2.17 Reversible Reactions and Equilibrium: 1-hour Pack

AQA 8464 · Calculator allowed · about 60 minutes

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

Industrial production of ammonia: the Haber process

Original context passage written for Revision Library.

Ammonia (NH_3) is manufactured on an industrial scale by the Haber process. Nitrogen is obtained from the air and hydrogen is obtained from natural gas. The two gases are purified, mixed in the correct ratio, and passed over an iron catalyst inside a reaction vessel held at a temperature of about 450°C and a pressure of about 200 atmospheres. The forward reaction, $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$, is exothermic. Not all of the nitrogen and hydrogen react, since the reaction reaches dynamic equilibrium rather than going to completion. As the mixture leaves the reactor it is cooled so that the ammonia liquefies and can be separated. The unreacted nitrogen and hydrogen are recycled back into the reactor.

1 Use the information above about the Haber process. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ (relative formula masses: $N_2 = 28$, $H_2 = 2$, $NH_3 = 17$)

(a) Calculate the maximum mass, in kg, of ammonia that could be produced from 28 kg of nitrogen reacting with an excess of hydrogen. **(3)**

.....

(b) In the actual industrial process, only 21.25 kg of ammonia is obtained from this reaction. Calculate the percentage yield. **(2)**

.....

(Total for Question 1 is 5 marks)

© Revision Library | revisionlibrary.co.uk

2 Higher tier only. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ (forward reaction exothermic). Extra nitrogen is added to the equilibrium mixture at constant temperature and volume.

(a) Predict the effect on the position of equilibrium of adding extra nitrogen. **(1)**

(b) Use Le Chatelier's principle to explain your answer to part (a). **(2)**

(c) In industry, ammonia is continually removed from the equilibrium mixture by cooling and liquefying it. State and explain the effect this has on the overall yield of ammonia. **(2)**

(Total for Question 2 is 5 marks)

© Revision Library | revisionlibrary.co.uk

3 A student investigates the effect of a catalyst on an equilibrium. The reaction is $A(g) \rightleftharpoons B(g)$. The student measures the time to reach equilibrium without and with a catalyst. Explain what changes the catalyst causes to the equilibrium position, the equilibrium constant, and the rates of the forward and backward reactions.

(a) State the effect of adding a catalyst on the position of equilibrium and the equilibrium constant Kc. **(1)**

(b) Explain how a catalyst affects the rates of the forward and backward reactions and why equilibrium is reached faster. **(2)**

(Total for Question 3 is 3 marks)

---

4 Higher tier only. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

(a) State the total number of moles of gas on the reactant side and on the product side of this equation. **(1)**

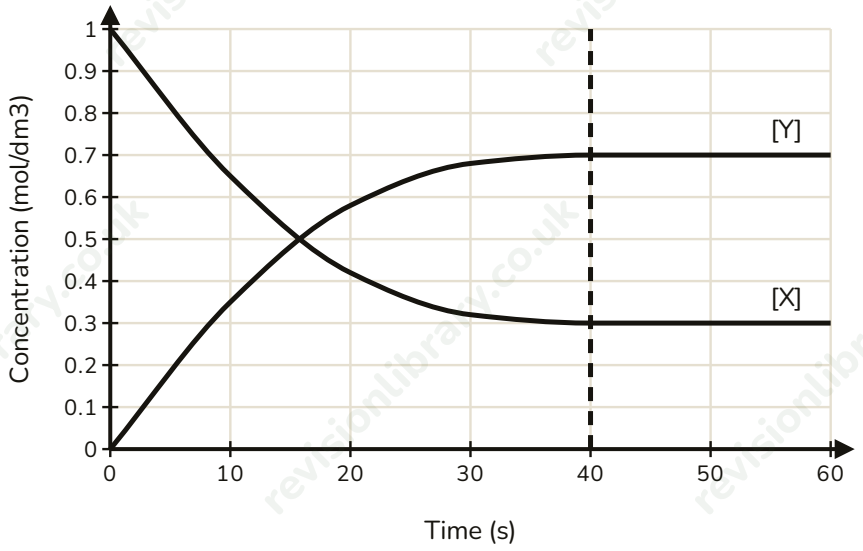
(b) Predict and explain the effect of increasing the pressure on the position of equilibrium. **(2)**

(c) State the effect of increasing the pressure on the percentage yield of ammonia. **(1)**

(Total for Question 4 is 4 marks)

© Revision Library | revisionlibrary.co.uk

5 Higher tier only. A student uses a colorimeter to monitor a reversible reaction, X ⇌ Y, as it approaches equilibrium in a closed flask. The graph below shows how the concentrations of reactant X and product Y change with time.



