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4 States of Matter

The study of the particles in solids, liquids and gases and the interactions between them is important in understanding the physical properties of substances.

4.1 The gaseous state: ideal and real gases and $pV = nRT$

4.2 The liquid state

STATES OF MATTER

4 States of matter

The study of the particles in solids, liquids and gases and the interactions between them is important in understanding the physical properties of substances.

	Learning outcomes Candidates should be able to:
4.1 The gaseous state: ideal and real gases and $pV = nRT$	a) state the basic assumptions of the kinetic theory as applied to an ideal gas b) explain qualitatively in terms of intermolecular forces and molecular size: (i) the conditions necessary for a gas to approach ideal behaviour (ii) the limitations of ideality at very high pressures and very low temperatures c) state and use the general gas equation $pV = nRT$ in calculations, including the determination of M_r
4.2 The liquid state	a) describe, using a kinetic-molecular model, the liquid state, melting, vaporisation, vapour pressure

KINETIC THEORY OF GASES

The idea that molecules in gases are in constant movement is called the kinetic theory of gases. This theory makes certain assumptions:

1. Gases are made up of tiny particles, “molecules” in a state of rapid, random motion.
2. Average kinetic energy of particles is directly proportional to the temperature of gas in Kelvin
3. All collisions are perfectly elastic i.e. there is no loss of kinetic energy.
4. Collisions between the molecules and the walls of the container give rise to pressure.

1

KINETIC THEORY OF GASES

5. The volume of molecules is negligible compared to the volume of the gas.
   (The distance between the gas molecules is much greater than the diameter of the molecules so the volume of the molecules is negligible)
6. Attractive forces between particles are negligible.

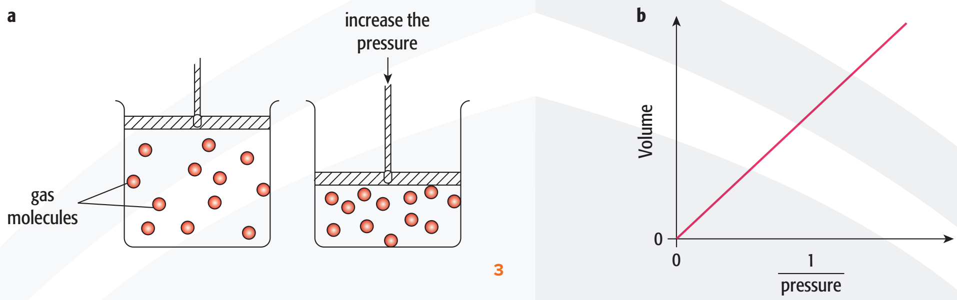
2

BOYLE'S LAW

The volume of a gas varies inversely with the pressure exerted by the gas if the number of moles and temperature of gas are held constant. This relationship is known as Boyle's law. The product of pressure (P) and volume (V) is a constant:

$$PV = k \text{ (constant)}$$

$$P_1V_1 = P_2V_2$$



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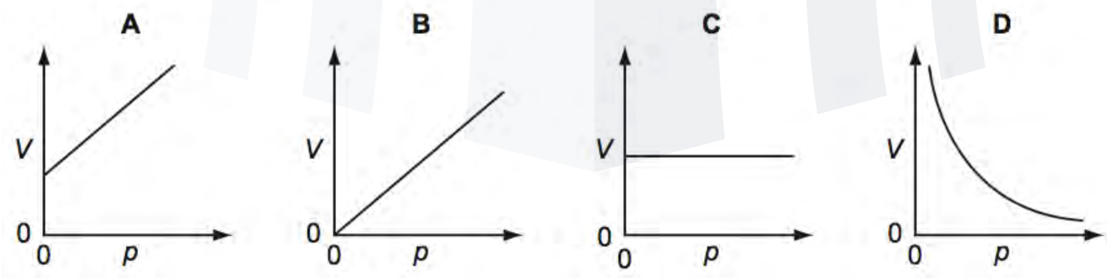
SKILL CHECK 1

Which diagram shows the correct graph of V against p for a fixed mass of an ideal gas at constant temperature?



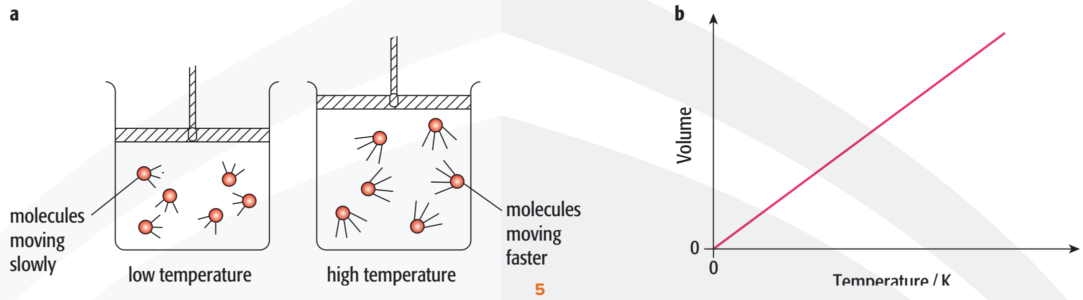
4

CHARLES' LAW

The volume of a gas varies directly with the absolute temperature (K) if pressure and number of moles of gas are constant.

Mathematically, the ratio of volume (V) and temperature (T) is a constant:

$$V/T = k \text{ (constant)}$$
$$V = kT$$



AVAGADRO’S LAW

Equal volumes of any ideal gas contain the same number of moles if measured under the same conditions of temperature and pressure.

Mathematically, the ratio of volume (V) to number of moles (n) is a constant:

$$V/n = k \text{ (constant)}$$
$$V = nk$$

IDEAL GAS LAW

Boyle's law (relating volume and pressure), Charles's law (relating volume and temperature), and Avogadro's law (relating volume to the number of moles) may be combined into a single expression relating all four terms.

This expression is the ideal gas law:

$$PV = nRT$$

P = pressure of the gas in Nm^{-2} n = number of moles of the gas

V = volume of the gas in m^3 T = absolute temperature of the gas in K

R = a constant referred to as the Universal gas constant*

Unit and value of R = 8.31 J mol^{-1} K^{-1}

7

SKILL CHECK 2

The general gas equation can be used to calculate the M_r value of a gas.

For a sample of a gas of mass *m* g, which expression will give the value of M_r?

A $M_r = \frac{mpV}{RT}$ **B** $M_r = \frac{pVRT}{m}$ **C** $M_r = \frac{mRT}{pV}$ **D** $M_r = \frac{pV}{mRT}$

8

SKILL CHECK 3

The volume of a sample of ammonia is measured at a temperature of 60°C and a pressure of 103 kP_a. The volume measured is 5.37×10^{-3} m^3.

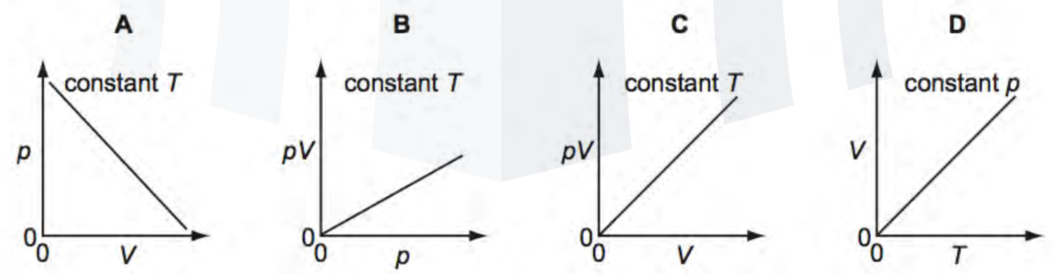
What is the mass of the sample of ammonia, given to two significant figures?

A 0.00019 g **B** 0.0034 g **C** 0.19 g **D** 3.4 g

9

SKILL CHECK 4

Which diagram correctly describes the behaviour of a fixed mass of an ideal gas? (*T* is measured in K.)



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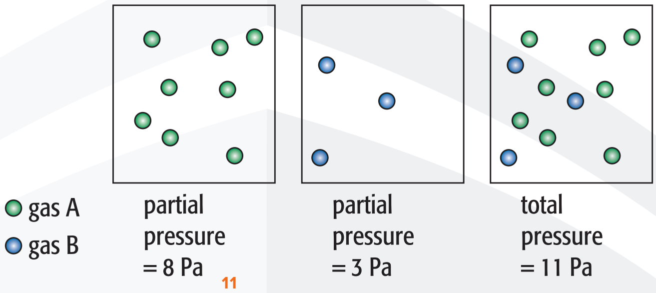
DALTON'S LAW OF PARTIAL PRESSURES

A mixture of gases exerts a pressure that is the sum of the pressures that each gas would exert if it were present alone under the same conditions.

Consider two gases A and B occupying a given volume individually at a given temperature. Let their pressures be p_a = 8 Pa and p_b = 3 Pa. Now consider the same amount of the two gases A and B occupying the same volume at the same temperature all together.



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DALTON'S LAW OF PARTIAL PRESSURES

Let the total pressure be PT. Then according to Dalton's law:

$$PT = p_a + p_b$$

p_a and p_b are referred to as partial pressures

Hence p = x P where p is the partial pressure, and x is the mol fraction of the gas

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SKILL CHECK 5

a. 80 g of oxygen, 140 g of nitrogen, 44 g of carbon dioxide and 60 g of argon when confined in a vessel exerted pressure of a 3.6×10^6 Nm^{-2}. Hence calculate the partial pressure of each of the gases.

b. A mixture of gases at a pressure 7.50×10^4 Nm^{-2} has the volume composition 40% nitrogen, 35% oxygen and 25% carbon dioxide. What is the partial pressure of each gas?

c. 2.0 dm^3 of nitrogen at a pressure of 1.0×10^5 Pa and 5.0 dm^3 of hydrogen at a pressure of 5.0×10^5 Pa are injected into a 10 dm^3 vessel. What is the pressure of the mixture of the gases?

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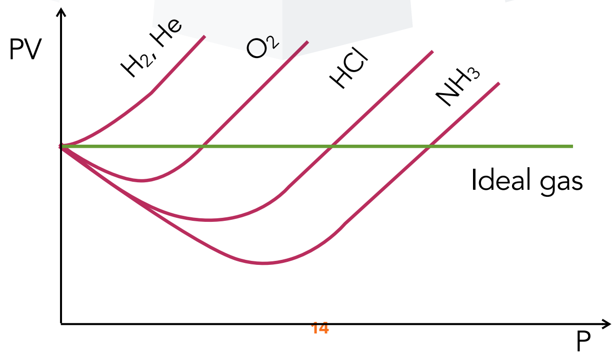
REAL GASES VS IDEAL GAS

The validity of Boyle's Law was tested over a wide range of pressures and it was found that none of the gases obeyed the law.

If the gases obeyed Boyle's law, the plots of PV against P should be parallel to the x axis. None of the gases gave such a graph. Two types of deviations are seen.



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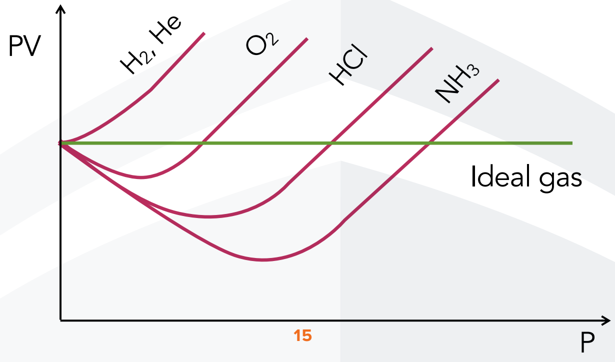
REAL GASES VS IDEAL GAS

All gases except hydrogen and helium, first showed a minimum, and then increased with increasing pressure.

Hydrogen and helium never showed a minimum, always increasing with increasing pressure. (+ve deviation).



REAL GASES VS IDEAL GAS

The hypothetical gas, which would strictly obey the gas laws, is called the ideal gas or perfect gas, in contrast to all known gases which are referred to as real gases. Ideal gas is one that obeys the gas laws/ $pV = nRT$ under all conditions of temperature and pressure

These show us that gases do not always behave exactly as we expect an ideal gas to behave. This is because real gases do not always obey the kinetic theory in two ways:

1. There is not zero attraction between the molecules
2. We cannot ignore the volume of the molecules themselves.

REAL GASES VS IDEAL GAS

These differences are especially noticeable at very high pressures and very low temperatures. Under these conditions:

- The molecules are close to each other
- The volume of the molecules is not negligible compared with the volume of the container
- There are Van der Waals' forces of attraction between the molecules
- Attractive forces pull the molecules towards each other and away from the walls of the container
- The effective volume of the gas is smaller than expected for an ideal gas.

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REAL GASES VS IDEAL GAS

In hydrogen and helium the intermolecular attractions are negligible and hence they do not get compressed more than expected, and hence they do not show a minimum.

The two assumptions would become true only when the volume occupied by the gas tends to infinity. Volume would tend to infinity when pressure decreases and temperature increases.

Thus real gases tend to be ideal i.e tend to obey the gas laws at low pressures and high temperatures.

Conversely at very high pressures and very low temperatures the laws become invalid.

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SKILL CHECK 6

Which would behave the **least** like an ideal gas at room temperature?

A carbon dioxide

B helium

C hydrogen

D nitrogen

THE LIQUID STATE

The particles in a liquid are still close to each other but have enough kinetic energy to keep sliding past each other in fairly random way, but not as freely as gas particles do.

For brief periods, the particles in liquids are arranged in slightly ordered way. but this order is always broken up when the particles gain kinetic energy from neighbouring particles.

THE LIQUID STATE

When we heat a liquid:

Energy transferred to the liquid makes the particles move faster.

Forces of attraction between particles weaken.

Particles with most energy are the first to escape from forces holding them together.

The liquid evaporates - this happens at temperatures below the boiling point.

THE LIQUID STATE

Forces weaken enough for all particles to become free from each other.

The liquid boils.

This change is called **vaporisation**.

The energy required to change one mole of liquid to one mole of gas is called enthalpy change of vaporisation.

THE LIQUID STATE

When we cool a vapour, the particles:

Lose kinetic energy so the molecules move around less quickly.

Experience increasing forces of attraction.

Move more slowly and become closer. The gas liquefies.

This change of state is called **condensation**. These changes in state are reversible. These changes involve opposite energy transfers.

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THE LIQUID STATE

At equilibrium the concentration of water molecules in the vapour remains constant.

$$\text{water molecules in liquid} \xrightleftharpoons{\text{equal rate of movement}} \text{water molecules in vapour}$$

Pressure exerted by a vapour in equilibrium with its liquid is called vapour pressure.

The temperature at which vapour pressure is equal to the atmospheric pressure is the boiling point of the liquid.

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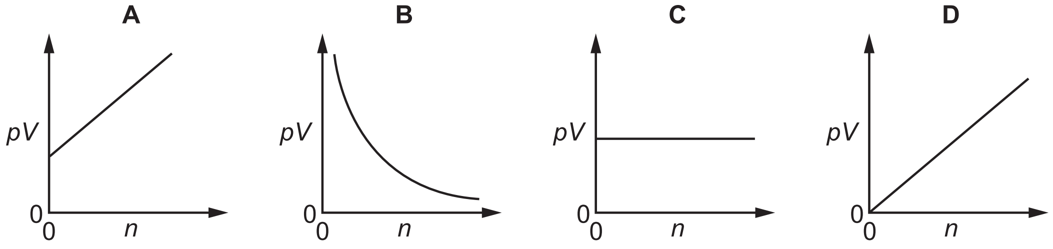
STATES OF MATTER WS 1

SECTION A

1 Which diagram shows the correct graph of pV against n for an ideal gas at constant temperature?



2 Measured values of the pressure, volume and temperature of a known mass of a gaseous compound are to be substituted into the equation $pV = nRT$.

The measurements are used to calculate the relative molecular mass, M_r, of a compound.

Which conditions of pressure and temperature would give the most accurate value of M_r?

	pressure	temperature
A	high	high
B	high	low
C	low	high
D	low	low

3 *Use of the Data Booklet is relevant to this question.*

When an evacuated fluorescent light tube of volume $300\,cm^3$ is filled with a gas at 300 K and 101 kPa, the mass of the tube increases by 1.02 g. The gas obeys the ideal gas equation $pV = nRT$.

What is the identity of the gas?

A argon

B krypton

C neon

D nitrogen

4 *Use of the Data Booklet is relevant to this question.*

Iodine is a black, shiny, non-metallic solid and a member of Group VII. It sublimes easily on heating to give a purple vapour.

A sample of iodine vapour of mass 6.35 g has a volume of $1.247\,dm^3$ when maintained at constant temperature and a pressure of 1.00×10^5 Pa.

If iodine vapour acts as an ideal gas, what is the temperature of the iodine vapour?

A 300 K **B** 600 K **C** 300 000 K **D** 600 000 K

5 *Use of the Data Booklet is relevant to this question.*

In an experiment, 12.0 dm^3 of oxygen, measured under room conditions, is used to burn completely 0.10 mol of propan-1-ol.

What is the final volume of gas, measured under room conditions?

A 7.20 dm^3 **B** 8.40 dm^3 **C** 16.8 dm^3 **D** 18.00 dm^3

6 Flask X contains 5 dm^3 of helium at 12 kPa pressure and flask Y contains 10 dm^3 of neon at 6 kPa pressure.

If the flasks are connected at constant temperature, what is the final pressure?

A 8 kPa **B** 9 kPa **C** 10 kPa **D** 11 kPa

7 Argon is a gas used to fill electric light bulbs.

Under which conditions of pressure and temperature will argon behave most like an ideal gas?

	pressure	temperature
A	high	high
B	high	low
C	low	high
D	low	low

8 What will make it more likely that a gas will approach ideal behaviour?

A higher pressure

B lower temperature

C more polar molecules

D weaker intermolecular forces

9 At a temperature of 2500 K and a pressure of 1.00×10^{-4} Pa a sample of 0.321 g of sulfur vapour has a volume of 2.08×10^{6} m^3.

What is the molecular formula of sulfur under these conditions?

