

Ammonia, the Haber process and fertilisers: practice questions

This question set covers the manufacture of ammonia by the Haber process, reversible reactions and equilibrium, the test for ammonia and for ammonium ions, how ammonium salts are made and how ammonia is released from them, and why farmers use NPK fertilisers. It is written for Cambridge O Level Chemistry 5070 and Cambridge IGCSE Chemistry 0620. It matches the syllabus topics on reversible reactions and equilibrium, acids, bases and salts (making salts), stoichiometry (moles, percentage yield and gas volumes), the chemistry of the environment (fertilisers) and the identification of ions and gases. There are 60 marks in total. A full answer scheme is at the end.

IGCSE 0620 Core students: dynamic equilibrium, the Haber process conditions, changing the position of equilibrium and the compromise conditions are Supplement (Extended) content. They are tested in A2, A3, A4, B2, B3, B8, C1 and C2. The mole calculations in C3 are also mainly Supplement content. O Level 5070 students should try every question.

Key ideas

- Haber process: $\text{N}_2(\text{g}) + 3\text{H}_2(\text{g}) \rightleftharpoons 2\text{NH}_3(\text{g})$. The forward reaction is exothermic (ΔH is about -92 kJ/mol).
- Raw materials: nitrogen from the air; hydrogen from methane (natural gas).
- Typical conditions: about 450°C , about 200 atm (20 000 kPa) and an iron catalyst.
- In a closed system a reversible reaction reaches dynamic equilibrium: the forward and backward rates are equal and the concentrations stay constant.
- Higher pressure moves the equilibrium to the side with fewer moles of gas ($4 \text{ mol} \rightarrow 2 \text{ mol}$, so to the right). Higher temperature moves it in the endothermic direction (to the left), so the yield of ammonia goes down.
- The conditions are a compromise: a low temperature gives a better yield but the rate is too slow; a very high pressure gives a better yield but costs too much and is less safe. A catalyst speeds up the forward and backward reactions equally and does not change the yield.
- Test for ammonia: damp red litmus paper turns blue.
- Ammonia + acid $\rightarrow$ ammonium salt, e.g. $\text{NH}_3 + \text{HNO}_3 \rightarrow \text{NH}_4\text{NO}_3$. When an ammonium salt is warmed with an alkali, ammonia gas is given off.
- NPK fertilisers supply nitrogen, phosphorus and potassium, the main elements plants take from the soil, to improve plant growth.

Relative atomic masses: H = 1, N = 14, O = 16, S = 32, Cl = 35.5, K = 39. One mole of any gas takes up 24 dm^3 at room temperature and pressure (r.t.p.).

Section A: multiple choice

Choose one answer for each question. Each question is worth 1 mark. The questions are numbered A1 to A8, to match the answers.

A1 Where does the nitrogen used in the Haber process come from? [1]

- A the air
- B crude oil
- C sea water
- D limestone

A2 Which row shows the usual conditions for the Haber process? [1]

	temperature	pressure	catalyst
A	450 °C	200 atm	iron
B	450 °C	2 atm	vanadium(V) oxide
C	200 °C	450 atm	iron
D	45 °C	200 atm	nickel

A3 The pressure on the equilibrium mixture $\text{N}_2(\text{g}) + 3\text{H}_2(\text{g}) \rightleftharpoons 2\text{NH}_3(\text{g})$ is increased. The temperature stays the same. What happens? [1]

- A The equilibrium moves to the left because there are fewer moles of gas on the left.
- B The equilibrium moves to the right because there are fewer moles of gas on the right.
- C The equilibrium does not move because pressure only changes the rate.
- D The equilibrium moves to the right because the forward reaction is exothermic.

A4 What does the iron catalyst do in the Haber process? [1]

- A It increases the percentage of ammonia in the equilibrium mixture.
- B It increases the rate of the forward reaction only.
- C It increases the rates of the forward and backward reactions equally, so equilibrium is reached faster.
- D It makes the reaction go to completion, so the yield becomes 100%.

