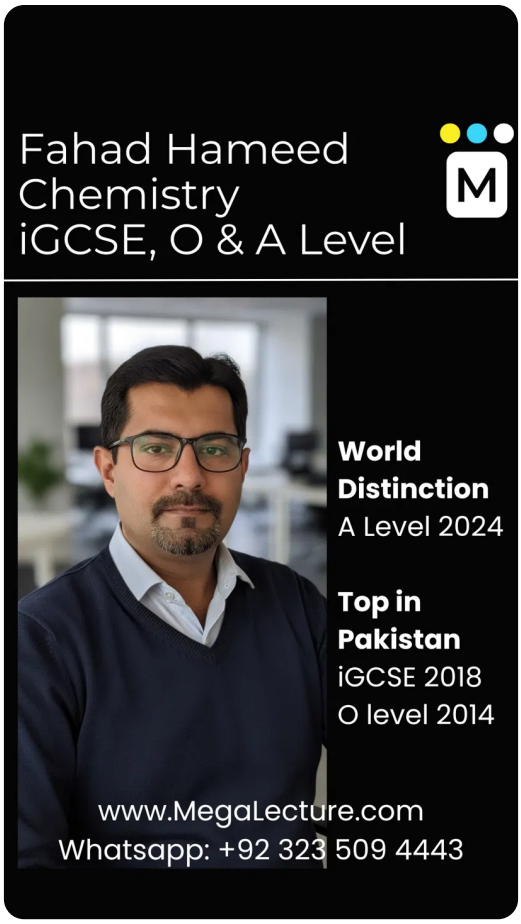
MEGA LECTURE · A LEVEL CHEMISTRY

# Chapter 12: Chemical Equilibrium

OCR A Level Chemistry A (H432) — Structured Practice Worksheet




| SPECIFICATION | TOTAL MARKS | SUGGESTED TIME |
|---|---|---|
| 3.1.6 Equilibrium: dynamic equilibrium, Le Chatelier, $K_c$, industrial applications | 95 | 1 hour 55 minutes |

MEGA LECTURE · A LEVEL CHEMISTRY

# Chapter 12: Chemical Equilibrium

OCR A Level Chemistry A (H432) — Structured Practice Worksheet

| SPECIFICATION | TOTAL MARKS | SUGGESTED TIME |
|---|---|---|
| 3.1.6 Equilibrium: dynamic equilibrium, Le Chatelier, $K_c$, industrial applications | 95 | 1 hour 55 minutes |

**Instructions to candidates**

- Answer **all** questions in the spaces provided. Show all working in calculations.
- Marks are shown in brackets [ ] at the end of each part.

## Question 1 — Dynamic equilibrium

3.1.6

a. State what is meant by a *dynamic equilibrium*, referring to the rate of the forward and backward reactions. **[3]**

b. State two conditions necessary for a chemical system to reach equilibrium. **[2]**

c. Explain why, at equilibrium, the concentrations of reactants and products remain constant even though the reaction has not stopped. **[3]**

**Question 1 total: 8 marks**

## Question 2 — Le Chatelier's principle: concentration

3.1.6

$Fe^{3+}(aq) + SCN^{-}(aq) \rightleftharpoons FeSCN^{2+}(aq)$ (pale yellow) (colourless) (deep red)

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

b. Predict and explain the observation when extra $Fe^{3+}(aq)$ is added to this equilibrium mixture. **[3]**

c. Predict and explain the observation when the $FeSCN^{2+}$ product is removed (e.g. by adding a reagent that precipitates it). **[3]**

d. State how the position of equilibrium is defined to have shifted in part (b). **[2]**

**Question 2 total: 10 marks**

## Question 3 — Le Chatelier's principle: pressure and volume 3.1.6

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92 \text{ kJ mol}^{-1}$

a. State and explain the effect of increasing the pressure on the position of equilibrium in this reaction. **[3]**

b. State the effect of increasing pressure on the yield of ammonia. **[2]**

c. A different equilibrium, $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$, has equal numbers of gas moles on each side. Explain why changing the pressure has no effect on the position of this equilibrium. **[3]**

d. Explain why increasing pressure increases the *rate* at which equilibrium is reached, even in a reaction where pressure does not affect the position of equilibrium. **[2]**