A S **B** S_2 **C** S_4 **D** S_8

10 The complete combustion of 2 moles of a straight chain alkane produces 400 dm^3 of carbon dioxide measured at 301 K and 1×10^{5} Pa. Carbon dioxide can be assumed to behave as an ideal gas under these conditions.

What is the formula of the straight chain alkane?

A C_8H_{18} **B** $C_{16}H_{34}$ **C** $C_{20}H_{42}$ **D** $C_{40}H_{82}$

11 Which gas sample contains the **fewest** molecules?

A 1.00 dm^3 of carbon dioxide at 27 °C and 2.0 kPa

B 1.00 dm^3 of hydrogen at 100 °C and 2.0 kPa

C 1.00 dm^3 of nitrogen at 300 °C and 4.0 kPa

D 1.00 dm^3 of oxygen at 250 °C and 3.0 kPa

12 All gases listed are at the same pressure.

Which gas will most closely approach ideal behaviour?

A ammonia at 100 K

B ammonia at 500 K

C neon at 100 K

D neon at 500 K

13 The gas laws can be summarised in the ideal gas equation.

$$pV = nRT$$

0.960 g of oxygen gas is contained in a vessel of volume $7.00 \times 10^{-3}\,m^3$ at a temperature of 30 °C.

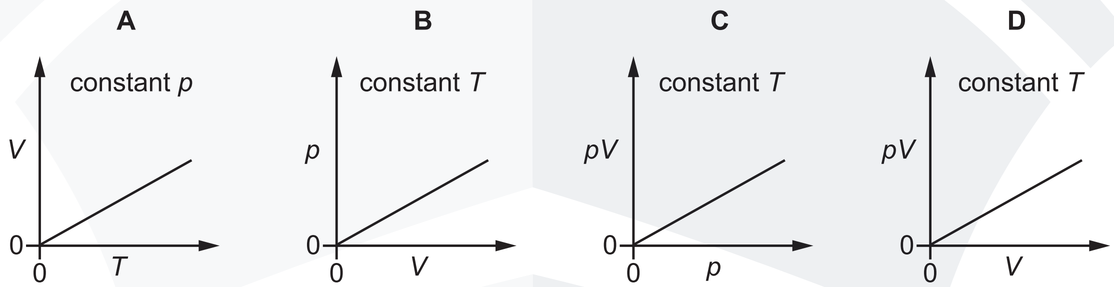
Assume that the gas behaves as an ideal gas.

What is the pressure in the vessel?

A 1.07 kPa **B** 2.14 kPa **C** 10.8 kPa **D** 21.6 kPa

[M'18 P12 Q7]

14 Which diagram correctly describes the behaviour of a fixed mass of an ideal gas? (*T* is measured in K.)



[J'18 P13 Q6]

15 What is a basic assumption of the kinetic theory, as applied to an ideal gas?

A Collisions between gas molecules are elastic.

B Each gas molecule occupies a finite volume.

C Gases consist of particles that experience the force of gravity.

D Gas molecules attract each other with weak intermolecular forces.

[N'18 P11 Q2]

16 In this question you should assume methane behaves as an ideal gas.

The gas laws can be summarised in the ideal gas equation below.

$$pV = nRT$$

The volume of a sample of methane is measured at a temperature of 60 °C and a pressure of 103 kPa. The volume measured is $5.37 \times 10^{-3}\,m^3$.

What is the mass of the sample of methane, given to two significant figures?

A 0.0032 g **B** 0.018 g **C** 3.2 g **D** 18 g

[N'18 P11 Q5]

17 Flask X contains 5 dm^3 of helium at 12 kPa pressure and flask Y contains 10 dm^3 of neon at 6 kPa pressure.

If the flasks are connected at constant temperature, what is the final pressure?

A 8 kPa **B** 9 kPa **C** 10 kPa **D** 11 kPa

[N'18 P11 Q5]

STATES OF MATTER WS 2

1 A mixture of neon and argon has a mass of 0.275 g. The mixture was placed in a gas syringe at a temperature of 25 °C and a pressure of 100 kPa. Under these conditions the mixture was found to occupy a volume of 200 cm^3.

(i) Calculate the average M_r of the mixture.

average M_r = ... [2]

(ii) Use your answer to **(i)** to calculate the percentage of neon in the mixture.
Give your answer to **three** significant figures.

percentage of neon = ... % [1]

Neon and argon can both be obtained by fractional distillation of liquid air as they have different boiling points.

Neon has a boiling point of 27.3 K. The boiling point of argon is 87.4 K.

(i) Name the force that has to be overcome in order to boil neon or argon and explain what causes it.

....

....

.... [3]

(ii) Explain why argon has a higher boiling point than neon.

....

....

.... [2]

2 Aluminium reacts with chlorine to form a white, solid chloride that contains 79.7% chlorine and sublimes (changes straight from a solid to a gas) at 180 °C.

(i) Describe the structure and bonding in this compound. Suggest how it explains the low sublimation temperature.

....

....

....

....

.... [2]

(ii) Calculate the empirical formula of the chloride. You must show your working.

empirical formula = ... [2]

At 200 °C and 100 kPa, a 1.36 g sample of this chloride occupied a volume of 200 cm^3.

(iii) Calculate the relative molecular mass, M_r, of the chloride. Give your answer to **three** significant figures.

M_r = ... [2]

(iv) Deduce the molecular formula of this chloride at 200 °C.

.... [1]

3 **T** is an alcohol, C_xH_yO. A gaseous sample of **T** occupied a volume of 20 cm^3 at 120 °C and 100 kPa.

The sample was completely burned in 200 cm^3 of oxygen (an excess). The final volume, measured under the same conditions as the gaseous sample, was 250 cm^3.

Under these conditions, all water present is vaporised. Removal of the water vapour from the gaseous mixture decreased the volume to 170 cm^3.

Treating the remaining gaseous mixture with concentrated alkali, to absorb carbon dioxide, decreased the volume to 110 cm^3.

The equation for the complete combustion of **T** can be represented as shown.

$$C_xH_yO + zO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O$$

(i) Use the data given to calculate the value of *x*.

x = ... [1]

(ii) Use the data given to calculate the value of *y*.

y = ... [1]

(iii) Complete the equation for the complete combustion of the alcohol, **T**.

.... + ...O_2 → ....CO_2 + ...H_2O

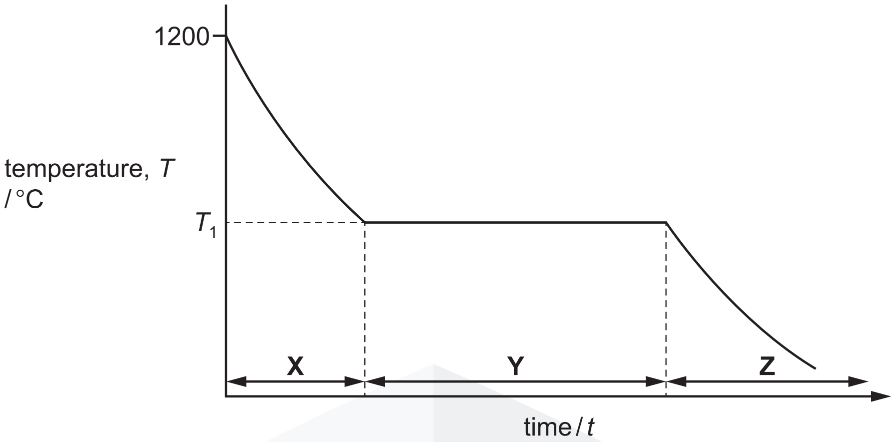
[1]

(v) Use the general gas equation to calculate the mass of **T** present in the original 20 cm^3 gaseous sample, which was measured at 120 °C and 100 kPa.

Give your answer to **three** significant figures. Show your working.

mass = ... g [3]

4 **(c)** The graph represents how the temperature of a sample of copper (melting point 1085 °C) changes as it is gradually cooled from 1200 °C.



(i) Identify the state(s) of matter present during each stage of the process shown in the graph.

X ....

Y ....

Z ....

[2]

(ii) State what is happening to the energy and movement of the particles in the copper during stage **X**.

....

....

.... [2]

(iii) Explain why the temperature stays constant at T_1 during stage **Y**.

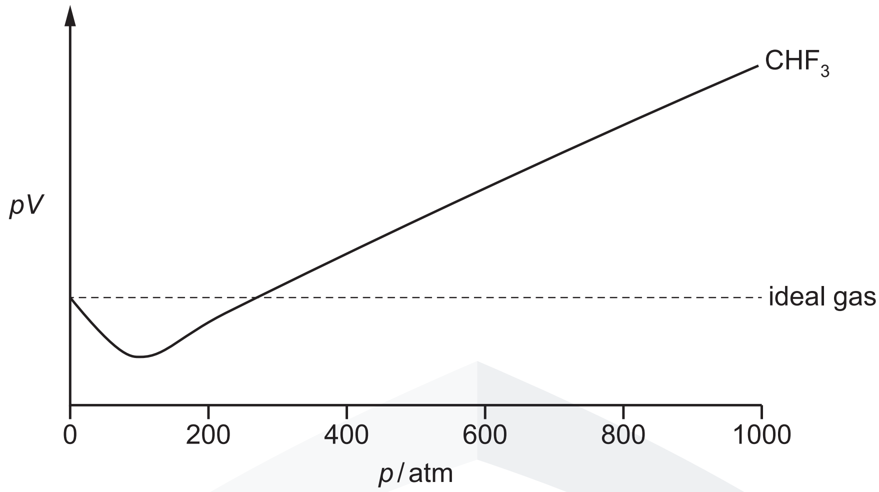
....

....

....

.... [2]

5 **(b)** The graph shows the relationship between pV and p at a given temperature for CHF_3 and an ideal gas.



(i) CHF_3 is not an ideal gas.

State **three** basic assumptions that scientists make about the properties of ideal gases.

1 ....

2 ....

3 ....
[3]

(ii) Explain why CHF_3 deviates from the properties of an ideal gas at pressures greater than 300 atm.

....

....

....

.... [2]

[N'18 P22 Q3]

6 A mixture of neon and argon has a mass of 0.275 g. The mixture was placed in a gas syringe at a temperature of 25 °C and a pressure of 100 kPa. Under these conditions the mixture was found to occupy a volume of 200 cm^3.

(i) Calculate the average M_r of the mixture.

average M_r = ... [2]

(ii) Use your answer to **(i)** to calculate the percentage of neon in the mixture.
Give your answer to **three** significant figures.

percentage of neon = ... % [1]

Neon and argon can both be obtained by fractional distillation of liquid air as they have different boiling points.

Neon has a boiling point of 27.3 K. The boiling point of argon is 87.4 K.

(i) Name the force that has to be overcome in order to boil neon or argon and explain what causes it.

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....

.... [3]

(ii) Explain why argon has a higher boiling point than neon.

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....

.... [2]

7 Aluminium reacts with chlorine to form a white, solid chloride that contains 79.7% chlorine and sublimes (changes straight from a solid to a gas) at 180 °C.

(i) Describe the structure and bonding in this compound. Suggest how it explains the low sublimation temperature.

....

....

....

....

.... [2]

(ii) Calculate the empirical formula of the chloride. You must show your working.

empirical formula = ... [2]

At 200 °C and 100 kPa, a 1.36 g sample of this chloride occupied a volume of 200 cm^3.

(iii) Calculate the relative molecular mass, M_r, of the chloride. Give your answer to **three** significant figures.

M_r = ... [2]

(iv) Deduce the molecular formula of this chloride at 200 °C.

.... [1]

STATES OF MATTER WS 3

SECTION A

1 Flask X contains 1 dm^3 of helium at 2 kPa pressure and flask Y contains 2 dm^3 of neon at 1 kPa pressure.

If the flasks are connected at constant temperature, what is the final pressure?

A $1\frac{1}{3}$ kPa **B** $1\frac{1}{2}$ kPa **C** $1\frac{2}{3}$ kPa **D** 2 kPa

2 In an experiment using a gas syringe, 0.10 g of a gas is found to occupy 83.1 cm^3, measured at standard pressure (1.0×10^5 Pa) and 27 °C.

What is the relative molecular mass of the gas?

A $\dfrac{0.10 \times 8.31 \times 27}{1.0 \times 10^5 \times 83.1}$

B $\dfrac{0.10 \times 8.31 \times 300}{1.0 \times 10^5 \times 83.1}$

C $\dfrac{0.10 \times 8.31 \times 27}{1.0 \times 10^5 \times 83.1 \times 10^{-6}}$

D $\dfrac{0.10 \times 8.31 \times 300}{1.0 \times 10^5 \times 83.1 \times 10^{-6}}$

3 Which expression gives the pressure exerted by 1.6×10^{-3} mol of N_2 in a container of volume 3.0 dm^3 at 273 °C?

A $\dfrac{1.6 \times 10^{-3} \times 8.31 \times 273}{3.0 \times 10^{-6}}$ Pa

B $\dfrac{1.6 \times 10^{-3} \times 8.31 \times (273 + 273)}{3.0 \times 10^{-6}}$ Pa

C $\dfrac{1.6 \times 10^{-3} \times 8.31 \times 273}{3.0 \times 10^{-3}}$ Pa

D $\dfrac{1.6 \times 10^{-3} \times 8.31 \times (273 + 273)}{3.0 \times 10^{-3}}$ Pa

4 Which mass of gas would occupy a volume of 3 dm^3 at 25 °C and 1 atmosphere pressure?
[1 mol of gas occupies 24 dm^3 at 25 °C and 1 atmosphere pressure.]

A 3.2 g O_2 gas

B 5.6 g N_2 gas

C 8.0 g SO_2 gas

D 11.0 g CO_2 gas

5 Flask X contains 5 dm^3 of helium at 12 kPa pressure and flask Y contains 10 dm^3 of neon at 6 kPa pressure.

If the flasks are connected at constant temperature, what is the final pressure?

A 8 kPa **B** 9 kPa **C** 10 kPa **D** 11 kPa

6 A 2 g sample of hydrogen at temperature *T* and of volume *V* exerts a pressure *p*. Deuterium, $^{2}_{1}H$, is an isotope of hydrogen.

Which of the following would also exert a pressure *p* at the same temperature *T*?

A 2 g of deuterium of volume V

B 4 g of deuterium of volume $\frac{V}{2}$

C a mixture of 1 g of hydrogen and 2 g of deuterium of total volume V

D a mixture of 2 g of hydrogen and 1 g of deuterium of total volume $2V$

7 A 2 g sample of hydrogen at temperature *T* and of volume *V* exerts a pressure *p*. Deuterium, $^{2}_{1}H$, is an isotope of hydrogen.

Which of the following would also exert a pressure *p* at the same temperature *T*?

A 2 g of deuterium of volume V

B 4 g of deuterium of volume $\frac{V}{2}$

C a mixture of 1 g of hydrogen and 2 g of deuterium of total volume V

D a mixture of 2 g of hydrogen and 1 g of deuterium of total volume $2V$

8 Which of the following least resembles an ideal gas?

A ammonia

B helium

C hydrogen

D trichloromethane

9 Which gas closely approaches ideal behaviour at room temperature and pressure?

A ammonia

B carbon dioxide

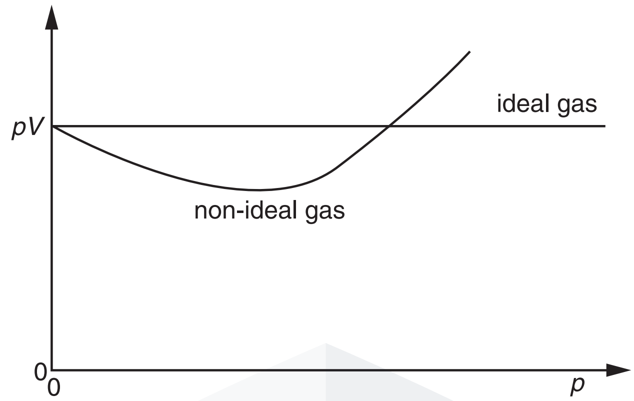
C helium

D oxygen

10 Which gas is likely to deviate most from ideal gas behaviour?

A HCl **B** He **C** CH_4 **D** N_2

11 The value of pV is plotted against p for two gases, an ideal gas and a non-ideal gas, where p is the pressure and V is the volume of the gas.



Which of the following gases shows the greatest deviation from ideality?

A ammonia

B ethene

C methane

D nitrogen

12 Which of the following would behave most like an ideal gas at room temperature?

A carbon dioxide

B helium

C hydrogen

D nitrogen

13 At room temperature and pressure chlorine does not behave as an ideal gas.

At which temperature and pressure would the behaviour of chlorine become more ideal?

	pressure / kPa	temperature / K
A	50	200
B	50	400
C	200	200
D	200	400

14 The gas laws can be summarised in the ideal gas equation.

$$pV = nRT$$

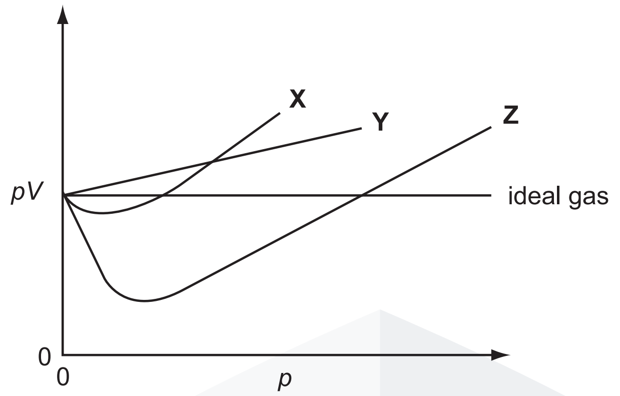
0.56 g of ethene gas is contained in a vessel at a pressure of 102 kPa and a temperature of 30 °C.

What is the volume of the vessel?

A 49 cm^3 **B** 494 cm^3 **C** 48 900 cm^3 **D** 494 000 cm^3

15 For an ideal gas, the plot of pV against p is a straight line. For a real gas, such a plot shows a deviation from ideal behaviour. The plots of pV against p for three real gases are shown below.

The gases represented are ammonia, hydrogen and nitrogen.