A5 Which test and result shows that a gas is ammonia? [1]

- A damp blue litmus paper turns red
- B damp red litmus paper turns blue
- C limewater turns milky
- D a glowing splint relights

A6 Which mixture gives off ammonia when it is warmed? [1]

- A ammonium chloride and dilute hydrochloric acid
- B ammonium sulfate and aqueous sodium hydroxide
- C potassium nitrate and water
- D potassium chloride and calcium hydroxide

A7 A farmer mixes two compounds to make a fertiliser that contains all three of nitrogen, phosphorus and potassium. Which pair should the farmer use? [1]

- A NH_4NO_3 and KCl
- B $(\text{NH}_4)_3\text{PO}_4$ and KCl
- C KNO_3 and K_2SO_4
- D $(\text{NH}_4)_2\text{SO}_4$ and NH_4NO_3

A8 Which compound has the highest percentage by mass of nitrogen? [1]

- A NH_4Cl
- B NH_4NO_3
- C $(\text{NH}_4)_2\text{SO}_4$
- D KNO_3

Section B: short answer

The questions are numbered B1 to B8, to match the answers.

B1 State where each raw material for the Haber process comes from.

(a) nitrogen (b) hydrogen [2]

B2 Write the balanced symbol equation for the Haber process. Include state symbols and the correct sign for a reversible reaction. [2]

B3 The Haber process reaches dynamic equilibrium in a closed system. Explain what is meant by *dynamic equilibrium*. [3]

B4 Describe a test to show that a fertiliser contains ammonium ions. Give the result. [2]

B5 Ammonia reacts with dilute sulfuric acid.

(a) Name the salt formed. [1]

(b) Write the balanced symbol equation for this reaction. [2]

B6 A gardener wants to make the soil in a vegetable patch less acidic, and also wants to feed the plants. In a bucket of water she mixes slaked lime (calcium hydroxide) with a plant feed that contains ammonium chloride. She then pours the mixture onto the soil.

(a) Write the balanced symbol equation for the reaction between ammonium chloride and calcium hydroxide. [2]

(b) Explain why mixing these two substances is wasteful. [1]

B7 (a) State why farmers add NPK fertilisers to soil. [1]

(b) State one reason why plants need nitrogen. [1]

B8 The gas mixture leaving the reactor in a Haber plant contains ammonia, nitrogen and hydrogen. Describe how the ammonia is separated from the mixture and what happens to the nitrogen and hydrogen that have not reacted. [3]

Section C: structured questions

Question C1

The table gives the percentage of ammonia in the equilibrium mixture at different temperatures and pressures. The values are approximate.

temperature / °C	% ammonia at 100 atm	% ammonia at 200 atm	% ammonia at 300 atm
300	52	63	71
400	25	36	47
500	11	18	26
600	5	8	14

- (a) On graph paper, plot the percentage of ammonia (y-axis) against temperature (x-axis) for 200 atm. Draw a smooth curve through your points. [2]
- (b) Use your curve to find the percentage of ammonia at 450 °C and 200 atm. [1]
- (c) Describe and explain how increasing the pressure affects the percentage of ammonia at a fixed temperature. [2]
- (d) Describe and explain how increasing the temperature affects the percentage of ammonia at a fixed pressure. [2]
- (e) The table shows that 300 °C gives a much higher percentage of ammonia than 450 °C. Explain why the industry still uses about 450 °C. [2]

Question C2

- (a) Explain, in terms of particles, why increasing the pressure increases the rate of the Haber process. [2]
- (b) A higher pressure than 200 atm would give a higher yield. Suggest two reasons why a much higher pressure is not used. [2]
- (c) State the effect of the iron catalyst on
- the rate of reaction [1]
 - the percentage of ammonia at equilibrium. [1]
- (d) Extra nitrogen is added to the equilibrium mixture. The temperature and pressure stay the same. State and explain what happens to the amount of ammonia. [2]

Question C3

This question is about calculations based on the equation $\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3$.

- (a) Calculate the maximum mass of ammonia that could be made from 56 tonnes of nitrogen. Show your working. [2]
- (b) A plant actually produces 17 tonnes of ammonia from this 56 tonnes of nitrogen. Calculate the percentage yield. [1]
- (c) 60 dm³ of nitrogen is used at r.t.p. Assume the reaction goes to completion. Calculate
- the volume of hydrogen needed [1]
 - the volume of ammonia formed. [1]
- (d) 3.4 g of ammonia is passed into excess dilute sulfuric acid.
- $$2\text{NH}_3 + \text{H}_2\text{SO}_4 \rightarrow (\text{NH}_4)_2\text{SO}_4$$
- Calculate the mass of ammonium sulfate formed. [3]

Question C4

Ammonium nitrate, NH_4NO_3 , and ammonium sulfate, $(\text{NH}_4)_2\text{SO}_4$, are both used as fertilisers.