**Question 3 total: 10 marks**

## Question 4 — Le Chatelier's principle: temperature

3.1.6

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92 \text{ kJ mol}^{-1}$ (forward reaction exothermic)

a. State and explain the effect of increasing the temperature on the position of equilibrium and the yield of ammonia. **[3]**

b. State the effect of decreasing the temperature on the yield of ammonia. **[2]**

c. Explain why, despite the effect on yield described in (a), a moderately high temperature (about 450 °C) is used industrially rather than a very low temperature. **[3]**

d. Explain, using Le Chatelier's principle, why the equilibrium constant $K_c$ for an exothermic reaction decreases as temperature increases. **[3]**

**Question 4 total: 11 marks**

## Question 5 — Catalysts and equilibrium

3.1.6

a. State the effect of a catalyst on the position of equilibrium and on the value of $K_c$. **[2]**

b. Explain why a catalyst has no effect on the position of equilibrium, in terms of its effect on the forward and reverse reaction rates. **[3]**

c. State the practical benefit of using a catalyst in an industrial equilibrium process such as the Haber process, given that it does not change the equilibrium yield. **[2]**

**Question 5 total: 7 marks**

## Question 6 — Writing $K_c$ expressions

3.1.6

a. Write the expression for $K_c$, including units, for each of the following equilibria. **[9]**

| Equilibrium | $K_c$ expression (with units) |
|---|---|
| $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ | |
| $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$ | |
| $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$ | |

**Question 6 total: 9 marks**

## Question 7 — Calculating $K_c$

3.1.6

At a fixed temperature, 2.00 mol of hydrogen and 2.00 mol of iodine vapour are mixed in a 5.00 $dm^3$ container and allowed to reach equilibrium: $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$. At equilibrium, the mixture contains 3.20 mol of HI.

a. Construct an ICE (initial, change, equilibrium) table and determine the equilibrium amounts, in mol, of $H_2$, $I_2$ and HI. **[4]**

b. Calculate the equilibrium concentrations, in mol $dm^{-3}$, of each species. **[3]**

c. Calculate the value of $K_c$ for this reaction at this temperature, including its units. **[3]**

**Question 7 total: 10 marks**

## Question 8 — Kc calculation with an ICE table (moles change) 3.1.6

1.00 mol of $PCl_5(g)$ is placed in a 2.00 $dm^3$ container and allowed to reach equilibrium: $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$. At equilibrium, 0.65 mol of $PCl_5$ remains.

a. Determine the equilibrium amounts, in mol, of $PCl_5$, $PCl_3$ and $Cl_2$. **[4]**

b. Calculate the equilibrium concentrations of each species. **[3]**

c. Write the expression for $K_c$ and calculate its value, including units. **[3]**

d. State and explain the effect on the value of $K_c$ if the temperature is increased, given that the forward reaction (decomposition of $PCl_5$) is endothermic. **[2]**

**Question 8 total: 12 marks**

## Question 9 — Industrial application: the Haber process 3.1.6

a. Write the equation for the Haber process, including state symbols. **[2]**

b. State the typical industrial conditions used: temperature, pressure and catalyst. **[3]**

c. Explain why these conditions represent a compromise between equilibrium yield, rate of reaction, and cost, rather than the conditions that would give the theoretical maximum yield. **[4]**

d. Unreacted $N_2$ and $H_2$ are recycled back into the reactor rather than discarded. Explain the economic and environmental benefit of this. **[3]**

**Question 9 total: 12 marks**

## Question 10 — Extended response

Synoptic

**The Haber process operates at approximately 450 °C and 200 atm, using an iron catalyst, even though a lower temperature and a much higher pressure would each individually give a greater equilibrium yield of ammonia. Explain, using ideas about equilibrium position, reaction rate, and economic cost, why these particular conditions are chosen industrially. [6]**

*This question is marked using a level of response.*

**Question 10 total: 6 marks**

**PAPER TOTAL: 95 MARKS**

# MARK SCHEME — Chapter 12: Chemical Equilibrium

*Award marks independently unless stated. ECF applies to calculations.*

**Q1 (a) [3]**

- A dynamic equilibrium exists in a closed system when the rate of the forward reaction equals the rate of the backward (reverse) reaction. (2)
- Both reactions are still occurring (continuously), just at equal rates. (1)

**Q1 (b) [2]**

- The system must be closed (no matter can enter or leave). (1)
- Temperature (and pressure, for gaseous systems) must be constant. (1)

**Q1 (c) [3]**

- Reactants are being converted to products by the forward reaction and products are being converted back to reactants by the reverse reaction at the same time. (1)
- Since the forward and reverse rates are equal, reactants are used up at exactly the same rate as they are reformed. (1)
- So there is no net change in the concentration of any species, even though both reactions continue. (1)