What are the identities of the gases **X**, **Y** and **Z**?

	X	Y	Z
A	ammonia	nitrogen	hydrogen
B	hydrogen	nitrogen	ammonia
C	nitrogen	ammonia	hydrogen
D	nitrogen	hydrogen	ammonia

16 Under which set of conditions is a gas most likely to behave ideally?

	temperature	pressure
A	high	high
B	high	low
C	low	high
D	low	low

17 The gas laws can be summarised in the ideal gas equation.

$$pV = nRT$$

0.96 g of oxygen gas is contained in a glass vessel of volume 7000 cm^3 at a temperature of 30 °C.

What is the pressure in the vessel?

A 1.1 kPa **B** 2.1 kPa **C** 10.8 kPa **D** 21.6 kPa

18 Ethanol has a boiling point of 78 °C. At 101 kPa and 79 °C ethanol vapour does not perfectly obey the gas equation $pV = nRT$.

What is the reason for this?

A Ethanol vapour is in equilibrium with ethanol liquid at 79 °C.

B There are intermolecular forces between the molecules of ethanol vapour.

C The vapourisation of ethanol liquid is an endothermic process.

D Vapours will not obey the gas equation perfectly at such a low pressure.

19 When 0.15 g of an organic compound is vaporised, it occupies a volume of 65.0 cm^3 at 405 K and 1.00×10^5 Nm^{-2}.

Using the expression $pV = nRT$, which of the following expressions should be used to calculate the relative molecular mass, M_r, of the compound?

A $\dfrac{0.15 \times 65 \times 10^{-6} \times 1 \times 10^5}{8.31 \times 405}$

B $\dfrac{0.15 \times 8.31 \times 405}{1 \times 10^5 \times 65 \times 10^{-3}}$

C $\dfrac{0.15 \times 65 \times 10^{-3} \times 1 \times 10^5}{8.31 \times 405}$

D $\dfrac{0.15 \times 8.31 \times 405}{1 \times 10^5 \times 65 \times 10^{-6}}$

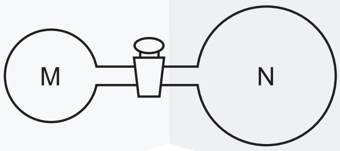
20 Iodine is a black, shiny, non-metallic solid and a member of Group VII. It sublimes easily on heating to give a purple vapour.

A sample of iodine vapour of mass 6.35 g has a volume of 1.247 dm^3 when maintained at constant temperature and a pressure of 1.00×10^5 Pa.

If iodine vapour acts as an ideal gas, what is the temperature of the iodine vapour?

A 300 K **B** 600 K **C** 300 000 K **D** 600 000 K

21 Two glass vessels M and N are connected by a closed valve.



M contains helium at 20 °C at a pressure of 1×10^5 Pa. N has been evacuated, and has three times the volume of M. In an experiment, the valve is opened and the temperature of the whole apparatus is raised to 100 °C.

What is the final pressure in the system?

A 3.18×10^4 Pa

B 4.24×10^4 Pa

C 1.25×10^5 Pa

D 5.09×10^5 Pa

22 When an evacuated glass tube of volume 200 cm^3 is filled with a gas at 300 K and 101 kPa, the mass of the tube increases by 1.06 g.

What is the identity of the gas?

A argon

B krypton

C neon

D xenon

23 The gas laws can be summarised in the ideal gas equation below.

$$pV = nRT$$

0.96 g of oxygen gas is contained in a glass vessel of volume $7.0 \times 10^{-3}\,m^3$ at a temperature of 30 °C.

Assume the gas behaves as an ideal gas.

What is the pressure in the vessel?

A 1.1 kPa **B** 2.1 kPa **C** 10.8 kPa **D** 21.6 kPa

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 An ideal gas obeys the gas laws under all conditions of temperature and pressure.

Which of the following are true for an ideal gas?

1 The molecules have negligible volume.

2 There are no forces of attraction between molecules.

3 The molecules have an average kinetic energy which is proportional to its absolute temperature.

2 What are assumptions of the kinetic theory of gases and hence of the ideal gas equation, $PV = nRT$?

1 Molecules move without interacting with one another except for collisions.

2 Intermolecular forces are negligible.

3 Intermolecular distances are much greater than the molecular size.

3 Which equations apply to an ideal gas?
[p = pressure, V = volume, M = molar mass, ρ = density, c = concentration, R = gas constant, T = temperature]

1 $p = \dfrac{\rho RT}{M}$ **2** $pV = MRT$ **3** $pV = \dfrac{cRT}{M}$

4 When a sample of a gas is compressed at constant temperature from 1500 kPa to 6000 kPa, its volume changes from 76.0 cm^3 to 20.5 cm^3.

Which statements are possible explanations for this behaviour?

1 The gas behaves non-ideally.

2 The gas partially liquefies.

3 Gas is adsorbed on to the vessel walls.

5 The gas laws can be summarised in the ideal gas equation.

$$pV = nRT$$

where each symbol has its usual meaning.

Which statements are correct?

1 One mole of an ideal gas occupies the same volume under the same conditions of temperature and pressure.

2 The density of an ideal gas at constant pressure is inversely proportional to the temperature, T.

3 The volume of a given mass of an ideal gas is doubled if its temperature is raised from 25 °C to 50 °C at constant pressure.

6 A student borrowed a friend's chemistry notes and copied out the notes in the box below.

Which statements are correct?

A gas behaves **less** like an ideal gas when the gas

1 is at low pressure.

2 is at low temperature.

3 can be easily liquefied.

7 Which equations can apply to an ideal gas?
[p = pressure, V = volume, M = molar mass, ρ = density, c = concentration, R = gas constant, T = temperature]

1 $p = \frac{\rho RT}{M}$ **2** $pV = \frac{cRT}{M}$ **3** $pV = MRT$

8 What are basic assumptions of the kinetic theory as applied to an ideal gas?

1 Gas particles are in continuous random motion.

2 Gas particles experience no intermolecular forces.

3 The volume of each gas particle is zero.

9 In this question, all gases can be assumed to behave ideally.

A chemist heats a mixture of nitrogen and oxygen gases in a sealed container at a constant temperature until the mixture reaches a dynamic equilibrium containing N_2(g), O_2(g) and NO(g).

$$N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$$

The chemist repeats the experiment at the same temperature using the same initial amounts of N_2(g) and O_2(g), but at a much higher pressure.

Which statements about the second experiment at higher pressure are correct?

1 At higher pressure, there are more particles per unit volume.

2 The composition of the equilibrium mixture does not change.

3 There are more collisions per second so equilibrium is reached faster.

10 When a sample of a gas is compressed at constant temperature from 1500 kPa to 6000 kPa, its volume changes from 76.0 cm^3 to 20.5 cm^3.

Which statements are possible explanations for this result?

1 The gas does not behave ideally.

2 The gas partially liquefies.

3 Some of the gas is lost from the container.

STATES OF MATTER WS 4

1 **(a)** State **two** assumptions of ideal gas behaviour.

(i) ....

....

(ii) ....

....[2]

Use of the *Data Booklet* is relevant in (b) and (c).

(b) The ideal gas equation is $pV = nRT$. Explain as fully as you can the meaning of the following terms, and give the units for each to correspond with the value of R given in the *Data Booklet*.

(i) p ....

....

(ii) V ....

....

(iii) T ....

....[6]

(c) **(i)** When an evacuated glass bulb of volume 63.8 cm^3 is filled with a gas at 24 °C and 99.5 kPa, the mass increases by 0.103 g. Deduce whether the gas is ammonia, nitrogen or argon.

(ii) Explain why ammonia is the most likely of these three gases to deviate from ideal gas behaviour.

....

....

....

....

....[5]

2 This question is about the physical chemistry of gases, with particular emphasis on the inert gas argon. Argon exists in the atmosphere as single atoms.

(a) State **two** of the assumptions of the kinetic theory as applied to an inert gas.

(i) ....

....

(ii) ....

....
[2]

(b) How many atoms of argon are present in **one** mole of the gas?

....[1]

(c) You are to calculate the percentage of the volume occupied by the atoms themselves in one mole of argon at room temperature and pressure.

(i) Use the *Data Booklet* to calculate the volume of one atom of argon.
[volume = $\frac{4}{3}\pi r^3$ $\pi = 3.14$]

(ii) Use your answer to **(c)(i)** to calculate the volume of one mole of argon atoms.

(iii) State the volume occupied by one mole of argon (assume it to behave as an ideal gas) at room temperature and pressure.

....

(iv) What percentage of this volume is occupied by the atoms themselves?

(v) Explain how your answer to **(c)(iv)** justifies one of your assumptions in **(a)**.

....

....
[5]

(d) Argon is used to fill electric light bulbs. These have a fine filament of a metal wire, usually tungsten, which glows white hot from its electrical resistance to the current.

Suggest why argon, rather than air, is used to fill electric light bulbs.

....

....

....

....[2]

3 Some intercontinental jet airliners use kerosene as fuel. The formula of kerosene may be taken as $C_{14}H_{30}$.

(a) To which homologous series of compounds does kerosene belong?

.... [1]

(b) When kerosene burns in an excess of air, carbon dioxide and water form.
Balance the following equation for the complete combustion of kerosene.

$$......C_{14}H_{30}(l) + ...O_2(g) \rightarrow ......CO_2(g) + ...H_2O(g)$$ [1]

(c) **In this section, give your answers to <u>one</u> decimal place.**

The flight path from Beijing to Paris is approximately 8195 km.
A typical intercontinental jet airliner burns 10.8 kg of kerosene for each kilometre covered.

(i) Calculate the mass, in tonnes, of $C_{14}H_{30}$ burnt on a flight from Beijing to Paris.
[1 tonne = 1 000 kg]

(ii) Use your equation in **(b)** to calculate the mass, in tonnes, of CO_2 produced during this flight.

[4]

Bicycles may be carried on commercial airliners. When carried on airliners, bicycles are placed in the luggage hold. This is a part of the aircraft which, in flight, will have different temperatures and air pressures from those at sea level.

This question concerns the change in pressure in an inflated bicycle tyre from when it is at sea level to when it is in the hold of an airliner in flight.

(d) At sea level and a temperature of 20 °C an inflated bicycle tyre contains 710 cm^3 of air at an internal pressure of 6×10^5 Pa.

Use the general gas equation $PV = nRT$ to calculate the amount, in moles, of air in the tyre at sea level.

[2]

The same bicycle, with its tyres inflated at sea level as described in **(d)** above, is placed in the luggage hold of an airliner. At a height of 10 000 m, the temperature in the luggage hold is 5 °C and the air pressure is 2.8×10^4 Pa.

(e) Assuming the volume of the tyre does not change, use your answer to **(d)** to calculate the pressure inside the tyre at a height of 10 000 m.

[2]

4 The kinetic theory of gases is used to explain the large scale (macroscopic) properties of gases by considering how individual molecules behave.

(a) State **two** basic assumptions of the kinetic theory as applied to an ideal gas.

(i) ....

....

(ii) ....

.... [2]

(b) State **two** conditions under which the behaviour of a real gas approaches that of an ideal gas.

(i) ....

(ii) .... [2]

(c) Place the following gases in decreasing order of ideal behaviour.

ammonia, neon, nitrogen

most ideal .... **least ideal**

Explain your answer.

....

.... [3]

(d) By using the kinetic-molecular model, explain why a liquid eventually becomes a gas as the temperature is increased.

....

....

....

....[2]

(e) Ethane, CH_3CH_3, and fluoromethane, CH_3F are *iso*-electronic, that is they have the same total number of electrons in their molecules.

Calculate the **total** number of electrons in one molecule of CH_3F.

[1]

(f) The boiling points of these two compounds are given below.

compound	bp/K
CH_3CH_3	184.5
CH_3F	194.7

Suggest explanations for the following.

(i) the close similarity of the boiling points of the two compounds

....

....

(ii) the slightly higher boiling point of CH_3F

....

....

[2]

5 When a 0.148 g sample of **A** was vapourised at 60°C, the vapour occupied a volume of 67.7 cm^3 at a pressure of 101 kPa.

Use the general gas equation $pV = nRT$ to calculate M_r of **A**.

M_r =......................

6 An organic compound, **E**, has the following composition by mass:
C, 48.7%; H, 8.1%; O, 43.2%.

(a) Calculate the empirical formula of **E**.

[2]

(b) When vaporised in a suitable apparatus, 0.130 g of **E** occupied a volume of 58.0 cm^3 at 127 °C and 1.00×10^5 N m^{-2}.

(i) Use the expression $pV = \frac{mRT}{M_r}$ to calculate M_r of **E**,

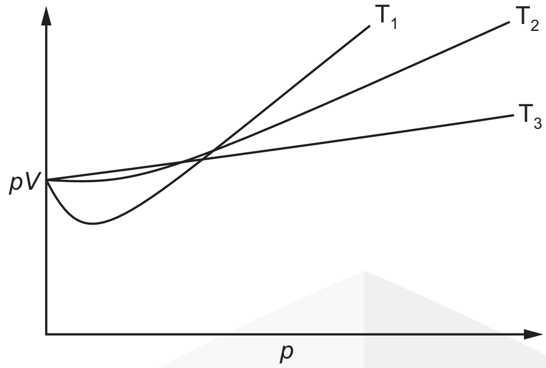
where m is the mass of **E**.

(ii) Hence calculate the molecular formula of **E**.

[4]

7 The relationship $pV = nRT$ can be derived from the laws of mechanics by assuming ideal behaviour for gases.

(a) The graph represents the relationship between pV and p for a real gas at three different temperatures, T_1, T_2 and T_3.



(i) Draw **one** line on the graph to show what the relationship should be for the same amount of an **ideal** gas. [1]

(ii) State and explain, with reference to the graph, which of T_1, T_2 or T_3 is the lowest temperature.

....

.... [1]

(iii) Explain your answer to **(ii)** with reference to intermolecular forces.

....

.... [1]

(iv) State and explain the effect of pressure on the extent to which a gas deviates from ideal behaviour.

....

....

....

.... [2]

(b) A flask with a volume of $100\,cm^3$ was first weighed with air filling the flask, and then with another gas, **Y**, filling the flask. The results, measured at 26 °C and 1.00×10^5 Pa, are shown.

Mass of flask containing air	= 47.930 g
Mass of flask containing **Y**	= 47.989 g
Density of air	= $0.00118\,g\,cm^{-3}$

Calculate the relative molecular mass, M_r, of **Y**.

M_r of **Y** = ... [4]

(c) Although nitrogen gas makes up about 79% of the atmosphere it does not easily form compounds.

(i) Explain why nitrogen is so unreactive.

....

.... [1]

(ii) Explain why the conditions in a car engine lead to the production of oxides of nitrogen.

....

.... [1]

(iii) Give an equation for a reaction involved in the removal of nitrogen monoxide, NO, from a car's exhaust gases, in the catalytic converter.

.... [1]

One of the main reasons for reducing the amounts of oxides of nitrogen in the atmosphere is their contribution to the formation of acid rain.

(iv) Write an equation for the formation of nitric acid from nitrogen dioxide, NO_2, in the atmosphere.

.... [1]

(v) Write equations showing the catalytic role of nitrogen monoxide, NO, in the oxidation of atmospheric sulfur dioxide, SO_2.

....

.... [2]

Equilibria

This topic illustrates that many chemical reactions are reversible and involve an equilibrium process. The consideration of the many factors that can affect an equilibrium is an important aspect of physical chemistry.

a explain, in terms of rates of the forward and reverse reactions, what is meant by a reversible reaction and dynamic equilibrium ☐

b state Le Chatelier's principle and apply it to deduce qualitatively (from appropriate information) the effects of changes in temperature, concentration or pressure on a system at equilibrium ☐

c state whether changes in temperature, concentration or pressure or the presence of a catalyst affect the value of the equilibrium constant for a reaction ☐

d deduce expressions for equilibrium constants in terms of concentrations, K_c , and partial pressures, K_p (treatment of the relationship between K_p and K_c is not required) ☐

e calculate the values of equilibrium constants in terms of concentrations or partial pressures from appropriate data ☐

f calculate the quantities present at equilibrium, given appropriate data (such calculations will not require the solving of quadratic equations) ☐

g describe and explain the conditions used in the Haber process and the Contact process, as examples of the importance of an understanding of chemical equilibrium in the chemical industry ☐

EQUILIBRIA

7 Equilibria

This topic illustrates that many chemical reactions are reversible and involve an equilibrium process. The consideration of the many factors that can affect an equilibrium is an important aspect of physical chemistry.

	Learning outcomes Candidates should be able to:
7.1 Chemical equilibria: reversible reactions; dynamic equilibrium	a) explain, in terms of rates of the forward and reverse reactions, what is meant by a *reversible reaction* and *dynamic equilibrium* b) state Le Chatelier's principle and apply it to deduce qualitatively (from appropriate information) the effects of changes in temperature, concentration or pressure on a system at equilibrium c) state whether changes in temperature, concentration or pressure or the presence of a catalyst affect the value of the equilibrium constant for a reaction d) deduce expressions for equilibrium constants in terms of concentrations, K_c, and partial pressures, K_p (treatment of the relationship between K_p and K_c is not required) e) calculate the values of equilibrium constants in terms of concentrations or partial pressures from appropriate data f) calculate the quantities present at equilibrium, given appropriate data (such calculations will *not* require the solving of quadratic equations) g) describe and explain the conditions used in the Haber process and the Contact process, as examples of the importance of an understanding of chemical equilibrium in the chemical industry

EQUILIBRIA

REVERSIBLE REACTIONS

In most reactions the reactants are completely converted to products i.e. the reaction proceeds in one direction only. Such reactions are referred to as **irreversible reactions**.

There are some reactions, which can be **reversed** by altering the conditions of the reactions.

For example when gaseous ammonia and hydrogen chloride are brought together at room temperature white dense fumes of ammonium chloride is formed.

However, on heating, ammonium chloride decomposes to give ammonia and hydrogen chloride. Such reactions are described as **reversible reactions**.

2

REVERSIBLE REACTIONS

If in a reversible reaction the conditions required for the forward reaction and the backward reaction are the same, a stage will be reached when the rate of the forward reaction becomes equal to the rate of the backward reaction.