- (a) Calculate the percentage by mass of nitrogen in each compound. Use your answers to state which is the better source of nitrogen per kilogram. [2]
- (b) Describe how a student could make pure, dry crystals of ammonium sulfate from aqueous ammonia and dilute sulfuric acid. [3]
- (c) Solid ammonium sulfate is warmed with aqueous sodium hydroxide. Write the balanced symbol equation for the reaction. [2]

Total: Section A 8 marks, Section B 20 marks, Section C 32 marks = 60 marks.

Answers

Section A

A1 A. Air is about 78% nitrogen. The nitrogen is separated from liquid air by fractional distillation.

A2 A. Option B gives the conditions for the Contact process, not the Haber process.

A3 B. There are 4 moles of gas on the left ($1 + 3$) and 2 on the right. Higher pressure moves the equilibrium towards fewer moles of gas.

A4 C. A catalyst does not change the position of equilibrium, so it does not change the yield.

A5 B. Ammonia is the only common alkaline gas.

A6 B. An ammonium salt warmed with an alkali gives off ammonia. A has no alkali, and C and D contain no ammonium ions.

A7 B. $(\text{NH}_4)_3\text{PO}_4$ supplies N and P, and KCl supplies K. A has no P, C has no P, and D has only N.

A8 B. For each compound, work out $(\text{total mass of N} \div M_r) \times 100$. B has the highest value. Remember that NH_4NO_3 contains two N atoms. (Question C4(a) practises this calculation in full.)

Section B

B1 (a) the air (by fractional distillation of liquid air) [1]
 (b) methane / natural gas (reacted with steam) [1]

B2 $\text{N}_2(\text{g}) + 3\text{H}_2(\text{g}) \rightleftharpoons 2\text{NH}_3(\text{g})$
 Correct formulae and balancing [1]. $\rightleftharpoons$ sign and all state symbols (g) [1].

B3

- the rate of the forward reaction equals the rate of the backward reaction [1]
- the concentrations (amounts) of reactants and products stay constant (do not change) [1]
- both reactions are still going on; the reaction has not stopped [1]

Not credited on its own: "it happens in a closed system". This is a condition for reaching equilibrium, not what dynamic equilibrium means. Do not accept "the concentrations of reactants and products are equal".

B4 Warm the fertiliser with aqueous sodium hydroxide [1]. The gas given off turns damp red litmus paper blue (the gas is ammonia) [1].

The litmus must be damp, and the colour change must be from red to blue.

B5 (a) ammonium sulfate [1]

(b) $2\text{NH}_3 + \text{H}_2\text{SO}_4 \rightarrow (\text{NH}_4)_2\text{SO}_4$

Correct formulae [1]. Correct balancing [1].

B6 (a) $2\text{NH}_4\text{Cl} + \text{Ca}(\text{OH})_2 \rightarrow \text{CaCl}_2 + 2\text{H}_2\text{O} + 2\text{NH}_3$

Correct formulae [1]. Correct balancing [1].

(b) Calcium hydroxide is an alkali, so it releases the nitrogen as ammonia gas, which escapes into the air. That nitrogen is lost from the plant feed and the plants cannot use it [1].

B7 (a) To supply the elements nitrogen, phosphorus and potassium, for improved plant growth / a bigger crop yield [1]

(b) To make proteins (and chlorophyll), which helps growth, especially of leaves [1]. Also accept: for healthy / improved growth.

Beyond the Chemistry syllabus: the exam requires only that N, P and K are needed for (improved) plant growth. For interest, phosphorus helps root growth, and potassium helps flowers and fruit to develop and helps plants resist disease.

B8

- The mixture is cooled [1].
- The ammonia condenses (turns into a liquid) because it has a higher boiling point than nitrogen and hydrogen. It is then removed as a liquid [1].
- The nitrogen and hydrogen that have not reacted are still gases. They are recycled back into the reactor [1].

Section C

C1

(a) All four points plotted correctly (63, 36, 18 and 8% at 300, 400, 500 and 600 °C), to within half a small square [1]. A smooth curve through the points, not straight lines joining them [1].