(a) State the time at which the reaction mixture first reaches equilibrium. **(1)**

(b) Explain what the constant concentrations from 40 s onwards show about the mixture. Then use your knowledge to explain what is meant by dynamic equilibrium. **(2)**

(c) Explain why the concentrations of X and Y are not equal to each other at equilibrium, even though both are constant. **(1)**

(Total for Question 5 is 4 marks)

© Revision Library | revisionlibrary.co.uk

6 Higher tier only. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ (forward reaction exothermic). The temperature of the reaction vessel is increased, with the pressure held constant.

(a) Predict the effect on the position of equilibrium. **(1)**

(b) Use Le Chatelier's principle to explain your answer. **(2)**

(c) State the effect of this temperature increase on the percentage yield of ammonia at equilibrium. **(1)**

(Total for Question 6 is 4 marks)

---

7 Higher tier only. A chemical company operates a reactor at equilibrium, producing ammonia by the Haber process. The engineers first decrease the temperature of the reactor, and then also increase the pressure, while keeping the amounts of nitrogen and hydrogen the same.

(a) State and explain the effect of decreasing the temperature alone on the yield of ammonia and on the rate at which equilibrium is reached. **(2)**

(b) State and explain the additional effect of then increasing the pressure. **(2)**

(c) Despite these yield increases, industrial chemists do not use the lowest possible temperature and the highest possible pressure. Explain why. **(2)**

(Total for Question 7 is 6 marks)

© Revision Library | revisionlibrary.co.uk

8 Higher tier only. A sealed container initially holds 4.0 mol of nitrogen and 9.0 mol of hydrogen. The mixture is left until equilibrium is reached:

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

At equilibrium, 1.5 mol of ammonia has been formed.

(a) Use the mole ratio in the equation to calculate the number of moles of nitrogen and of hydrogen that have reacted. **(2)**

(b) Calculate the number of moles of nitrogen and of hydrogen present at equilibrium. **(2)**

(c) Even after a very long time, not all of the nitrogen and hydrogen are converted into ammonia. Suggest why. **(1)**

(Total for Question 8 is 5 marks)

© Revision Library | revisionlibrary.co.uk

9 Extended response (6 marks): Ethanoic acid and ethanol react to form ethyl ethanoate and water in a reversible esterification: $CH_3COOH(aq) + C_2H_5OH(aq) \rightleftharpoons CH_3COOC_2H_5(aq) + H_2O(l)$. A student investigates the effect of removing water on the yield of ester at constant temperature. Describe and explain what happens to the equilibrium position and to the value of Kc when water is removed, and suggest one practical way the student could remove water during the experiment. Include consideration of whether the change is temporary or permanent and any experimental limitations.

(Total for Question 9 is 6 marks)

---

10 *Higher tier only. Ammonia is manufactured industrially using the Haber process at a temperature of about 450°C, a pressure of about 200 atmospheres, and an iron catalyst. These conditions do not give the highest possible equilibrium yield of ammonia.
Explain why these particular conditions are used.

(Total for Question 10 is 6 marks)

© Revision Library | revisionlibrary.co.uk

Mark scheme · 2.17 Reversible Reactions and Equilibrium: 1-hour Pack

Question 1

(a) moles of N_2 = 28000 / 28 = 1000 mol oe (or equivalent working in kg: 28 kg / (28 kg/kmol) = 1 kmol) **M1**

(a) moles of NH_3 = 1000 x 2 = 2000 mol, using the mole ratio $N_2 : NH_3 = 1 : 2$ **M1**

(a) mass of NH_3 = 2000 x 17 = 34000 g = 34 kg cao **A1**

(a) Answer: 34 kg

(b) percentage yield = (actual yield / theoretical yield) x 100 = (21.25 / 34) x 100 (allow ft from candidate's answer to part a) **M1**

(b) 62.5% cao (ft consistent with their part a answer) **A1**

(b) Answer: 62.5%

Question 2

(a) the position of equilibrium shifts to the right (towards the products/ammonia) **B1**

(a) Answer: The position of equilibrium shifts to the right, towards the products (ammonia).