Then the system is said to be in a state of chemical equilibrium.

The equilibrium is dynamic. i.e. the forward and the backward reactions keep on occurring continually without affecting the concentration of the components.

Thus, at equilibrium the concentration of the constituents do not change with time.

3

CHARACTERISTICS OF THE EQUILIBRIUM STATE

A system is said to be in a state of dynamic equilibrium when in a reversible reaction, the rate of the forward reaction is equal to the rate of the backward reaction.

1. The rate of the forward reaction is equal to the rate of the backward reaction.
2. The concentration of the constituents at equilibrium does not change with time.
3. Equilibrium is a dynamic state – opposing changes at molecular level are continually taking place.
4. The position of equilibrium is sensitive to changes of temperature and pressure or concentration.
5. The equilibrium may be attained from either direction.

4

EQUILIBRIUM LAW

For an equilibrium reaction of the form:

$$wA \; + \; xB \; \rightleftharpoons \; yC \; + \; zD$$

Then (at a constant temperature) = $\dfrac{[C]^y \cdot [D]^z}{[A]^w \cdot [B]^x}$ = a constant, (K_c)

Where [ ] denotes the equilibrium concentration in mol dm^{-3}. $\mathbf{K_c}$ is known as the **Equilibrium Constant.**

Note: Solids are NOT a part of equilibrium expressions because the concentration of solids is ALWAYS constant.

5

EXAMPLE 1

Consider the reaction $2SO_2(g) \; + \; O_2(g) \; \rightleftharpoons \; 2SO_3(g)$

If the equilibrium concentrations are:

SO_2: 0.016 mol dm^{-3} O_2: 0.0083 mol dm^{-3} SO_3: 0.15 mol dm^{-3},

Calculate the value of the equilibrium constant K_c , stating its units.

$$K_c = \frac{[SO_3]^2}{[SO_2]^2 \times [O_2]} = \frac{(0.15)^2}{(0.016)^2 \times 0.0083} = 1.1 \times 10^4 \text{ mol}^{-1} \text{ dm}^3$$

The units can be calculated by realizing:

$$\frac{\text{conc}^2}{\text{conc}^2 \times \text{conc}} = \frac{1}{\text{conc}} \qquad \text{which is} = \frac{1}{\text{mol dm}^{-3}} = \text{mol}^{-1} \text{ dm}^3$$

6

EXAMPLE 2

What are the units of the equilibrium constant K_c for the following reactions?

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

(b) $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

a) Units are $\dfrac{conc^2}{conc \times conc^3} = \dfrac{1}{conc^2} = mol^{-2}\,dm^6$

b) Units are $\dfrac{conc^2}{conc \times conc}$ = no units as all the concentration terms cancel

7

CALCULATING K_C – EXAMPLE 1

Consider the equilibrium **$P + 2Q \rightleftharpoons R + S$** (all species are aqueous)

One mole of P and one mole of Q are mixed in 1 dm^3 water. Once equilibrium has been achieved 0.6 moles of P are present. How many moles of Q, R and S are present at equilibrium? What is the K_c?

	P	Q	R	S
initial moles	1	1	0	0
moles that reacted	______	______	______	______
moles @ equilibrium	0.6	______	______	______
[conc] @ equilibrium	______	______	______	______

8

CALCULATING K_C – EXAMPLE 1

The method is:

1. Construct the balanced equation, including state symbols (aq), (g) etc.
2. Write down the expression for K_c.
3. Calculate the moles of each substance that reacted.
4. Calculate the moles of each substance at equilibrium.
5. Divide these by the volume to get the concentration of each substance, use V if no volume given.
6. Put the equilibrium values into the expression for Kc and calculate the answer and work out the units.

9

CALCULATING K_C – EXAMPLE 1

Consider the equilibrium $P + 2Q \rightleftharpoons R + S$ (all species are aqueous)

One mole of P and one mole of Q are mixed in 1 dm^3 water. Once equilibrium has been achieved 0.6 moles of P are present.

	P	Q	R	S
initial moles	1	1	0	0
moles that reacted	0.4	0.8	0.4	0.4
moles @ equilibrium	0.6	0.2	0.4	0.4
[conc] @ equilibrium	**0.6**	**0.2**	**0.4**	**0.4**

$$K_c = \frac{[R] \times [S]}{[P] \times [Q]^2} = \frac{0.4 \times 0.4}{0.6 \times (0.2)^2} = 6.67$$

- If 0.6 mol of P remain of the original 1 mol, 0.4 mol have reacted.
- The equation states that 2 moles of Q react with every 1 mole of P.
- This means that 0.8 (2 x 0.4) moles of Q have reacted, leaving 0.2 moles.
- One mole of R and S are produced from every mole of P that reacts.
- This means 0.4 moles of R and 0.4 moles of S are present at equilibrium.

10

CALCULATING K_c – EXAMPLE 2

One mole of ethanoic acid reacts with one mole of ethanol at 298K. When equilibrium is reached it is found that two thirds of the acid has reacted. Calculate the value of K_c.

$$CH_3COOH(l) + CH_3CH_2OH(l) \rightleftharpoons CH_3CO_2CH_2CH_3(l) + H_2O(l)$$

	CH_3COOH	CH_3CH_2OH	$CH_3CO_2CH_2CH_3$	H_2O
initial moles	1	1	0	0
moles that reacted	$^2/_3$	$^2/_3$	$^2/_3$	$^2/_3$
moles @ equilibrium	$1 - {}^2/_3 = {}^1/_3$	$1 - {}^2/_3 = {}^1/_3$	$^2/_3$	$^2/_3$
[conc] @ equilibrium	$^1/_3$ / V	$^1/_3$ / V	$^2/_3$ / V	$^2/_3$ / V

$$K_c = \frac{[CH_3CO_2CH_2CH_3][H_2O]}{[CH_3COOH][CH_3CH_2OH]} = \frac{{}^2/_3 / V \;.\; {}^2/_3 / V}{{}^1/_3 / V \;.\; {}^1/_3 / V} = 4$$

11

CALCULATING K_c – EXAMPLE 3

2.6 mol of ethanoic acid, CH_3COOH, was mixed with 1.6 mol of ethan–1,2–diol and allowed to reach equilibrium when 1.1 mol of the ester $CH_3COOCH_2CH_2OCOCH_3$, was present. The total volume was 250cm^3. Calculate the value of the equilibrium constant, K_c.

$$2CH_3COOH(l) + CH_2(OH)CH_2OH(l) \rightleftharpoons CH_3COOCH_2CH_2OCOCH_3(l) + 2H_2O(l)$$

12

CALCULATING K_C — EXAMPLE 3

	CH_3COOH	$CH_2(OH)CH_2OH$	ester	H_2O
initial moles	2.6	1.6	0	0
moles that reacted	2.2	1.1	1.1	2.2
moles @ equilibrium	0.4	0.5	1.1	2.2
[conc] @ equilibrium	0.4 / 0.25 = 1.6	0.5 / 0.25 = 2.0	1.1 / 0.25 = 4.4	2.2 / 0.25 = 8.8

$$K_C = \frac{[CH_3COOCH_2CH_2OCOCH_3] \times [H_2O]^2}{[CH_3COOH]^2 \times [CH_2(OH)CH_2OH]} = \frac{4.4 \times (8.8)^2}{(1.6)^2 \times 2} = 67 \text{ (no units)}$$

13

CALCULATIONS INVOLVING K_C

Calculate the amount of hydrogen iodide at equilibrium when 1.0 mol of hydrogen and 1.0 mol of iodine are heated at a temperature T until equilibrium is reached in a container of volume 10dm^3.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \qquad K_c = 49 \text{ (no units)}$$

14

CALCULATIONS INVOLVING K_C

This can be done in some cases where the number of molecules on the two sides are the same:

1. Write down the expression for K_c (there will always be a mark for this).
2. Assume that x moles of the substance(s) on the left have reacted.
3. Calculate the equilibrium moles of each substance and their concentrations in terms on x.
4. Substitute these values into the expression for K_c and solve for x by taking the square root of both sides.

15

CALCULATIONS INVOLVING K_C

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \qquad K_c = \frac{[HI]^2}{[H_2][I_2]} = 49$$

Let x mol of hydrogen that react.

	H_2	I_2	HI
initial moles	1	1	0
moles that reacted	x	x	2x
moles @ equilibrium	1 − x	1 − x	2x
[conc] @ equilibrium	(1 − x) / 10	(1 − x) / 10	2x / 10

16

CALCULATIONS INVOLVING K_C

$$K_c = \frac{[HI]^2}{[H_2][I_2]} = \frac{(2x/10)}{(1-x)/10 \,.\, (1-x)/10} = \frac{4x^2}{(1-x)^2} = 49$$

$$\frac{2x}{1-x} = \pm 7$$

$$\frac{2x}{1-x} = +7$$

$2x = 7 - 7x$

$9x = 7$

$x = 7/9 = 0.78$

As the moles of HI at equilibrium is 2x, there are 1.56 moles of HI at equilibrium.

$$\frac{2x}{1-x} = -7$$

$2x = -7 + 7x$

$-5x = -7$

$x = -7/5 = -1.4$

As the moles of H_2 at equilibrium is 1 – x, that would result in – 0.4 moles of H_2 at equilibrium. **NOT POSSIBLE**

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EQUILIBRIUM CONSTANT K_P

K_p is the equilibrium constant in terms of the partial pressures of the gases in the equilibrium reaction.

For the reaction: $nA(g) + mB(g) \rightleftharpoons xC(g) + yD(g)$

$$K_p = \frac{pC^x \times pD^y}{pA^n \times pB^m}$$

Partial pressure of gas A:
p(A) = mole fraction of A x total pressure

$$\text{Mole fraction of A} = \frac{\text{moles of A}}{\text{total moles of gas}}$$

1. Use the value of the partial pressure of any gas in the equilibrium mixture.
2. As with K_c, the units of K_p depend on the stoichiometry of the reaction.

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EXAMPLE 1

Calculate the partial pressure of sulfur dioxide in a mixture containing 0.016 mol SO_2, 0.0083 mol O_2 and 0.15 mol SO_3 in a vessel at a pressure of 7.0 atm. and hence the K_p of the following reaction:

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

Total number of moles = 0.016 + 0.0083 + 0.15 = 0.1743 mol

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EXAMPLE 1

SO_2: Mole fraction of SO_2 = 0.016 / 0.1743 = 0.0918

Partial Pressure of SO_2 = 0.0918 x 7.0 = 0.643 atm

O_2: Mole fraction of O_2 = 0.0083 / 0.1743 = 0.0476

Partial Pressure of O_2 = 0.0476 x 7.0 = 0.333 atm

SO_3: Partial Pressure of SO_3 = 7 − (0.643 + 0.333) = 6.024

$$K_p = \frac{p(SO_3)^2}{p(SO_2)^2 \times p(O_2)} = \frac{(6.024)^2}{(0.643)^2 \times 0.333} = 264 \text{ atm}^{-1}$$

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EXAMPLE 2

When some phosphorous pentachloride PCl_5, was heated to a temperature T in a container, 78% of it decomposed and the pressure in the container was 2.2 atm.

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$$

Calculate the value of the equilibrium constant Kp.

$$K_p = \frac{p(PCl_3) \times p(Cl_2)}{p(PCl_5)}$$

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EXAMPLE 2

The method is:

1. Write down the expression for K_p.
2. Calculate the moles of each substance at equilibrium – starting amount is given, assume there was 1 mol of the reactant on the left.
3. Add up all the equilibrium moles to get the total number of moles. Work out the mole fraction of each gas (moles/total moles). Work out the partial pressure of each gas (mole fraction x total pressure).
4. Put these partial pressures into the expression for K_p and calculate its value with units.

22

EXAMPLE 2

Assume that there was 1 mol of PCl_5 to start with. As 78% reacted, 0.22 mol was present at equilibrium. 0.78 mol of PCl_3 and Cl_2 were formed.

	PCl_5	PCl_3	Cl_2
initial moles	1	0	0
moles that reacted	0.78	0.78	0.78
moles @ equilibrium	0.22	0.78	0.78
mole fraction	0.22/1.78 = 0.124	0.78/1.78 = 0.438	0.78/1.78 = 0.438
partial pressure	0.124 x 2.2 = 0.273	0.438 x 2.2 = 0.964	0.438 x 2.2 = 0.964

$$K_p = \frac{p(PCl_3) \times p(Cl_2)}{p(PCl_5)} = \frac{0.964 \times 0.964}{0.272} = 3.42 \text{ atm}$$

23

CALCULATING Kp

When nitrogen (1 mole) and hydrogen (3 moles) react at constant temperature at a pressure of 8×10^6 Pa, the equilibrium mixture was found to contain 0.7 moles of ammonia. Calculate K_p.

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

	N_2	H_2	NH_3
initial moles	1	3	0
moles that reacted	0.35	1.05	0.7
moles @ equilibrium	0.65	1.95	0.7
partial pressure	$0.65/3.3 \times 8 \times 10^6$	$1.95/3.3 \times 8 \times 10^6$	$0.7/3.3 \times 8 \times 10^6$

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CALCULATING K_P

$$K_p = \frac{p(NH_3)^2}{p(N_2) \times p(H_2)^3} = \frac{(1.7 \times 10^6)^2}{(1.58 \times 10^6) \times (4.77 \times 10^6)^3}$$

$$= 1.73 \times 10^{-14}\ Pa^{-2}$$

Note: The ratio of partial pressures is the same as the mole ratio at equilibrium.

25

SKILL CHECK

When nitrogen (1 mole) and hydrogen (3 moles) react at constant temperature at a pressure of 8 x ^{6} Pa, the equilibrium mixture was found to contain 0.7 moles of ammonia. Calculate K_p.

26

SKILL CHECK

Given that PCl_5 at 700 K and 1.1 atm total pressure dissociated 33%, find K_p.

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$$

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SKILL CHECK

A chemist carries out an investigation on the equilibrium system shown below.

$$2CO(g) + 2NO(g) \rightleftharpoons 2CO_2(g) + N_2(g)$$

The chemist mixes 0.46 mol of CO with 0.45 mol of NO. The mixture is left to reach equilibrium at constant temperature.

The chemist analyses the equilibrium mixture and finds that 0.25 mol NO remains and the total pressure was 5 atm. What is the value of K_p.

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SKILL CHECK

1.0 mol of N_2O_4 was allowed to reach equilibrium at 400K. At equilibrium the partial pressure of N_2O_4 was found to be 0.15 atm. Given that the K_p for the reaction is 48 atm, calculate the partial pressure of NO_2 in the equilibrium mixture.

$$\mathbf{N_2O_4\,(g) \rightleftharpoons 2\,NO_2\,(g)}$$

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VALUE OF K AND THE EXTENT OF A REACTION

If the value of K_c is large it means that the position of the equilibrium is well to the right (towards products).

If the value of K_c is close to 1 it means that the position of the equilibrium is close to being halfway.

If the value of K_c is very small (< 1), the position of equilibrium is well to the left (towards reactants).

Reminder: the concentration of pure solids and pure liquids is a constant and so is not included in the expression for K_c.

e.g. $C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g)$

$$K_c = \frac{[CO][H_2]}{[H_2O]}$$

30

VALUE OF K AND THE EXTENT OF A REACTION

Only the partial pressures of gases are included in the expression for K*p*; the other substances are ignored.

Example State the expression for Kp for the reaction

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$$

and calculate the pressure of carbon dioxide when calcium carbonate is heated to 800°C given that K_p = 0.80 atm.

$K_p = p(CO_2) = 0.80$ atm

The two solids must be omitted from the expression for K_p

31

LE CHATELIER'S PRINCIPLE

If a **change in condition** is made to a **closed system** in equilibrium, the system responds to **counteract the change** as much as possible.

Conditions include concentration, pressure and temperature

The system **counteracts the change** by making the **direction** of the reaction move **against** the change.

Note: Catalysts do **not** affect the position of equilibrium! They only speed up the rate of reaching equilibrium – getting there faster!

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EFFECT OF CONCENTRATION ON EQUILIBRIUM

TWO GENERAL RULES:

1. If the concentration of a substance is increased, the system will counteract the change by forcing the reaction to go in the direction that uses up the 'extra' substance.
2. If the concentration of a substance is decreased, the system will counteract the change by forcing the reaction to go in the direction that makes more of the substance.

Example

$$A(g) + 2B(g) \rightleftharpoons 2C(g) \quad \Delta H = -\ 200\ kJ\ mol^{-1}$$

If concentration of C is increased, the equilibrium will move in a way so as to oppose the change, that is, decrease C by favoring the backward reaction.

33

EFFECT OF CONCENTRATION ON EQUILIBRIUM

If concentration of a reactant increases. → The reaction goes **FORWARD**. → Equilibrium moves to the right. → The 'extra' reactant is used up, more products are made.

$$CH_3COOH(l) + C_2H_5OH(l) \rightleftharpoons CH_3COOC_2H_5(l) + H_2O(l)$$

The 'extra product is used up, more reactants are made. ← Equilibrium moves to the left ← The reaction **REVERSES**. ← If concentration of a product increases.

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EFFECT OF PRESSURE ON EQUILIBRIUM

If pressure increases → The reaction goes to the side with fewer gas molecules. → Equilibrium moves to the left. → There are fewer gas molecules so pressure falls

$$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g)$$

2 molecules — 4 molecules

If pressure decreases → The reaction goes to the side with more gas molecules Equilibrium moves to the left. → Equilibrium moves to the right. → There are more gas molecules so pressure rises.

35

EFFECT OF TEMPERATURE ON EQUILIBRIUM

Le Chatelier's principle also works for temperature changes.

If the **temperature is increased**, the reaction will go in the direction that **reduces** the temperature by **taking in energy** (converting heat energy to chemical energy), i.e. the **endothermic** direction.

If the **temperature is decreased**, the reaction will go in the direction that **increases** the temperature by **giving out energy** (converting chemical energy to heat energy), i.e. the **exothermic** direction.