**Q2 (a) [2]**

- If a system at equilibrium is subjected to a change (in concentration, pressure or temperature)... (1)
- ...the position of equilibrium shifts to counteract (oppose/minimise) that change. (1)

**Q2 (b) [3]**

- The solution becomes a more intense/deeper red colour. (1)
- Adding $Fe^{3+}$ increases the concentration of a reactant. (1)
- The equilibrium shifts right (forward) to remove/use up some of the added $Fe^{3+}$, increasing [$FeSCN^{2+}$]. (1)

**Q2 (c) [3]**

- The remaining solution becomes paler / less red (or, if all $FeSCN^{2+}$ is precipitated, colourless/pale yellow). (1)
- Removing $FeSCN^{2+}$ decreases the concentration of the product. (1)
- The equilibrium shifts right (forward) to replace some of the removed $FeSCN^{2+}$. (1)

**Q2 (d) [2]**

- The position of equilibrium has shifted to the right / towards the products (forward direction). (2)

**Q3 (a) [3]**

- Increasing pressure shifts the equilibrium towards the side with fewer gas moles. (1)
- There are 4 mol of gas on the left (1 + 3) and 2 mol of gas on the right. (1)
- So the equilibrium shifts to the right (forward), towards $NH_3$, to reduce the number of gas particles/oppose the increase in pressure. (1)

**Q3 (b) [2]**

- Increasing pressure increases the yield of ammonia. (2)

**Q3 (c) [3]**

- There are 2 mol of gas on each side of the equation. (1)
- Increasing pressure affects the forward and reverse reactions equally, as there is no change in the number of gas particles to oppose. (1)
- So the position of equilibrium does not shift when pressure changes. (1)

**Q3 (d) [2]**

- Increasing pressure increases the concentration of gas particles (more particles per unit volume). (1)
- This increases the frequency of collisions between particles, increasing both the forward and reverse reaction rates, so equilibrium is reached faster. (1)

**Q4 (a) [3]**

- Increasing temperature shifts the equilibrium in the endothermic direction. (1)
- The forward reaction is exothermic, so the reverse (endothermic) reaction is favoured — equilibrium shifts left/back towards $N_2$ and $H_2$. (1)
- The yield of ammonia decreases. (1)

**Q4 (b) [2]**

- Decreasing temperature increases the yield of ammonia (favours the exothermic forward reaction). (2)

**Q4 (c) [3]**

- Although a lower temperature would give a higher equilibrium yield, the rate of reaction would be very slow at low temperature. (1)
- It would take too long (be uneconomical) to reach equilibrium at a very low temperature. (1)
- 450 °C is a compromise that gives a reasonably fast rate while still achieving an acceptable (if not maximum) yield, which is more economically efficient overall. (1)

**Q4 (d) [3]**

- Increasing temperature shifts the equilibrium position towards the reactants (endothermic/reverse direction) for an exothermic forward reaction. (1)
- This means the equilibrium concentration of products decreases relative to reactants. (1)
- Since $K_c$ = [products]/[reactants] (raised to appropriate powers), a smaller products-to-reactants ratio means $K_c$ decreases as temperature increases. (1)

**Q5 (a) [2]**

- A catalyst has no effect on the position of equilibrium. (1)
- A catalyst has no effect on the value of $K_c$. (1)

**Q5 (b) [3]**

- A catalyst provides an alternative pathway with lower activation energy for both the forward and reverse reactions. (1)
- It speeds up the forward and reverse reactions by exactly the same factor. (1)
- Since both rates increase equally, equilibrium is reached faster but the equilibrium position (and $K_c$) is unchanged. (1)

**Q5 (c) [2]**

- A catalyst allows equilibrium (and the same equilibrium yield) to be reached much more quickly. (1)
- This increases the rate of production of the desired product, making the process more economically efficient/profitable per unit time. (1)

**Q6 (a) [9] — 3 marks each (expression + units)**

- $K_c = [NH_3]^2 / ([N_2][H_2]^3)$; units = $mol^{-2}\ dm^6$. (3)
- $K_c = [SO_3]^2 / ([SO_2]^2[O_2])$; units = $mol^{-1}\ dm^3$. (3)
- $K_c = [HI]^2 / ([H_2][I_2])$; no units (dimensionless). (3)

**Q7 (a) [4]**

- Initial: $H_2$ = 2.00, $I_2$ = 2.00, HI = 0. (1)
- Change: $H_2$ = −1.60, $I_2$ = −1.60, HI = +3.20 (from stoichiometry, since 2 mol HI forms per 1 mol $H_2$ and $I_2$ reacted). (2)
- Equilibrium: $H_2$ = 0.40 mol, $I_2$ = 0.40 mol, HI = 3.20 mol. (1)