(b) Any value from 24% to 28% [1]. Also accept a value read correctly from the candidate's own curve.

Reading from a smooth curve gives about 25–27%. The straight-line midpoint between 36% (400 °C) and 18%

(500 °C) is 27%, which is slightly too high, because the curve bends: it falls steeply at first and then levels off.

(c) Describe: the percentage of ammonia goes up as the pressure goes up [1].

Explain: there are fewer moles of gas on the right (2) than on the left (4), so higher pressure moves the equilibrium to the right [1].

(d) Describe: the percentage of ammonia goes down as the temperature goes up [1].

Explain: the forward reaction is exothermic, so higher temperature moves the equilibrium in the endothermic direction, which is to the left [1].

(e) At 300 °C the rate of reaction is too slow [1]. At 450 °C the yield is lower, but equilibrium is reached quickly enough to make more ammonia per hour. The temperature is a compromise between yield and rate [1].

Also accept: the iron catalyst does not work well at lower temperatures.

C2

(a) At higher pressure the gas particles are closer together, so there are more particles in each unit of volume [1]. This means they collide more often, so there are more successful collisions each second [1].

(b) Any two of [1 each]:

- it is expensive to build equipment (thicker pipes and reactor walls) strong enough
- more energy is needed for the compressors, so running costs are higher
- it is more dangerous because of the risk of leaks or explosions

(c) (i) The rate goes up, so equilibrium is reached faster [1].

(ii) No effect, because the position of equilibrium does not change [1].

(d) The amount of ammonia increases [1]. Adding a reactant moves the position of equilibrium to the right, which uses up some of the extra nitrogen (the equilibrium opposes the change) [1].

C3

(a) Worked answer:

- From the equation, 1 mol N₂ makes 2 mol NH₃.
- M_r(N₂) = 28 and M_r(NH₃) = 14 + 3 = 17. So 28 g of N₂ makes 2 × 17 = 34 g of NH₃ [1].
- Scaling up: 28 tonnes of N₂ makes 34 tonnes of NH₃, so 56 tonnes makes 2 × 34 = **68 tonnes** [1].

(b) percentage yield = $17 \div 68 \times 100 = \mathbf{25\%}$ [1]. Allow error carried forward (ecf) from (a).

(c) The volume ratio is the same as the mole ratio: N₂ : H₂ : NH₃ = 1 : 3 : 2.

(i) hydrogen = 3 × 60 = **180 dm³** [1]

(ii) ammonia = 2 × 60 = **120 dm³** [1]

(d) Worked answer:

- moles of NH₃ = $3.4 \div 17 = 0.20$ mol [1]
- mole ratio NH₃ : (NH₄)₂SO₄ = 2 : 1, so moles of (NH₄)₂SO₄ = $0.20 \div 2 = 0.10$ mol [1]
- M_r of (NH₄)₂SO₄ = (2 × 18) + 32 + (4 × 16) = 132. Mass = $0.10 \times 132 = \mathbf{13.2\text{ g}}$ [1]

C4

(a) Worked answer:

- NH_4NO_3 : $M_r = 14 + 4 + 14 + 48 = 80$. % N = $(2 \times 14) \div 80 \times 100 = \mathbf{35.0\%}$
- $(\text{NH}_4)_2\text{SO}_4$: $M_r = 132$. % N = $(2 \times 14) \div 132 \times 100 = \mathbf{21.2\%}$
- Both percentages correct [1].
- Ammonium nitrate is the better source because each kilogram contains more nitrogen [1].
Allow ecf from the candidate's percentages.

A common error is to use only one N atom for ammonium nitrate. It has two: one in NH_4^+ and one in NO_3^- .

(b) Any three of [1 each]:

- Titrate: add dilute sulfuric acid from a burette to a measured volume of aqueous ammonia, with an indicator, until it is exactly neutralised. Record the volume of acid used.
- Repeat with the same volumes but no indicator (or remove the indicator with activated charcoal), so the salt is pure.
- Heat the solution gently to evaporate some of the water until it reaches the crystallisation point, then leave it to cool so crystals form.
- Filter off the crystals, rinse them with a little cold distilled water and dry them between filter papers or in a warm place.

(c) $(\text{NH}_4)_2\text{SO}_4 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O} + 2\text{NH}_3$

Correct formulae [1]. Correct balancing [1].