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EFFECT OF TEMPERATURE ON EQUILIBRIUM

Example

$$A(g) \;+\; 2B(g) \;\rightleftharpoons\; 2C(g) \qquad \Delta H = -200\ \text{kJ mol}^{-1}$$

If temperature increases, the equilibrium shifts in a way so as to decrease the temperature of the system. Hence, the backward reaction is favored as it is the endothermic reaction and results in a temperature decrease.

Note:

- Low temperatures favor exothermic reactions.
- High temperatures favor endothermic reactions.

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EXOTHERMIC CHANGES

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

The **FORWARD** reaction is **exothermic. It gives out energy. Increases** the temperature.

Therefore...

The **REVERSE** reaction is **endothermic. It takes in energy. Decreases** the temperature

If the temperature increases. → The system will go in the **endothermic** direction. → The reaction **REVERSES.** → More reactants (N_2 and H_2) are made.

If the temperature decreases. → The system will go in the **exothermic** direction. → The reaction goes FORWARD → More product (NH_3) is made.

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EXOTHERMIC CHANGES

$N_2O_4(g) \rightleftharpoons 2NO_2(g)$ **ΔH = + 57 kJ mol⁻¹**

The **FORWARD** reaction is **endothermic** ⟷ Therefore... ⟷ The **REVERSE** reaction is **exothermic**

If the temperature increases. → The system will go in the **endothermic** direction. → The reaction goes FORWARD → More product (NO_2) is made.

If the temperature decreases. → The system will go in the **exothermic** direction. → The reaction **REVERSES.** → More reactants (N_2O_4) are made.

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CONDITIONS AFFECTING EQUILIBRIUM – EXAMPLE 1

Ethanol is made on an industrial scale by reacting ethene with steam at 300°C.

$$C_2H_4(g) + H_2O(g) \rightleftharpoons C_2H_5OH(g)$$

Explain the effect that each of the following changes has on the yield of ethanol.

A. Increasing the pressure.

B. Increasing the concentration of ethene.

C. Using a catalyst.

40

CONDITIONS AFFECTING EQUILIBRIUM – EXAMPLE 1

A. Increasing the pressure would increase the yield of ethanol. There are two molecules on the left of the equation and only one on the right. The system would act to reduce the increased pressure by forming fewer gas molecules, moving the equilibrium to the right (forward reaction).

B. Increasing the concentration of ethene would increase the yield of ethanol. The system would act to reduce the increased concentration by moving to the right (forward reaction) and forming more products.

C. Catalyst have no effect on yield – they only affect the rate.

41

CHOOSING THE CONDITIONS

For industrial processes, the best conditions give high yields (more products) at a fast rate.

Changing conditions affects both rate and position of equilibrium.

'Compromise conditions' of pressure and temperature are used to give reasonable yields at fast rates.

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CHOOSING THE CONDITIONS

CHANGES	RATE	EQUILIBRIUM POSITION (YIELD)
Increased concentration of reactants	**Faster**	Moves to the right More products = **higher yield**
Increased pressure (gases)	**Faster**	Moves to the side of the reaction with **fewer gas molecules** For some reactions this decreases yield
Increased temperature	**Faster**	Moves in the **endothermic** direction For exothermic reactions this **decreases** yield
Use of a **catalyst**	**Faster**	**No effect**

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CONDITIONS AFFECTING EQUILIBRIUM – EXAMPLE 2

Explain whether the yield of the following reactions would increase or decrease if the temperature was increased.

A. $C_2H_4(g) + H_2O(g) \rightleftharpoons C_2H_5OH(g)$ $\Delta H = -46\ kJ\ mol^{-3}$

B. $N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$ $\Delta H = +90\ kJ\ mol^{-3}$

C. $H_2O(g) + C(s) \rightleftharpoons CO(g) + H_2(g)$ $\Delta H = +13\ kJ\ mol^{-3}$

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CONDITIONS AFFECTING EQUILIBRIUM – EXAMPLE 2

A. The reaction is **exothermic** in the forward direction. An increase in the temperature moves the reaction in the **endothermic** direction, so it **reverses** and **less yield** of C_2H_5OH is formed.

B. The reaction is **endothermic** in the forward direction. An increase in the temperature moves the reaction in the **endothermic** direction, so it **goes forward** and **more yield** of NO is formed.

C. The reaction is **endothermic** in the forward direction. An increase in the temperature moves the reaction in the **endothermic** direction, so it **goes forward** and **more yield** of CO and H_2 is formed.

45

EFFECT OF TEMPERATURE ON K

In the following case:

$$\mathbf{A(g) + 2B(g) \rightleftharpoons 2C(g)\ \Delta H = -200\ kJ\ mol^{-1}}$$

Only temperature affects K_c and K_p. If temperature increases, K_c decreases. This is because increasing temperature will make the reaction move backwards, increasing the value of the denominator and lowering the value of numerator.

Note: Always write the effect on equilibrium and rate. For example, for an exothermic reaction, a **low temperature** would **slow down** the rate and **increase** the yield.

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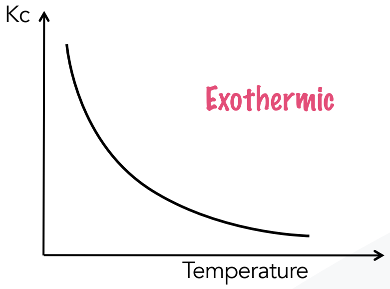
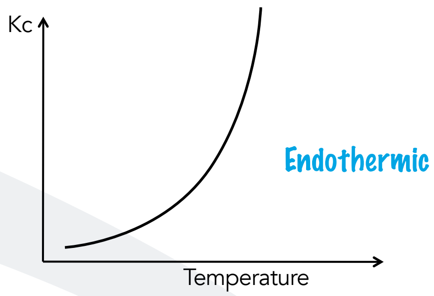
EFFECT OF TEMPERATURE ON K





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ACID AND BASES

ACIDS AND BASES

ARRHENIUS THEORY

Acids are substances that produce **H^+ ions** when they dissolve in water.

Bases are substances that react with H^{++} ions to produce water.

Alkalis are bases which dissolve in water to produce OH^- ions.

Hence, the stronger the dissociation, the stronger the acid.

However, H^+ ions exist as Hydronium H_3O^+ ions, associating with water molecules by coordinate bonds.

2

ARRHENIUS THEORY

Arrhenius theory limits itself to the concentration of H^+ and OH^- ions determining the strength of acids and bases.

Hence, this theory is restricted to polar solvents like water.

However, this is also why Hydrochloric and Ethanoic acid show acidity.

strong acid: $HCl \rightarrow H^+ + Cl^-$

weak acid: $CH_3CO_2H \rightleftharpoons H^+ + CH_3CO_2^-$

3

BRONSTED-LOWRY THEORY

According to this, an acid is a proton (H+) **donor**, and bases are proton **acceptors**.

In the following reaction HCl is an acid because it donates a proton to water. This means that water is acting as a Brønsted– Lowry base. The water is accepting a proton.

H^+ donated

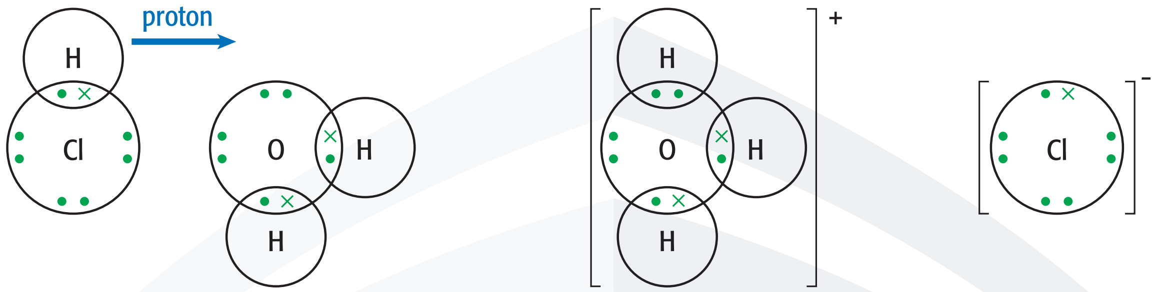
$$\underset{\text{acid}}{HCl(g)} + \underset{\text{base}}{H_2O(l)} \rightarrow H_3O^+(aq) + Cl^-(aq)$$

4

BRONSTED-LOWRY THEORY

Also, a base has to be a substance with a lone pair, to coordinate with the proton.

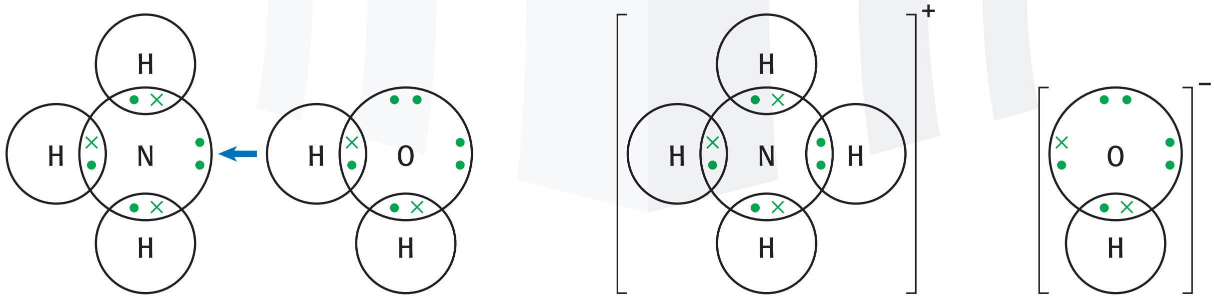
$$HCl(g) + H_2O(l) \longrightarrow H_3O^+(aq) + Cl^-(aq)$$



5

BRONSTED-LOWRY THEORY

$$NH_3(g) + H_2O(l) \longrightarrow NH_4^+(aq) + OH^-(aq)$$



The proton, H^+, is donated by the water and accepted by the ammonia…

…forming the positive ammonium ion…

…and the negative hydroxide ion.

6

BRONSTED-LOWRY THEORY

$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$

A conjugate acid is a base that has accepted a proton.

A conjugate base is an acid that has donated a proton.

Hence, the NH_4^+ ion is said to be the conjugate acid of NH_3, and likewise, NH_3 is the conjugate base of NH_4^+ ion.

H_2O is the conjugate acid of the OH^- ion, and the OH^- ion is the conjugate base of H_2O.

7

BRONSTED-LOWRY THEORY

This suggests that a substance can both be an acid and a base depending on the situation.

conjugate pair

$$\underset{\text{acid}}{HCl(g)} + \underset{\text{base}}{H_2O(l)} \rightleftharpoons \underset{\text{acid}}{H_3O^+(aq)} + \underset{\text{base}}{Cl^-(aq)}$$

conjugate pair

conjugate pair

$$\underset{\text{base}}{NH_3(g)} + \underset{\text{acid}}{H_2O(l)} \rightleftharpoons \underset{\text{acid}}{NH_4^+(aq)} + \underset{\text{base}}{OH^-(aq)}$$

conjugate pair

8

STRENGTH OF ACIDS

The strength of acids is judged by their tendency to donate protons.

The strength of bases is judged by their tendency to accept protons.

$$HCl + H_2O \rightarrow H_3O^+ + Cl^-$$

The above reaction proceeds to completion, therefore, HCl is a stronger acid than H_3O^+, and H_2O is a stronger base than Cl^-.

9

STRENGTH OF ACIDS

$$CH_3CO_2H + H_2O \rightleftharpoons H_3O^+ + CH_3CO_2^-$$

Th above reaction however is a reversible reaction, with the equilibrium position well towards the left.

H_3O^+ is a stronger acid than CH_3CO_2H, and $CH_3CO_2^-$ is a stronger base than H_2O.

Hence, strong acids have weak conjugate bases, and vice versa.

10

SKILL CHECK 1

Identify which reactants are acids and which are bases:

(a) $NH_4^+ + H_2O \rightleftharpoons NH_3 + H_3O^+$

(b) $HCOOH + HClO_2 \rightleftharpoons HCOOH_2^+ + ClO_2^-$

(c) $HClO_4 + CH_3COOH \rightleftharpoons ClO_4^- + CH_3COOH_2^+$

(d) $H_2SO_4 + HNO_3 \rightleftharpoons HSO_4^- + H_2NO_3^+$

(e) $H_2S + H_2O \rightleftharpoons HS^- + H_3O^+$

11

EQUILIBRIA WS 1

SECTION A

1 In an experiment, 2.00 mol of hydrogen and 3.00 mol of iodine were heated together in a sealed container and allowed to reach equilibrium at a fixed temperature. The container had a fixed volume of 1.00 dm^3. At equilibrium, there were 2.40 mol of iodine present in the mixture.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$$

What is the value of the equilibrium constant, K_c?

A 0.107 **B** 0.357 **C** 0.429 **D** 2.33

2 An aqueous solution was prepared containing a mixture of 1.0 mol of $AgNO_3$ and 1.0 mol of $FeSO_4$ in 1.00 dm^3 of water. When equilibrium was established, there was 0.44 mol of $Ag^+(aq)$ in the mixture.

$$Ag^+(aq) + Fe^{2+}(aq) \rightleftharpoons Ag(s) + Fe^{3+}(aq)$$

What is the numerical value of K_c?

A 0.62 **B** 1.40 **C** 1.62 **D** 2.89

3 The equation for the reaction between carbon monoxide and hydrogen is shown.

$$CO(g) + 3H_2(g) \rightleftharpoons CH_4(g) + H_2O(g)$$

What are the units of K_p for this reaction?

A kPa **B** kPa^{-1} **C** kPa^2 **D** kPa^{-2}

4 When solid ammonium chloride dissociates at a certain temperature in a 0.500 dm^3 container, ammonia and hydrogen chloride are formed.

$$NH_4Cl(s) \rightleftharpoons NH_3(g) + HCl(g)$$

The initial amount of ammonium chloride was 1.00 mol, and when the system had reached equilibrium there was 0.300 mol of ammonium chloride.

What is the numerical value of K_c for this reaction under these conditions?

A 0.490 **B** 1.63 **C** 1.96 **D** 3.27

5 The equilibrium constant, K_c, for the reaction shown is 2 $mol^{-2}\,dm^6$, at 600 K.

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

What is the concentration of NH_3 at equilibrium, at 600 K, when the equilibrium concentrations of N_2 and H_2 are both 2 $mol\,dm^{-3}$?

A $\sqrt{8}$ $mol\,dm^{-3}$ **B** $\sqrt{16}$ $mol\,dm^{-3}$ **C** $\sqrt{32}$ $mol\,dm^{-3}$ **D** 32 $mol\,dm^{-3}$

6 Catalysts are an important feature of many industrial processes and biochemical reactions.

Which row correctly describes the effect of a catalyst on a reversible chemical reaction?

	position of equilibrium	effect on value of ΔH
A	moved to right	decreased
B	unaffected	decreased
C	unaffected	increased
D	unaffected	unaffected

7 The table shows the partial pressures in an equilibrium mixture formed by the Haber process.

substance	partial pressure / kPa
nitrogen	7000
hydrogen	8000
ammonia	4000

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

What is the numerical value of the equilibrium constant, K_p, for this reaction?

A 4.46×10^{-9}

B 4.76×10^{-5}

C 7.14×10^{-5}

D 2.24×10^{8}

8 Nitrogen reacts with hydrogen to produce ammonia.

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

A mixture of 2.00 mol of nitrogen, 6.00 mol of hydrogen and 2.40 mol of ammonia is allowed to reach equilibrium in a sealed vessel of volume 1 dm^3. It was found that 2.32 mol of nitrogen were present in the equilibrium mixture.

What is the value of K_c?

A $\dfrac{(1.76)^2}{(2.32)(6.96)^3}$

B $\dfrac{(1.76)^2}{(2.32)(6.32)^3}$

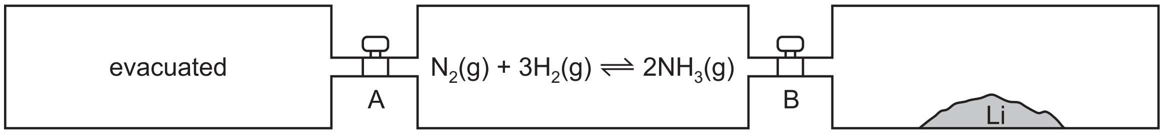
C $\dfrac{(2.08)^2}{(2.32)(6.32)^3}$

D $\dfrac{(2.40)^2}{(2.32)(6.00)^3}$

9 Lithium reacts with nitrogen at room temperature to form solid Li_3N.

Three vessels of equal volume are connected by taps, A and B, as shown.

10



At the start, A and B are closed, the left-hand vessel is evacuated, the middle vessel has the indicated reaction at equilibrium and the right-hand vessel contains lithium only.

Which action would allow the equilibrium mixture to contain the **most** ammonia?

A Keep both A and B closed.

B Open both A and B.

C Open A only.

D Open B only.

11 The table shows the partial pressures in an equilibrium mixture formed by the Haber process.

substance	partial pressure / kPa
nitrogen	7000
hydrogen	8000
ammonia	4000

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

What is the numerical value of the equilibrium constant, K_p, for this reaction?

A 4.46×10^{-9}

B 4.76×10^{-5}

C 7.14×10^{-5}

D 2.24×10^{8}

12 Hydrogen iodide dissociates into hydrogen and iodine.

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

In an experiment, b mol of hydrogen iodide were put into a sealed vessel at pressure p. At equilibrium, x mol of the hydrogen iodide had dissociated.

Which expression for K_p is correct?

A $\dfrac{x^2}{(b-x)^2}$ **B** $\dfrac{x^2p^2}{(b-x)^2}$ **C** $\dfrac{x^2p^2}{4b(b-x)}$ **D** $\dfrac{x^2}{4(b-x)^2}$

13 For the reaction shown, an equilibrium is established at a temperature of 700 K.

The equilibrium constant, K_p, for the reaction is 9.80 kPa. The partial pressure of N_2O_4 at equilibrium is 80.0 kPa.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g)$$

What is the partial pressure of NO_2 at equilibrium?

A 8.16 kPa **B** 28.0 kPa **C** 66.6 kPa **D** 784 kPa

14 Ammonia is produced by the Haber process.

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \qquad \Delta H^{\ominus} = -92\,\text{kJ mol}^{-1}$$

A fault in the temperature control during the process resulted in the temperature changing to 600 °C for two hours.