(b) the system acts to oppose (counteract) the increase in nitrogen concentration oe **B1**

(b) by reacting more of the nitrogen (and hydrogen) to form more ammonia, using up the extra nitrogen that was added oe **B1**

(b) Answer: The system opposes the increase in nitrogen concentration by reacting more nitrogen and hydrogen together to form more ammonia, using up the extra nitrogen added.

(c) the yield of ammonia increases **B1**

(c) because removing ammonia shifts the position of equilibrium to the right (forward) to replace the ammonia that has been removed oe **B1**

(c) Answer: The yield of ammonia increases, because removing ammonia from the mixture shifts the equilibrium position to the right to replace it, forming more ammonia.

Question 3

(a) no change to the position of equilibrium or to the equilibrium constant Kc, oe **B1**

(a) Answer: No change to the equilibrium position and no change to Kc.

(b) states catalyst provides an alternative lower-energy pathway so increases the rate(s) **M1**

(b) both forward and backward reaction rates increase so equilibrium is reached faster, oe **A1**

(b) Answer: A catalyst provides an alternative lower-energy pathway, increasing both forward and backward rates so equilibrium is reached faster.

Question 4

(a) reactant side = 4 mol of gas (1 + 3); product side = 2 mol of gas, both stated correctly **B1**

(a) Answer: Reactant side: 4 mol of gas (1 mol N_2 + 3 mol H_2). Product side: 2 mol of gas (2 mol NH_3).

(b) the position of equilibrium shifts to the right/towards the products (ammonia) **B1**

(b) because this is the side with fewer moles of gas, so shifting this way reduces the pressure, opposing the increase oe **B1**

(b) Answer: The equilibrium shifts to the right, towards ammonia, because that is the side with fewer moles of gas, which reduces the pressure and opposes the increase.

(c) the percentage yield increases **B1**

(c) Answer: The percentage yield of ammonia increases.

Question 5

(a) 40 s **B1**

(a) Answer: 40 s.

(b) equilibrium has been reached: both concentrations are constant (no longer change) from 40 s onwards oe **B1**

(b) at dynamic equilibrium the forward and reverse reactions continue at equal, non-zero rates oe **B1**

(b) Answer: The constant concentrations from 40 s onwards show that equilibrium has been reached: the concentrations no longer change. At dynamic equilibrium, the forward and reverse reactions continue at equal, non-zero rates.

(c) dynamic equilibrium only requires the forward and reverse rates to be equal, not the concentrations of reactant and product, which depend on the position of equilibrium for this reaction oe **B1**

(c) Answer: Dynamic equilibrium only requires the forward and reverse rates to be equal; the actual concentrations of X and Y depend on the position of equilibrium for this particular reaction, so they need not be equal.

Question 6

(a) the position of equilibrium shifts to the left (towards the reactants, N_2 and H_2) **B1**

(a) Answer: The position of equilibrium shifts to the left, towards the reactants.

(b) the system acts to oppose the increase in temperature oe **B1**

(b) by favouring the endothermic (reverse) reaction, which absorbs (takes in) the extra heat energy oe **B1**

(b) Answer: The system opposes the increase in temperature by favouring the endothermic reverse reaction, which absorbs the extra heat energy.

(c) the percentage yield decreases **B1**

(c) Answer: The percentage yield of ammonia decreases.

© Revision Library | revisionlibrary.co.uk

Question 7

(a) the yield of ammonia increases, because the forward reaction is exothermic and the equilibrium shifts to oppose the decrease in temperature by favouring the exothermic (forward) reaction oe **B1**

(a) the rate of reaching (a new) equilibrium decreases (is slower), because a lower temperature means a lower rate of reaction oe **B1**

(a) Answer: The yield of ammonia increases, since the forward reaction is exothermic and the equilibrium shifts to oppose the temperature decrease by favouring the forward reaction. However, the rate of reaching a new equilibrium decreases, because lower temperature means a slower rate of reaction.

(b) the yield of ammonia increases further **B1**

(b) because increasing pressure shifts the equilibrium further towards the side with fewer gas molecules (ammonia), opposing the increase in pressure oe **B1**

(b) Answer: The yield of ammonia increases further, because increasing the pressure shifts the equilibrium even more towards the ammonia side (fewer gas molecules), opposing the pressure increase.

(c) using the lowest possible temperature would make the rate of reaction far too slow to be economical, even though the equilibrium yield would be higher oe **B1**

(c) using extremely high pressure would require very strong, expensive equipment and higher running (energy/safety) costs, which would outweigh the benefit of the extra yield oe **B1**

(c) Answer: The lowest possible temperature would give too slow a rate of reaction to be economical, and extremely high pressure would require very strong, expensive equipment and much higher running and safety costs, outweighing the benefit of the extra yield.