**Q7 (b) [3]**

- $[H_2] = 0.40 \div 5.00 = 0.0800\ mol\ dm^{-3}$. (1)
- $[I_2] = 0.40 \div 5.00 = 0.0800\ mol\ dm^{-3}$. (1)
- $[HI] = 3.20 \div 5.00 = 0.640\ mol\ dm^{-3}$. (1)

**Q7 (c) [3]**

- $K_c = [HI]^2 / ([H_2][I_2]) = (0.640)^2 / (0.0800 \times 0.0800)$ (1)
- $= 0.4096 \div 0.00640$ (1)
- = 64.0 (no units). (1)

### Q8 (a) [4]

- Initial: $PCl_5 = 1.00$, $PCl_3 = 0$, $Cl_2 = 0$. (1)
- Change: $PCl_5 = -0.35$, $PCl_3 = +0.35$, $Cl_2 = +0.35$ (since 0.65 mol $PCl_5$ remains, 0.35 mol reacted). (2)
- Equilibrium: $PCl_5 = 0.65$ mol, $PCl_3 = 0.35$ mol, $Cl_2 = 0.35$ mol. (1)

### Q8 (b) [3]

- $[PCl_5] = 0.65 \div 2.00 = 0.325$ mol $dm^{-3}$. (1)
- $[PCl_3] = 0.35 \div 2.00 = 0.175$ mol $dm^{-3}$. (1)
- $[Cl_2] = 0.35 \div 2.00 = 0.175$ mol $dm^{-3}$. (1)

### Q8 (c) [3]

- $K_c = [PCl_3][Cl_2] / [PCl_5] = (0.175 \times 0.175) \div 0.325$ (1)
- $= 0.030625 \div 0.325 = 0.0942$ (1)
- Units: mol $dm^{-3}$. (1)

### Q8 (d) [2]

- $K_c$ increases as temperature increases. (1)
- Increasing temperature favours the endothermic (forward) reaction, shifting equilibrium towards more products, so [products]/[reactants] — and hence $K_c$ — increases. (1)

### Q9 (a) [2]

- $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ (1 species/balancing, 1 state symbols)

### Q9 (b) [3]

- Temperature: approximately 400–450 °C. (1)
- Pressure: approximately 200 atm. (1)
- Catalyst: iron (finely divided/with a promoter). (1)

### Q9 (c) [4]

- A lower temperature would give a higher equilibrium yield (exothermic forward reaction), but the rate would be far too slow to be economical. (1)
- 450 °C is a compromise giving an acceptable rate with a reasonable (though not maximum) yield. (1)
- A much higher pressure would increase the yield further (fewer gas moles on the product side), but very high pressures need very strong/expensive equipment and are costly and hazardous to maintain. (1)
- 200 atm is a compromise between improving yield/rate and keeping equipment and running costs manageable. (1)

### Q9 (d) [3]

- Recycling unreacted $N_2$ and $H_2$ means less raw material is wasted, reducing the cost of the process. (1)
- Over time, effectively all of the nitrogen and hydrogen fed into the process is eventually converted to ammonia, improving overall efficiency despite the low single-pass yield. (1)
- Environmentally, this reduces the amount of unreacted gas that would otherwise need to be vented/wasted, reducing resource use and waste. (1)

### Q10 [6] — Level of response

- **Level 3 (5–6):** Explains the compromise for both temperature and pressure fully and correctly, referring to equilibrium position/yield, reaction rate, and economic/practical cost for each variable.
- **Level 2 (3–4):** Explains the compromise for one variable (temperature or pressure) fully, with a partial or less complete explanation for the other.
- **Level 1 (1–2):** States that a compromise is made but with limited or generic reasoning; little reference to rate, yield or cost specifically.

***Indicative content:*** *A lower temperature would shift the exothermic equilibrium further towards ammonia, increasing yield, but would make the reaction rate too slow to be commercially viable — 450 °C balances an acceptable rate against a reduced (but still workable) yield, and the iron catalyst is used to increase the rate further without affecting the equilibrium position or yield. A higher pressure would shift the equilibrium further towards ammonia (fewer gas moles on the product side), increasing yield and also increasing rate (higher concentration of gas particles), but the cost of building and maintaining plant and pipework capable of withstanding very high pressures rises sharply, and there are greater safety risks — 200 atm is chosen as an economic compromise that gives a reasonably good yield and rate without excessive capital/running costs.*

**END OF MARK SCHEME · 95 marks**