What effect did this have on the ammonia production during this time?

A Ammonia was formed faster. The equilibrium yield decreased.

B Ammonia was formed faster. The equilibrium yield increased.

C Ammonia was formed slower. The equilibrium yield decreased.

D Ammonia was formed slower. The equilibrium yield increased.

15 Ammonia is manufactured from nitrogen and hydrogen using the Haber process.

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

What is the expression for K_c for this equilibrium?

A $\dfrac{2[NH_3(g)]}{[N_2(g)] + 3[H_2(g)]}$

B $\dfrac{2[NH_3(g)]}{[N_2(g)] \times 3[H_2(g)]}$

C $\dfrac{[NH_3(g)]^2}{[N_2(g)] + [H_2(g)]^3}$

D $\dfrac{[NH_3(g)]^2}{[N_2(g)] \times [H_2(g)]^3}$

16 Two moles of compound P were placed in a sealed container. The container was heated and P was partially decomposed to produce Q and R only. A dynamic equilibrium between P, Q and R was established.

At equilibrium x moles of R were present and the total number of moles present was $\left(2 + \dfrac{x}{2}\right)$.

What is the equation for this reversible reaction?

A $P \rightleftharpoons 2Q + R$

B $2P \rightleftharpoons 2Q + R$

C $2P \rightleftharpoons Q + R$

D $2P \rightleftharpoons Q + 2R$

17 A reaction involved in the Contact process is shown.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H^{\ominus} = -197\,kJ\,mol^{-1}$$

The reaction is investigated at 200 kPa and 700 K and the value of the equilibrium constant, K_p, is found to be Y. The reaction is then investigated at 1000 kPa and 700 K and the value of K_p is found to be Z.

Which statement comparing Y and Z is correct?

A Y and Z are the same.

B Y is greater than Z.

C Z is 2.2 times greater than Y.

D Z is 5.0 times greater than Y.

18 Nitrogen dioxide, NO_2, is a brown gas.

Dinitrogen tetroxide, N_2O_4, is a colourless gas.

An equilibrium is established between NO_2 and N_2O_4 in a closed vessel.

$$\underset{\text{brown}}{2NO_2(g)} \rightleftharpoons \underset{\text{colourless}}{N_2O_4(g)} \qquad \Delta H = -57\,kJ\,mol^{-1}$$

Which row describes the effects of changing conditions on the colour of an equilibrium mixture of NO_2 and N_2O_4?

	increasing the pressure	increasing the temperature
A	colour becomes darker	colour becomes darker
B	colour becomes darker	colour becomes lighter
C	colour becomes lighter	colour becomes darker
D	colour becomes lighter	colour becomes lighter

[W'17 2 Q9]

19 The reaction between sulfur dioxide and oxygen is reversible.

$$2SO_2 + O_2 \rightleftharpoons 2SO_3 \qquad \Delta H^{\ominus} = -196\,kJ\,mol^{-1}$$

Which conditions of pressure and temperature favour the **reverse** reaction?

	pressure	temperature
A	high	high
B	high	low
C	low	high
D	low	low

[M'18 P12 Q11]

20 In a particular reversible reaction the yield of product is increased

- if the temperature is increased;
- if the pressure is decreased.

Which equation could describe this reversible reaction?

A $CH_4(g) + H_2O(g) \rightleftharpoons 3H_2(g) + CO(g)$ $\Delta H = +206\,kJ\,mol^{-1}$

B $4NH_3(g) + 3O_2(g) \rightleftharpoons 2N_2(g) + 6H_2O(g)$ $\Delta H = -227\,kJ\,mol^{-1}$

C $2NO_2(g) \rightleftharpoons N_2O_4(g)$ $\Delta H = -58\,kJ\,mol^{-1}$

D $3O_2(g) \rightleftharpoons 2O_3(g)$ $\Delta H = +143\,kJ\,mol^{-1}$

[J'18 P12 Q10]

21 Hydrogen is produced industrially from methane as shown in the equation.

$$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \qquad \Delta H^{\ominus} = +205\,kJ\,mol^{-1}$$

Which conditions would most favour the formation of hydrogen?

	pressure	temperature
A	high	high
B	high	low
C	low	high
D	low	low

[J'18 P13 Q9]

22 The chemical equilibrium shown is formed when ammonia is produced in the Haber process.

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

The following concentrations are found to be present at equilibrium under certain conditions.

N_2	H_2	NH_3
$0.200\,mol\,dm^{-3}$	$0.300\,mol\,dm^{-3}$	$0.600\,mol\,dm^{-3}$

What is the numerical value of K_c under these conditions?

A 0.0150 **B** 6.0 **C** 10.0 **D** 66.7

[J'18 P13 Q10]

23 Silver chloride and silver iodide form equilibria when added to water.

$$AgCl(s) \rightleftharpoons Ag^+(aq) + Cl^-(aq) \qquad K_c = K_1$$

$$AgI(s) \rightleftharpoons Ag^+(aq) + I^-(aq) \qquad K_c = K_2$$

Each equilibrium position lies well to the **left**.

Silver iodide will not dissolve in aqueous ammonia. Silver chloride will dissolve in aqueous ammonia. Another equilibrium is formed.

$$Ag^+(aq) + 2NH_3(aq) \rightleftharpoons Ag(NH_3)_2^+(aq) \qquad K_c = K_3$$

The position of this equilibrium lies to the **right**.

What is the order of magnitude for these three equilibrium constants?

A $K_1 > K_2 > K_3$

B $K_2 > K_1 > K_3$

C $K_3 > K_1 > K_2$

D $K_3 > K_2 > K_1$

[J'18 P13 Q17]

24 In this question you should assume that all gases behave ideally.

Hydrogen and iodine react reversibly in the following reaction. The system reaches dynamic equilibrium.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \qquad \Delta H = -9.5\,kJ\,mol^{-1}$$

Which statement **must** be true for the K_p of this equilibrium to be constant?

A The partial pressures of H_2, I_2 and HI are equal.

B The external pressure is constant.

C The forward and reverse reactions have stopped.

D The temperature is constant.

[N'18 P11 Q9]

25 0.200 mol of sulfur dioxide and 0.200 mol of oxygen are placed in a 1.00 dm^3 sealed container. The gases are allowed to react until equilibrium is reached.

$$2SO_2 + O_2 \rightleftharpoons 2SO_3$$

At equilibrium there is 0.100 mol of SO_3 in the container.

What is the value of K_c?

A 0.150 $mol\,dm^{-3}$

B 0.800 $mol\,dm^{-3}$

C 1.25 $mol^{-1}\,dm^3$

D 6.67 $mol^{-1}\,dm^3$

[N'18 P11 Q10]

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 Methanoic acid molecules, HCO_2H, and hydrogen carbonate ions, HCO_3^-, can both behave as acids.

Why does a solution of methanoic acid have a lower pH than a solution of sodium hydrogen carbonate of the same concentration?

1 HCO_2H molecules dissociate more fully than HCO_3^- ions do.

2 Each HCO_2H molecule has two hydrogen atoms; each HCO_3^- ion only has one.

3 Methanoic acid is a weaker acid than sodium hydrogen carbonate.

2 The following equilibrium is an exothermic reaction in the forward direction.

$$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O(l)$$

What happens when the concentration of CrO_4^{2-} ions **increases and** the temperature **decreases**?

1 The concentration of $Cr_2O_7^{2-}$ ions increases.

2 The equilibrium constant increases.

3 The activation energy decreases.

3 R and S react together.

$$R + S \rightleftharpoons T$$

Which factors affect the rate of the forward reaction?

1 the activation energy of the reaction

2 the enthalpy change of the reaction

3 the equilibrium constant of the reaction

4 The Brønsted-Lowry theory describes acid and base character.

When concentrated sulfuric acid and concentrated nitric acid are mixed, the following reactions occur.

$$H_2SO_4 + HNO_3 \rightleftharpoons HSO_4^- + H_2NO_3^+$$

$$H_2NO_3^+ \rightleftharpoons H_2O + NO_2^+$$

$$H_2O + H_2SO_4 \rightleftharpoons HSO_4^- + H_3O^+$$

Which species are bases in these reactions?

1 HSO_4^-

2 HNO_3

3 NO_2^+

5 Which statements about reversible reactions are correct?

1 An increase in concentration of a reactant always increases the concentration of the product.

2 An increase in temperature always increases the rate at which the equilibrium is established.

3 An increase in temperature always increases the concentration of the product at equilibrium.

6 In this question, all gases can be assumed to behave ideally.

A chemist heats a mixture of nitrogen and oxygen gases in a sealed container at a constant temperature until the mixture reaches a dynamic equilibrium containing $N_2(g)$, $O_2(g)$ and $NO(g)$.

$$N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$$

The chemist repeats the experiment at the same temperature using the same initial amounts of $N_2(g)$ and $O_2(g)$, but at a much higher pressure.

Which statements about the second experiment at higher pressure are correct?

1 At higher pressure, there are more particles per unit volume.

2 The composition of the equilibrium mixture does not change.

3 There are more collisions per second so equilibrium is reached faster.

7 In the manufacture of sulfuric acid, the following exothermic reaction occurs.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

Which changes will move the position of the equilibrium to the right?

1 increasing the pressure

2 increasing the temperature

3 using twice as much catalyst

8 Methanol, CH_3OH, can be produced industrially by reacting CO with H_2.

$$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g) \qquad \Delta H = -91\,\text{kJ mol}^{-1}$$

The process can be carried out at 4×10^3 kPa and 1150 K.

Which statements about this reaction are correct?

1 Increasing the temperature will increase the rate of reaction because more effective collisions will occur.

2 Lowering the temperature will reduce the rate of reaction because the forward reaction is exothermic.

3 Increasing the pressure will reduce the rate of reaction because there are a larger number of moles on the left-hand side of the equation.

9 In the manufacture of sulfuric acid, the following exothermic reaction occurs.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

Which changes will move the position of the equilibrium to the right?

1 increasing the pressure

2 increasing the temperature

3 using twice as much catalyst

10 Ammonia and chlorine react together in the gas phase.

$$8NH_3 + 3Cl_2 \rightarrow N_2 + 6NH_4Cl$$

Which statements are correct?

1 Ammonia behaves as a reducing agent.

2 Ammonia behaves as a base.

3 The oxidation number of hydrogen changes.

[M'18 P12 Q33]

11 In which reactions does NH_3 behave as a Brønsted-Lowry acid?

1 $2NH_3 \rightarrow NH_2^- + NH_4^+$

2 $HSO_4^- + NH_3 \rightarrow SO_4^{2-} + NH_4^+$

3 $Ag^+ + 2NH_3 \rightarrow [Ag(NH_3)_2]^+$

[M'18 P12 Q34]

12 Which statements are correct when a reversible reaction is at equilibrium?

1 All species are at equal concentration.

2 The concentrations of all species remain constant.

3 The rate of the forward reaction equals the rate of the reverse reaction.

[J'18 P11 Q34]

13 Ammonia and chlorine react as shown.

$$8NH_3 + 3Cl_2 \rightarrow N_2 + 6NH_4Cl$$

Which statements are correct?

1 Each nitrogen atom is oxidised.

2 Each chlorine atom is reduced.

3 Ammonia behaves as a base.

[J'18 P13 Q33]

EQUILIBRIA WS 2

1 **(c)** At temperatures above 1500 K, HCl will decompose.

A sample of 0.300 mol of HCl decomposed in a sealed container.

The resulting equilibrium mixture was found to contain 1.50×10^{-2} mol of Cl_2.

(i) Calculate the amounts, in mol, of H_2 and HCl present in the equilibrium mixture.

H_2 = ... mol

HCl = ... mol
[2]

(ii) Calculate the mole fraction of each gas in the equilibrium mixture.

mole fraction of HCl = ...

mole fraction of H_2 = ...

mole fraction of Cl_2 = ...
[1]

(d) In another experiment under different conditions, an equilibrium mixture was produced with mole fractions for each species as shown.

species	mole fraction
HCl	0.88
H_2	0.06
Cl_2	0.06

(i) Write the expression for the equilibrium constant, K_p, for the decomposition of HCl.

$$2HCl(g) \rightleftharpoons H_2(g) + Cl_2(g)$$

K_p =

[1]

(ii) Explain why the total pressure of the system does **not** need to be known for K_p to be calculated for this experiment.

....

.... [1]

(iii) Calculate the value of K_p for this experiment.

K_p = ... [1]

20 **(b)** The equation for the preparation of hydrogen chloride using concentrated sulfuric acid is shown.

$$H_2SO_4 + NaCl \rightarrow NaHSO_4 + HCl$$

(i) Use the Brønsted-Lowry theory of acids and bases to identify the base and its conjugate acid in this reaction. Explain your answer.

Brønsted-Lowry base (base-**I**) = ...

conjugate acid (acid-**II**) = ...

....

....

....
[2]

(ii) Explain why the reaction of concentrated sulfuric acid and sodium iodide is **not** suitable for the preparation of hydrogen iodide.

....

....

....

.... [2]

2 **(c)** Hydrogen chloride undergoes a reversible reaction with oxygen.

$$4HCl(g) + O_2(g) \rightleftharpoons 2Cl_2(g) + 2H_2O(g)$$

The reaction is carried out at 400 °C in the presence of a copper(II) chloride catalyst.

(i) Use the data in the table to calculate the overall enthalpy change of reaction.

compound	enthalpy change of formation / $kJ\,mol^{-1}$
$HCl(g)$	–92
$H_2O(g)$	–242

enthalpy change of reaction = ... $kJ\,mol^{-1}$ [2]

(ii) State the **type** of catalyst used in this reaction. Explain how a catalyst is able to increase the rate of a chemical reaction.

....

....

....

.... [2]

(iii) The reaction exists in dynamic equilibrium.

The reaction was repeated at 1000 °C and the same pressure.

State and explain the effect on the composition of the equilibrium mixture of the change in temperature.

....

....

....

.... [2]

(iv) When 1.60 mol of HCl are mixed in a sealed container with 0.500 mol of O_2 at 400 °C, 0.600 mol of Cl_2 and 0.600 mol of H_2O are formed.

The total pressure inside the container is 1.50×10^5 Pa.

- Calculate the amounts, in mol, of HCl and O_2 in the equilibrium mixture.

HCl = ... mol

O_2 = ... mol

- Calculate the mole fraction of Cl_2 and hence the partial pressure of Cl_2 in the equilibrium mixture.

mole fraction of Cl_2 = ...

p_{Cl_2} = ... Pa

[3]

(v) In a separate experiment, an equilibrium reaction mixture was found to contain the four gases at the partial pressures shown in the table.

gas	HCl	O_2	Cl_2	H_2O
partial pressure / Pa	4.8×10^4	3.0×10^4	3.6×10^4	3.6×10^4

$$K_p = \frac{(p_{Cl_2})^2 \times (p_{H_2O})^2}{(p_{HCl})^4 \times p_{O_2}}$$

Use this information and the expression given for K_p to calculate a value for K_p. State the units of K_p.

K_p = ...

units = ...

[2]

(vi) The reaction is repeated without a catalyst.

State the effect of this on K_p.

.... [1]

3 Ammonia, NH_3, is manufactured from nitrogen and hydrogen by the Haber process.

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

(c) At a pressure of 2.00×10^7 Pa, 1.00 mol of nitrogen, $N_2(g)$, was mixed with 3.00 mol of hydrogen, $H_2(g)$. The final equilibrium mixture formed contained 0.300 mol of ammonia, $NH_3(g)$.

(i) Calculate the amounts, in mol, of $N_2(g)$ and $H_2(g)$ in the equilibrium mixture.

$N_2(g)$ = ... mol

$H_2(g)$ = ... mol
[2]

(ii) Calculate the partial pressure of ammonia, $p\text{NH}_3$, in the equilibrium mixture.

Give your answer to **three** significant figures.

$p\text{NH}_3$ = ... Pa [3]

(d) In another equilibrium mixture the partial pressures are as shown.

substance	partial pressure / Pa
$N_2(g)$	2.20×10^6
$H_2(g)$	9.62×10^5
$NH_3(g)$	1.40×10^4

(i) Write the expression for the equilibrium constant, K_p, for the production of ammonia from nitrogen and hydrogen.

K_p =

[1]

(ii) Calculate the value of K_p for this reaction.

State the units.

K_p = ...

units = ...

[2]

(iii) This reaction is repeated with the same starting amounts of nitrogen and hydrogen. The same temperature is used but the container has a smaller volume.

State the effects, if any, of this change on the yield of ammonia and on the value of K_p.

effect on yield of ammonia ....

effect on value of K_p ....

[2]

4 At 450 K phosphorus(V) chloride, $PCl_5(g)$, decomposes to form phosphorus(III) chloride, $PCl_3(g)$, and chlorine, $Cl_2(g)$. A dynamic equilibrium is established as shown.

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g) \qquad \Delta H = +124\,\text{kJ mol}^{-1}$$

(a) The enthalpy change of formation of $PCl_3(g)$ under these conditions is given.

$$\Delta H_f\ PCl_3(g) = -320\,\text{kJ mol}^{-1}$$

Calculate the enthalpy change of formation of $PCl_5(g)$ under these conditions.

Include a sign with your answer.

enthalpy change = ... kJ mol^{-1} [1]

(b) **(i)** State and explain the effect of increasing temperature on the rate of decomposition of $PCl_5(g)$.

....

....

.... [2]

(ii) State and explain the effect of increasing temperature on the percentage of $PCl_5(g)$ that decomposes.

....

....

.... [2]

(c) Explain the meaning of the term *dynamic equilibrium* and the conditions necessary for it to become established.

....

....

....

.... [2]

(d) When 2.00 mol of $PCl_5(g)$ are decomposed at 450 K and 1.00×10^5 Pa the resulting equilibrium mixture contains 0.800 mol of $Cl_2(g)$.

(i) Calculate the partial pressure of phosphorus(V) chloride, $pPCl_5$, in this equilibrium mixture.

$pPCl_5$ = ... Pa [2]

(ii) Write the expression for the equilibrium constant, K_p, for the decomposition of $PCl_5(g)$.

