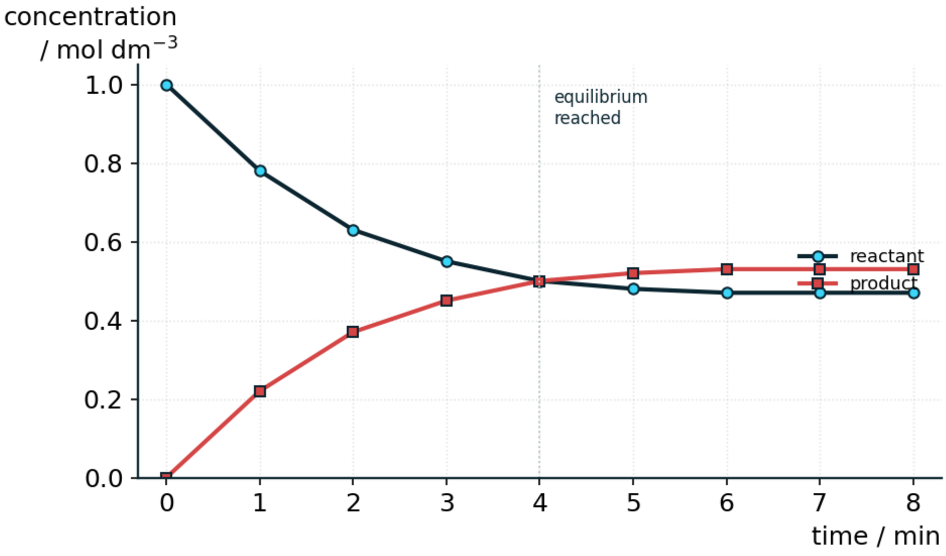
$K_c = (1.560)^2 \div (0.220 \cdot 0.220) =$ **50.3**. **M1 A1**

(c) State the units (if any) of K_c for this equilibrium, explaining your reasoning. **[2]**

K_c has **no units** (it is dimensionless). This is because the units of concentration (mol dm^{-3}) in the numerator, (mol dm^{-3})^2, exactly cancel with those in the denominator, (mol dm^{-3})^2, since the total power of concentration terms is the same (2) on both sides of the equation. **A1 R1**

Question 9 [7 marks]

The graph shows how the concentrations of a reactant and a product change with time as a reversible reaction approaches equilibrium in a closed system.



Concentration vs time as equilibrium is approached (given data).

(a) Using the graph, identify the approximate time at which equilibrium is first reached, and state how you can tell. **[2]**

Equilibrium is reached at approximately **t = 4 min**, shown by the point at which both concentration curves **become horizontal (constant)** and no longer change with time. **A1 A1**

(b) Explain, in terms of the dynamic nature of chemical equilibrium, why the concentrations remain constant after this point even though the reaction has not stopped. **[3]**

At equilibrium, both the **forward and reverse reactions are still occurring**, but they now proceed at **equal rates**. Reactant is still being converted to product, and product is still being converted back to reactant, but since these two rates are equal, there is **no net change** in the concentration of either species, so the concentrations appear constant (macroscopically) even though the system remains dynamic at the molecular level. **R1 R1 A1**

(c) Describe how the graph would differ if the initial concentration of the reactant were doubled (with all other conditions unchanged). **[2]**

Both curves would **start and finish at different concentration values** (higher for the reactant initially, and correspondingly higher equilibrium concentrations for both species assuming the same K_c), but the **general shape** of the curves (reactant decreasing, product increasing, both leveling off at equilibrium) would be the same, and equilibrium would likely be reached in a similar or shorter time due to the higher initial rate. **A1 R1**

Question 10 [6 marks]

Le Chatelier's principle can be used to predict how an equilibrium system responds to a change in conditions.

(a) State Le Chatelier's principle. **[2]**

Le Chatelier's principle states that if a change is imposed on a system at equilibrium, the **equilibrium position shifts to partially counteract (oppose) that change**, establishing a new equilibrium. **A1 A1**

(b) Predict and explain the effect of increasing the total pressure on the equilibrium position of $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$. **[2]**

The equilibrium shifts **towards the products (NH_3)**, since there are fewer moles of gas on the product side (2 mol) than the reactant side (4 mol); this partially counteracts the increase in pressure by reducing the total number of gas particles. **A1 R1**

(c) Predict and explain the effect of increasing the temperature on an equilibrium in which the forward reaction is exothermic. **[2]**

The equilibrium shifts **towards the reactants** (in the endothermic, reverse direction), since this absorbs some of the added heat energy, partially counteracting the increase in temperature; the yield of product decreases and K_c decreases. **A1 R1**