Question 8

(a) moles N_2 reacted = 1.5 / 2 = 0.75 mol, using the ratio N_2 : NH_3 = 1 : 2 **M1**

(a) moles H_2 reacted = 0.75 x 3 = 2.25 mol cao, using the ratio H_2 : NH_3 = 3 : 2 **A1**

(a) Answer: N_2 reacted = 0.75 mol; H_2 reacted = 2.25 mol

(b) moles N_2 at equilibrium = 4.0 - 0.75 = 3.25 mol (allow ft from candidate's answer to part a) **M1**

(b) moles H_2 at equilibrium = 9.0 - 2.25 = 6.75 mol cao (allow ft from candidate's answer to part a) **A1**

(b) Answer: N_2 at equilibrium = 3.25 mol; H_2 at equilibrium = 6.75 mol

(c) the reaction reaches dynamic equilibrium in this closed system, at which point the forward and reverse reactions occur at equal rates, so the reaction does not go to completion and some N_2 and H_2 remain oe **B1**

(c) Answer: The reaction reaches dynamic equilibrium in the closed container: the forward and reverse reactions continue at equal rates, so the reaction never goes to completion and some nitrogen and hydrogen always remain.

Question 9

Level 3 Detailed description and explanation: clearly explains that removing water shifts equilibrium to the right to form more ester, links to Le Chatelier and states Kc is unchanged, gives a suitable practical method for removing water and discusses temporary or permanent nature and limitations. **5-6**

Level 2 Partial explanation: states equilibrium shifts towards ester and that this increases yield, states Kc unchanged but with limited justification, and suggests a practical method without discussing limitations. **3-4**

Level 1 Simple statement: e.g. removing water increases ester yield, or suggests a method, with little or no explanation. **1-2**

Indicative content:

- Removing water shifts equilibrium to the right (towards products) according to Le Chatelier, increasing the yield of ethyl ethanoate.
- Kc is a constant at fixed temperature and does not change because only concentrations are changed; removing water changes the position of equilibrium but not Kc.
- Practical methods: use a drying agent (e.g. anhydrous sodium sulfate) to remove water, use a Dean-Stark apparatus to continuously remove water under reflux, or distil off the water if boiling points allow.
- Discuss temporary vs permanent: if water is removed continuously, the shift is maintained while removal continues; if drying agent becomes saturated the effect ends; removing water until completion may not drive reaction to 100% due to equilibrium constraints and side reactions.
- Experimental limitations: drying agents may absorb some ester or cause side reactions; Dean-Stark requires suitable solvent and heating and may not remove all water; temperature must remain constant because Kc depends on temperature.

© Revision Library | revisionlibrary.co.uk

Question 10

Level 1 Simple, isolated statement(s) are made about temperature, pressure or the catalyst, with little or no link to rate, yield or cost. **1-2**

Level 2 Some explanation is given of how temperature and/or pressure affect rate and yield, with limited or no reference to the catalyst, or to the idea of an overall economic compromise. **3-4**

Level 3 A clear, logically linked explanation is given, covering temperature, pressure and the catalyst, correctly relating each to rate and/or yield, and clearly explaining why a compromise is chosen for economic reasons. **5-6**

Indicative content:

- The forward reaction is exothermic, so a lower temperature would give a higher equilibrium yield of ammonia.
- However, a lower temperature gives a slower rate of reaction, so equilibrium would take too long to reach to be economical.
- 450°C is a compromise: it gives a fast enough rate while still achieving a reasonably good yield.
- Increasing pressure shifts the equilibrium towards the side with fewer gas molecules (the ammonia side), increasing the yield.
- However, very high pressures need stronger, more expensive reaction vessels and pipework, cost more energy to generate, and increase safety risk (of leaks or explosion).
- 200 atmospheres is a compromise between a higher yield and the cost/safety of achieving very high pressure.
- The iron catalyst increases the rate of both the forward and reverse reactions equally, so it does not change the position of equilibrium or the yield of ammonia.
- Using a catalyst means a lower temperature can be used than would otherwise be needed for a reasonable rate, saving energy costs without a large loss of yield.
- Overall, the conditions chosen balance the cost of achieving them against the value of the ammonia produced and the rate of production, in order to maximise profit.

© Revision Library | revisionlibrary.co.uk