K_p =

[1]

(iii) The partial pressures of $PCl_3(g)$ and of $Cl_2(g)$ in this equilibrium mixture are both 2.86×10^4 Pa.

Calculate the value of K_p and state its units.

K_p = ...

units = ...
[2]

5 **(c)** Hydrogen chloride undergoes a reversible reaction with oxygen.

$$4HCl(g) + O_2(g) \rightleftharpoons 2Cl_2(g) + 2H_2O(g)$$

The reaction is carried out at 400 °C in the presence of a copper(II) chloride catalyst.

(ii) State the **type** of catalyst used in this reaction. Explain how a catalyst is able to increase the rate of a chemical reaction.

....

....

....

.... [2]

(iii) The reaction exists in dynamic equilibrium.

The reaction was repeated at 1000 °C and the same pressure.

State and explain the effect on the composition of the equilibrium mixture of the change in temperature.

....

....

....

.... [2]

[M'17 2 Q2]

The equation for this stage of the Contact Process is shown.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H = -196\,kJ\,mol^{-1}$$

(d) **(i)** State and explain the effect of increasing temperature on the rate of production of SO_3.

....

....

....

.... [3]

(ii) State and explain the effect of increasing temperature on the yield of SO_3.

....

....

....

.... [3]

(e) The SO_3 produced is converted to sulfuric acid in two stages. In the first stage the SO_3 is reacted with concentrated sulfuric acid to produce oleum, $H_2S_2O_7$.
The oleum is then reacted with water to form sulfuric acid.

Suggest an equation for the reaction of oleum, $H_2S_2O_7$, with water to form sulfuric acid.

.... [1]

[J'18 P11 Q1]

6 **(d)** 2.00 moles of SO_2(g) and 2.00 moles of O_2(g) are sealed in a container with a suitable catalyst, at constant temperature and pressure. The resulting equilibrium mixture contains 1.98 moles of SO_3(g).
The total volume of the equilibrium mixture is 40.0 dm^3.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

(i) Write the expression for the equilibrium constant, K_c, for the reaction between SO_2(g) and O_2(g) to produce SO_3(g).

K_c =

[1]

(ii) Calculate the amount, in moles, of SO_2(g) and O_2(g) in the equilibrium mixture.

SO_2(g) = ... mol

O_2(g) = ... mol
[2]

(iii) Use your answers to **(d)(i)** and **(d)(ii)** to calculate the value of K_c for this equilibrium mixture. Give the units of K_c.

K_c = ...

units = ...
[3]

[J'18 P23 Q1]

7 **(c)** At a pressure of 2.00×10^7 Pa, 1.00 mol of nitrogen, $N_2(g)$, was mixed with 3.00 mol of hydrogen, $H_2(g)$. The final equilibrium mixture formed contained 0.300 mol of ammonia, $NH_3(g)$.

(i) Calculate the amounts, in mol, of $N_2(g)$ and $H_2(g)$ in the equilibrium mixture.

$N_2(g)$ = ... mol

$H_2(g)$ = ... mol
[2]

(ii) Calculate the partial pressure of ammonia, pNH_3, in the equilibrium mixture.

Give your answer to **three** significant figures.

pNH_3 = ... Pa [3]

(d) In another equilibrium mixture the partial pressures are as shown.

substance	partial pressure / Pa
$N_2(g)$	2.20×10^6
$H_2(g)$	9.62×10^5
$NH_3(g)$	1.40×10^4

(i) Write the expression for the equilibrium constant, K_p, for the production of ammonia from nitrogen and hydrogen.

K_p =

[1]

(ii) Calculate the value of K_p for this reaction.

State the units.

K_p = ...

units = ...

[2]

(iii) This reaction is repeated with the same starting amounts of nitrogen and hydrogen. The same temperature is used but the container has a smaller volume.

State the effects, if any, of this change on the yield of ammonia and on the value of K_p.

effect on yield of ammonia ....

effect on value of K_p ....

[2]

8 At 450 K phosphorus(V) chloride, $PCl_5(g)$, decomposes to form phosphorus(III) chloride, $PCl_3(g)$, and chlorine, $Cl_2(g)$. A dynamic equilibrium is established as shown.

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g) \qquad \Delta H = +124\,kJ\,mol^{-1}$$

(a) The enthalpy change of formation of $PCl_3(g)$ under these conditions is given.

$$\Delta H_f\ PCl_3(g) = -320\,kJ\,mol^{-1}$$

Calculate the enthalpy change of formation of $PCl_5(g)$ under these conditions.

Include a sign with your answer.

enthalpy change = ... $kJ\,mol^{-1}$ [1]

(b) **(i)** State and explain the effect of increasing temperature on the rate of decomposition of $PCl_5(g)$.

....

....

.... [2]

(ii) State and explain the effect of increasing temperature on the percentage of $PCl_5(g)$ that decomposes.

....

....

.... [2]

(c) Explain the meaning of the term *dynamic equilibrium* and the conditions necessary for it to become established.

....

....

....

.... [2]

(d) When 2.00 mol of PCl_5(g) are decomposed at 450 K and 1.00×10^5 Pa the resulting equilibrium mixture contains 0.800 mol of Cl_2(g).

(i) Calculate the partial pressure of phosphorus(V) chloride, $pPCl_5$, in this equilibrium mixture.

$pPCl_5$ = ... Pa [2]

(ii) Write the expression for the equilibrium constant, K_p, for the decomposition of PCl_5(g).

K_p =

[1]

(iii) The partial pressures of PCl_3(g) and of Cl_2(g) in this equilibrium mixture are both 2.86×10^4 Pa.

Calculate the value of K_p and state its units.

K_p = ...

units = ...
[2]

[W'17 P22 Q2]

EQUILIBRIA WS 3

SECTION A

1 For which equilibrium does K_c have *no units*?

A $C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g)$

B $CH_3OH(l) + CH_3CO_2H(l) \rightleftharpoons CH_3CO_2CH_3(l) + H_2O(l)$

C $Cu^{2+}(aq) + 4NH_3(aq) \rightleftharpoons Cu(NH_3)_4^{2+}(aq)$

D $N_2O_4(g) \rightleftharpoons 2NO_2(g)$

2 When 0.20 mol of hydrogen gas and 0.15 mol of iodine gas are heated at 723 K until equilibrium is established, the equilibrium mixture is found to contain 0.26 mol of hydrogen iodide.

The equation for the reaction is as follows.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$$

What is the correct expression for the equilibrium constant K_c?

A $\dfrac{2 \times 0.26}{0.20 \times 0.15}$

B $\dfrac{(2 \times 0.26)^2}{0.20 \times 0.15}$

C $\dfrac{(0.26)^2}{0.07 \times 0.02}$

D $\dfrac{(0.26)^2}{0.13 \times 0.13}$

3 Two equilibria are shown below.

reaction I $\quad 2X_2(g) + Y_2(g) \rightleftharpoons 2X_2Y(g)$

reaction II $\quad X_2Y(g) \rightleftharpoons X_2(g) + \frac{1}{2}Y_2(g)$

The numerical value of K_c for reaction I is 2.

Under the same conditions, what is the numerical value of K_c for reaction II?

A $\dfrac{1}{\sqrt{2}}$ **B** $\dfrac{1}{2}$ **C** $\dfrac{1}{4}$ **D** -2

4 For the reaction

$$W(aq) + 2X(aq) \rightleftharpoons 2Y(aq) + 3Z(aq)$$

what are the correct units for the equilibrium constant K_c?

A $mol\,dm^{-3}$ **B** $mol^2\,dm^{-6}$ **C** $mol^{-1}\,dm^3$ **D** $mol^{-2}\,dm^6$

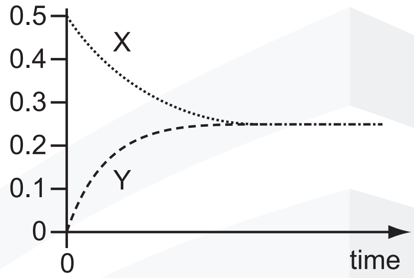
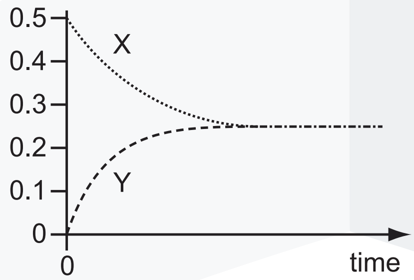
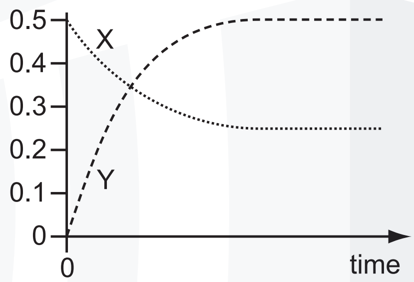
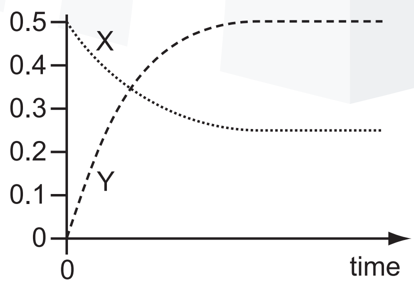
5 A dimer, X, is stable when solid but a dynamic equilibrium is set up in solution.

$$X(aq) \rightleftharpoons 2Y(aq)$$

A solution of X has an initial concentration of 0.50 mol dm^{-3}. When equilibrium has been reached [X(aq)] has fallen to 0.25 mol dm^{-3}.

The changes in [X(aq)] and [Y(aq)] are plotted against time until equilibrium is reached. The value of K_c is then calculated.

Which graph and value for K_c are correct?

	graph		K_c / mol dm^{-3}
A	concentration / mol dm^{-3}		1
B	concentration / mol dm^{-3}		2
C	concentration / mol dm^{-3}		1
D	concentration / mol dm^{-3}		2

6 In an experiment, *b* mol of hydrogen iodide were put into a sealed vessel under pressure p. At equilibrium, *x* mol of the hydrogen iodide had dissociated, the reaction being represented by the following equation.

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

Which expression for K_p is correct?

A $\dfrac{x^2}{(b-x)^2}$

B $\dfrac{x^2p^2}{(b-x)^2}$

C $\dfrac{x^2p^2}{4b(b-x)}$

D $\dfrac{x^2}{4(b-x)^2}$

7 The value of the equilibrium constant, K_c, for the reaction to form ethyl ethanoate from ethanol and ethanoic acid is 4.0 at 60 °C.

$$C_2H_5OH + CH_3CO_2H \rightleftharpoons CH_3CO_2C_2H_5 + H_2O$$

When 1.0 mol of ethanol and 1.0 mol of ethanoic acid are allowed to reach equilibrium at 60 °C, what is the number of moles of ethyl ethanoate formed?

A $\frac{1}{3}$ **B** $\frac{2}{3}$ **C** $\frac{1}{4}$ **D** $\frac{3}{4}$

8 Nitrogen dioxide decomposes on heating according to the following equation.

$$2NO_2(g) \rightleftharpoons 2NO(g) + O_2(g)$$

When 4 mol of nitrogen dioxide were put into a 1 dm^3 container and heated to a constant temperature, the equilibrium mixture contained 0.8 mol of oxygen.

What is the value of the equilibrium constant, K_c, at the temperature of the experiment?

A $\dfrac{0.8^2 \times 0.8}{4^2}$ **B** $\dfrac{1.6 \times 0.8}{2.4^2}$ **C** $\dfrac{1.6^2 \times 0.8}{4^2}$ **D** $\dfrac{1.6^2 \times 0.8}{2.4^2}$

9 Dinitrogen tetroxide dissociates into nitrogen dioxide on heating.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g)$$

In an experiment the partial pressures of the gases at equilibrium were found to be NO_2, 0.33 atm; N_2O_4, 0.67 atm.

What is the numerical value of K_p at the temperature of the experiment?

A 0.16 **B** 0.49 **C** 0.65 **D** 2.03

10 At a total pressure of 1.0 atm, dinitrogen tetraoxide is 50 % dissociated at a temperature of 60 °C, according to the following equation.

$$N_2O_4 \rightleftharpoons 2NO_2$$

What is the value of the equilibrium constant, K_p, for this reaction at 60 °C?

A $^1/_3$ atm **B** $^2/_3$ atm **C** $^4/_3$ atm **D** 2 atm

11 At high temperatures, steam decomposes into its elements according to the following equation.

$$2H_2O(g) \rightleftharpoons 2H_2(g) + O_2(g)$$

In one experiment at 1 atm pressure, it was found that 20 % of the steam had been converted into hydrogen and oxygen.

What are the values of the equilibrium partial pressures, in atm, of the components of this equilibrium?

	partial pressure of steam	partial pressure of hydrogen	partial pressure of oxygen
A	$\frac{0.80 \times 1}{1.0}$	$\frac{0.10 \times 1}{1.0}$	$\frac{0.10 \times 1}{1.0}$
B	$\frac{0.80 \times 1}{1.0}$	$\frac{0.133 \times 1}{1.0}$	$\frac{0.067 \times 1}{1.0}$
C	$\frac{0.80 \times 1}{1.0}$	$\frac{0.20 \times 1}{1.0}$	$\frac{0.10 \times 1}{1.0}$
D	$\frac{0.80 \times 1}{1.1}$	$\frac{0.20 \times 1}{1.1}$	$\frac{0.10 \times 1}{1.1}$

12 When vanadium(II) compounds are dissolved in water, the following equilibrium is established.

$$V^{2+} + H_2O \rightleftharpoons V^{3+} + \tfrac{1}{2}H_2 + OH^-$$

What would alter the composition of the equilibrium mixture in favour of the V^{2+} ions?

A adding an acid

B adding a reagent that selectively precipitates V^{3+} ions

C allowing the hydrogen to escape as it forms

D making the solution more alkaline

13 Which statement concerning the equilibrium reaction below is true?

$$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O(l)$$

A An increase in acid concentration will result in an increase in the concentration of $Cr_2O_7^{2-}(aq)$.

B A redox reaction is taking place.

C The addition of a catalyst will result in an increase in the concentration of $Cr_2O_7^{2-}(aq)$.

D The equilibrium constant, K_c, has no units.

14 For the equilibrium $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$, what will change the value of K_p?

A adding a catalyst

B adding more O_2

C increasing the pressure

D increasing the temperature

15 An experiment is set up to measure the rate of hydrolysis of methyl ethanoate.

$$CH_3CO_2CH_3 + H_2O \rightleftharpoons CH_3CO_2H + CH_3OH$$

The hydrolysis is found to be slow in neutral aqueous solution but it proceeds at a measurable rate when the solution is acidified with hydrochloric acid.

What is the function of the hydrochloric acid?

A to dissolve the methyl ethanoate

B to ensure that the reaction reaches equilibrium

C to increase the reaction rate by catalytic action

D to suppress ionisation of the ethanoic acid formed

16 The equilibrium

$$N_2(g) + O_2(g) \rightleftharpoons 2NO(g) \qquad \Delta H = +180\,\text{kJ mol}^{-1}$$

contributes to a series of reactions producing photochemical smog.

Which factors would affect the value of K_p of the above equilibrium?

	change in pressure	change in temperature	presence or absence of a catalyst
A	✓	✓	✗
B	✓	✗	✓
C	✗	✓	✓
D	✗	✓	✗

17 When sulfur trioxide is manufactured from sulfur dioxide and oxygen, using the Contact process, which condition affects the value of the equilibrium constant, K_c?

A adjusting the temperature

B adjusting the pressure

C using a catalyst

D removing SO_3 from the equilibrium mixture

18 The Haber process for the manufacture of ammonia is represented by the following equation.

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

Which statement is correct about this reaction when the temperature is increased?

A Both forward and backward rates increase.

B The backward rate only increases.

C The forward rate only increases.

D There is no effect on the backward or forward rate.

19 Swimming pool water can be kept free of harmful bacteria by adding aqueous sodium chlorate(I), $NaOCl$. This reacts with water to produce $HOCl$ molecules which kill bacteria.

$$OCl^-(aq) + H_2O \rightleftharpoons OH^-(aq) + HOCl(aq)$$

In bright sunshine, the OCl^- ion is broken down by ultra-violet light.

$$OCl^-(aq) + \text{uv light} \rightarrow Cl^-(aq) + \tfrac{1}{2}O_2(g)$$

Which method would maintain the highest concentration of $HOCl(aq)$?

A acidify the pool water

B add a solution of chloride ions

C add a solution of hydroxide ions

D bubble air through the water

20 The dissociation of dinitrogen tetraoxide into nitrogen dioxide is represented by the equation below.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g); \qquad \Delta H^\ominus = +57\,kJ\,mol^{-1}$$

If the temperature of an equilibrium mixture of the gases is increased at constant pressure, will the volume of the mixture increase or decrease and why?

A The volume will increase, but only because of a shift of equilibrium towards the right.

B The volume will increase, both because of a shift of equilibrium towards the right and also because of thermal expansion.

C The volume will stay the same, because any thermal expansion could be exactly counteracted by a shift of equilibrium towards the left.

D The volume will decrease, because a shift of equilibrium towards the left would more than counteract any thermal expansion.

21 PCl_5 dissociates as follows.

$$PCl_5(g) \rightarrow PCl_3(g) + Cl_2(g)$$

The extent of dissociation is 13% at 160 °C and 100% at 300 °C.

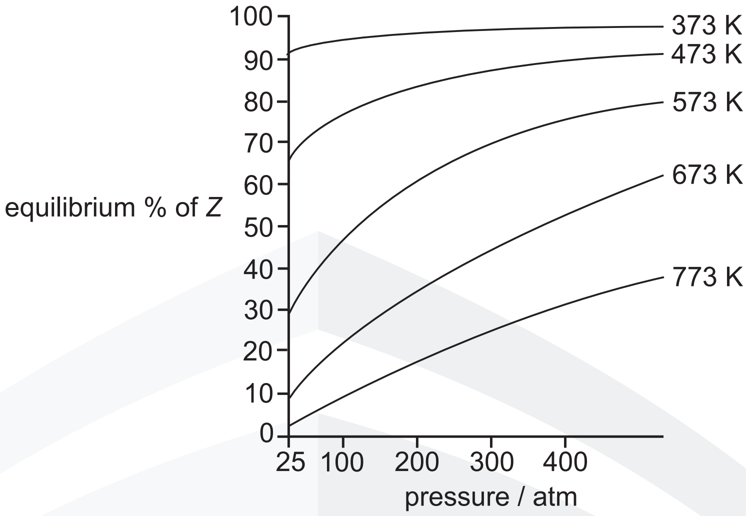
Which pair of statements about this formation of PCl_3 is correct?

	shape of PCl_3 molecule	the reaction is
A	pyramidal	endothermic
B	pyramidal	exothermic
C	trigonal	endothermic
D	trigonal	exothermic

22 In an industrial process, two gases *X* and *Y* react together to form a single gaseous product *Z*.

$$X(g) + Y(g) \rightleftharpoons Z(g)$$

The percentage yield of product *Z* varies according to the pressure and the temperature as shown in the graphs.



Which statement about this equilibrium reaction is correct?

A Decreasing the temperature decreases the value of the equilibrium constant.

B Decreasing the temperature increases the rate of this reaction.

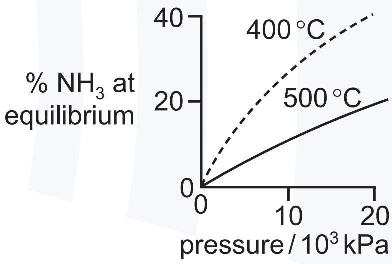
C Increasing the pressure increases the value of the equilibrium constant.

D The reaction is exothermic in the forward direction.

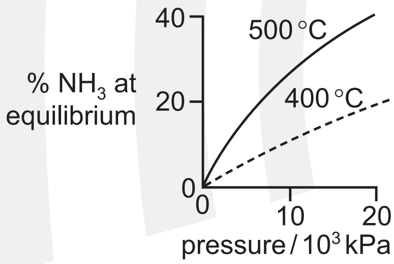
23 The percentage of ammonia obtainable, if equilibrium were established during the Haber process, is plotted against the operating pressure for two temperatures, 400 °C and 500 °C.

Which diagram correctly represents the two graphs?

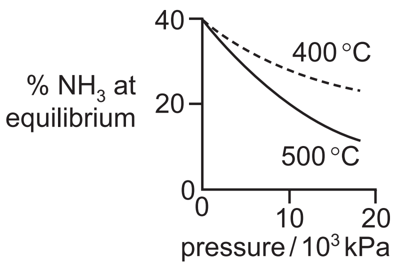
A



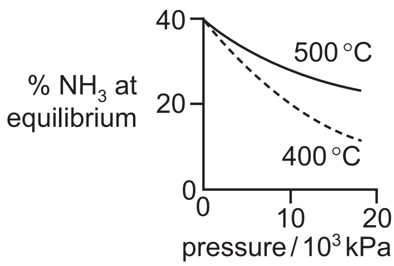
B



C



D



24 The table gives the concentrations and pH values of the aqueous solutions of two compounds, X and Y. Either compound could be an acid or a base.

	X	Y
concentration	$2\,mol\,dm^{-3}$	$2\,mol\,dm^{-3}$
pH	6	9

Student P concluded that X is a strong acid.

Student Q concluded that the extent of dissociation is lower in X(aq) than in Y(aq).

Which of the students are correct?

A both P and Q

B neither P nor Q

C P only

D Q only

25 Which substance, in $1\ mol\ dm^{-3}$ aqueous solution, would have the same hydrogen ion concentration as $1\,mol\,dm^{-3}$ of hydrochloric acid?

A ethanoic acid

B nitric acid

C sodium hydroxide

D sulphuric acid

26 Why is ethanoic acid a stronger acid in liquid ammonia than in aqueous solution?

A Ammonia is a stronger base than water.

B Ammonium ethanoate is completely ionised in aqueous solution.

C Ammonium ethanoate is strongly acidic in aqueous solution.

D Liquid ammonia is a more polar solvent than water.

27 The following equilibrium is set up in a mixture of concentrated nitric and sulfuric acids.

$$HNO_3 + H_2SO_4 \rightleftharpoons H_2NO_3^+ + HSO_4^-$$

Which row correctly describes the behaviour of each substance in the equilibrium mixture?

	HNO_3	H_2SO_4	$H_2NO_3^+$	HSO_4^-
A	acid	acid	base	base
B	acid	base	base	acid
C	base	acid	acid	base
D	base	acid	base	acid

28 The table shows the enthalpy change of neutralisation per mole of water formed, ΔH, for various acids and bases.

acid	base	ΔH / kJ mol^{-1}
hydrochloric acid	sodium hydroxide	–57.0
P	sodium hydroxide	–54.0
hydrochloric acid	**Q**	–52.0
nitric acid	**R**	–57.0

What are **P**, **Q** and **R**?

	P	**Q**	**R**
A	ethanoic acid	ammonia	potassium hydroxide
B	ethanoic acid	sodium hydroxide	ammonia
C	sulphuric acid	ammonia	potassium hydroxide
D	sulphuric acid	sodium hydroxide	ammonia

29 The esterification reaction

$$\text{ethanol + ethanoic acid} \rightleftharpoons \text{ethyl ethanoate + water}$$

is an equilibrium. The forward reaction is exothermic.

How can the value of the equilibrium constant K_C be increased?

A by adding a little concentrated sulfuric acid as a catalyst

B by increasing the initial concentration of ethanol

C by lowering the temperature

D by raising the temperature

30 An aqueous solution was prepared containing 1.0 mol of $AgNO_3$ and 1.0 mol of $FeSO_4$ in 1.00 dm^3 of water. When equilibrium was established, there was 0.44 mol of $Ag^+(aq)$ in the mixture.

$$Ag^+(aq) + Fe^{2+}(aq) \rightleftharpoons Ag(s) + Fe^{3+}(aq)$$

What is the numerical value of K_c?

A 0.35 **B** 0.62 **C** 1.62 **D** 2.89

31 For the equilibrium $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$, what will change the value of K_p?

A adding a catalyst

B adding more O_2

C increasing the pressure

D increasing the temperature

32 When gaseous iodine is heated with hydrogen at 450 °C, an equilibrium is established.

$$\underset{\text{colourless}}{H_2(g)} + \underset{\text{purple}}{I_2(g)} \rightleftharpoons \underset{\text{colourless}}{2HI(g)} \qquad \Delta H = +53\,\text{kJ mol}^{-1}$$

Which change of conditions will cause the purple colour of the equilibrium mixture to become paler?

A decrease in pressure

B decrease in temperature

C increase in pressure

D increase in temperature

33 For the reaction

$$W(aq) + 2X(aq) \rightleftharpoons 2Y(aq) + 3Z(aq)$$

what are the correct units for the equilibrium constant K_c?

A mol dm^{-3} **B** $\text{mol}^2\,\text{dm}^{-6}$ **C** $\text{mol}^{-1}\,\text{dm}^3$ **D** $\text{mol}^{-2}\,\text{dm}^6$

34 Two moles of compound P were placed in a vessel. The compound P was partly decomposed by heating. A dynamic equilibrium between chemicals P, Q and R was established.

At equilibrium, x mol of R were present and the total number of moles present was $(2 + x)$.

What is the equation for this equilibrium?

A $P \rightleftharpoons 2Q + R$

B $2P \rightleftharpoons 2Q + R$

C $2P \rightleftharpoons Q + R$

D $2P \rightleftharpoons Q + 2R$

35 Methanol is manufactured by reacting carbon dioxide and hydrogen.

$$CO_2(g) + 3H_2(g) \rightleftharpoons CH_3OH(g) + H_2O(g) \qquad \Delta H = -49\,\text{kJ mol}^{-1}$$

What would increase the equilibrium yield of methanol in this process?

A adding a catalyst

B adding an excess of steam

C increasing the pressure

D increasing the temperature

36 An experiment is set up to measure the rate of hydrolysis of ethyl ethanoate.

$$CH_3CO_2C_2H_5 + H_2O \rightleftharpoons CH_3CO_2H + C_2H_5OH$$

The hydrolysis is found to be slow in neutral aqueous solution but it proceeds at a measurable rate when the solution is acidified with hydrochloric acid.

What is the function of the hydrochloric acid?

A to dissolve the ethyl ethanoate

B to ensure that the reaction reaches equilibrium

C to increase the reaction rate by catalytic action

D to suppress ionisation of the ethanoic acid formed

37 The reaction between sulfur dioxide and oxygen is a dynamic equilibrium.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

What happens when the pressure of the system is increased?

A The rate of reaction will decrease and the position of the equilibrium will move to the left.

B The rate of reaction will decrease and the position of the equilibrium will move to the right.

C The rate of reaction will increase and the position of the equilibrium will move to the left.

D The rate of reaction will increase and the position of the equilibrium will move to the right.

38 Nitrogen reacts with hydrogen to produce ammonia.

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

A mixture of 2.00 mol of nitrogen, 6.00 mol of hydrogen, and 2.40 mol of ammonia is allowed to reach equilibrium in a sealed vessel of volume 1 dm^3 under certain conditions. It was found that 2.32 mol of nitrogen were present in the equilibrium mixture.

What is the value of K_c under these conditions?

A $\dfrac{(1.76)^2}{(2.32)(6.96)^3}$

B $\dfrac{(1.76)^2}{(2.32)(6.32)^3}$

C $\dfrac{(2.08)^2}{(2.32)(6.32)^3}$

D $\dfrac{(2.40)^2}{(2.32)(6.00)^3}$

39 Nitrogen reacts with hydrogen to produce ammonia.

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

A mixture of 1.00 mol of nitrogen, 3.00 mol of hydrogen and 1.98 mol of ammonia is allowed to reach equilibrium in a sealed vessel under certain conditions. It was found that 1.64 mol of nitrogen were present in the equilibrium mixture.

What is the value of K_c under these conditions?

A $\dfrac{(0.70)^2}{(1.64)(4.92)^3}$

B $\dfrac{(1.34)^2}{(1.64)(3.64)^3}$

C $\dfrac{(1.64)(4.92)^3}{(0.70)^2}$

D $\dfrac{(1.64)(3.64)^3}{(1.34)^2}$

40 The equilibrium constant, K_c, for the reaction $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$, is 60 at 450 °C.

What is the number of moles of hydrogen iodide in equilibrium with 2 mol of hydrogen and 0.3 mol of iodine at 450 °C?

A $\dfrac{1}{100}$ **B** $\dfrac{1}{10}$ **C** 6 **D** 36

41 Hydrogen and carbon dioxide gases are mixed in equal molar amounts at 800 K. A reversible reaction takes place.

$$H_2(g) + CO_2(g) \rightleftharpoons H_2O(g) + CO(g)$$

At equilibrium, the partial pressures of H_2 and CO_2 are both 10.0 kPa. K_p is 0.288 at 800 K.

What is the partial pressure of CO in the equilibrium mixture?

A 5.37 kPa **B** 18.6 kPa **C** 28.8 kPa **D** 347 kPa

42 The formation of hydrogen and ethyne, C_2H_2, from methane reaches dynamic equilibrium.

$$2CH_4(g) \rightleftharpoons 3H_2(g) + C_2H_2(g)$$

What are the units of K_c?

A $mol\,dm^{-3}$ **B** $mol^2\,dm^{-6}$ **C** $mol^3\,dm^{-9}$ **D** $mol^4\,dm^{-12}$

43 One mole of phosphorus(V) chloride, PCl_5, is heated to 600 K in a sealed flask of volume 1 dm^3. Equilibrium is established and measurements are taken.

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$$

The experiment is repeated with one mole of phosphorus(V) chloride heated to 600 K in a sealed flask of volume 2 dm^3.

How will the measurements vary?

A The equilibrium concentrations of $PCl_3(g)$ and $Cl_2(g)$ are higher in the second experiment.

B The equilibrium concentration of $PCl_5(g)$ is lower in the second experiment.

C The equilibrium concentrations of all three gases are the same in both experiments.

D The value of the equilibrium constant is higher in the second experiment.

44 In which reaction is the underlined substance acting as a base?

A $HNO_3 + \underline{H_2SO_4} \rightarrow H_2NO_3^+ + HSO_4^-$

B $HSiO_3^- + \underline{HCN} \rightarrow CN^- + H_2O + SiO_2$

C $HNO_2 + \underline{HCO_3^-} \rightarrow H_2O + CO_2 + NO_2^-$

D $C_6H_5O^- + \underline{CH_2ClCO_2H} \rightarrow C_6H_5OH + CH_2ClCO_2^-$

45 One molecule of haemoglobin, Hb, can bind with four molecules of oxygen according to the following equation.

$$Hb(aq) + 4O_2(aq) \rightleftharpoons Hb(O_2)_4(aq)$$

When the equilibrium concentration of O_2 is 7.6×10^{-6} mol dm^{-3}, the equilibrium concentrations of Hb and $Hb(O_2)_4$ are equal.

What is the value of K_c for this equilibrium?

A 3.0×10^{20} **B** 1.3×10^{5} **C** 7.6×10^{-6} **D** 3.3×10^{-21}

46 Nitrogen dioxide, NO_2, exists in equilibrium with dinitrogen tetroxide, N_2O_4.

$$2NO_2(g) \rightleftharpoons N_2O_4(g) \qquad \Delta H = -57 \text{ kJ mol}^{-1}$$

Which conditions give the greatest percentage of $N_2O_4(g)$ at equilibrium?

	pressure	temperature
A	high	high
B	high	low
C	low	high
D	low	low

47 When a sample of HI is warmed to a particular temperature the equilibrium below is established.

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

At this temperature, it is found that the partial pressure of HI(g) is 28 times the partial pressure of $H_2(g)$.

What is the value of K_p at this temperature?

A 1.28×10^{-3} **B** 0.035 **C** 28 **D** 784

48 A mixture of nitrogen and hydrogen gases, at a temperature of 500 K, was put into an evacuated vessel of volume 6.0 dm^3. The vessel was then sealed.

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

The mixture was allowed to reach equilibrium. It was found that 7.2 mol of N_2 and 12.0 mol of H_2 were present in the equilibrium mixture. The value of the equilibrium constant, K_c, for this equilibrium is 6.0×10^{-2} at 500 K.

What is the concentration of ammonia present in the equilibrium mixture at 500 K?

A 0.58 mol dm^{-3}

B 0.76 mol dm^{-3}

C 3.5 mol dm^{-3}

D 27 mol dm^{-3}

49 Ammonia is made by the Haber process. The reactants are nitrogen and hydrogen.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H \text{ –ve}$$

What will increase the rate of the forward reaction?

A adding argon to the mixture but keeping the total volume constant

B decreasing the temperature

C increasing the total pressure by reducing the total volume at constant temperature

D removing ammonia as it is made but keeping the total volume of the mixture the same

50 Nitrogen monoxide reacts with oxygen in a reversible reaction according to the equation shown below.

$$2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$$

The partial pressures of each of the components in an equilibrium mixture are shown in the table.

partial pressure NO / kPa	partial pressure O_2 / kPa	partial pressure NO_2 / kPa
10	30	20

What is the numerical value of the equilibrium constant, K_p, for this equilibrium?

A 6.67×10^{-2} **B** 1.33×10^{-1} **C** 7.50 **D** 15.0

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 A reversible reaction is catalysed.

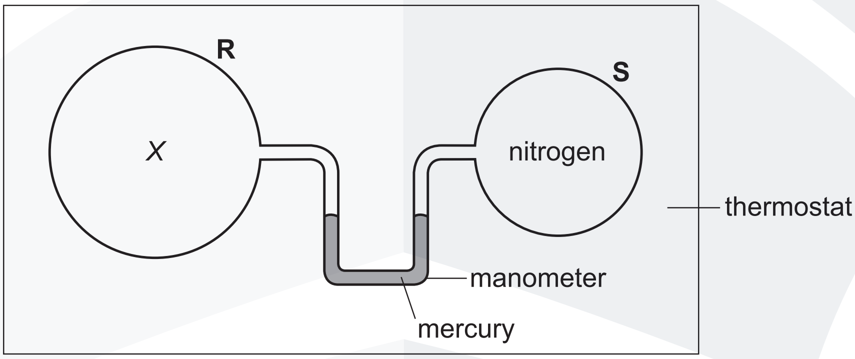
Which statements about the effects of the catalyst on this system are correct?

1 The catalyst alters the mechanism of the reaction.

2 The catalyst reduces the energy of activation (the energy barrier) for both the forward and the backward reaction.

3 The catalyst alters the composition of the equilibrium mixture.

2 Two bulbs **R** and **S**, connected by a mercury manometer, are held in a thermostat, as shown. The volume of **R** is twice that of **S**. **R** contains gas, *X*, at the same pressure as the nitrogen in **S**.



When the temperature is increased, which gases in bulb **R** would cause the mercury level in the right-hand limb of the manometer to rise?

1 an equilibrium mixture $N_2F_4(g) \rightleftharpoons 2NF_2(g)$; ΔH positive

2 an equilibrium mixture $CH_3NC(g) \rightleftharpoons CH_3CN(g)$; ΔH negative

3 nitrogen

3 Hydroxyapatite, $Ca_5(PO_4)_3OH$, is the main constituent of tooth enamel. In the presence of saliva, the following equilibria exist.

$$Ca_5(PO_4)_3OH(s) \rightleftharpoons 5Ca^{2+}(aq) + 3PO_4^{3-}(aq) + OH^-(aq)$$

$$HPO_4^{2-}(aq) \rightleftharpoons H^+(aq) + PO_4^{3-}(aq)$$

Which of the following statements help to explain why tooth enamel is dissolved more readily when saliva is acidic?

1 The hydroxide ions are neutralised by the acid.

2 The phosphate ion $PO_4^{3-}(aq)$ accepts $H^+(aq)$

3 Calcium ions react with acids.

4 Under given conditions, what governs the rate of a forward reaction?

1 the activation energy of the reaction

2 the enthalpy change of the reaction

3 the equilibrium constant of the reaction

5 Carbon monoxide burns readily in oxygen to form carbon dioxide.

What can be deduced from this information?

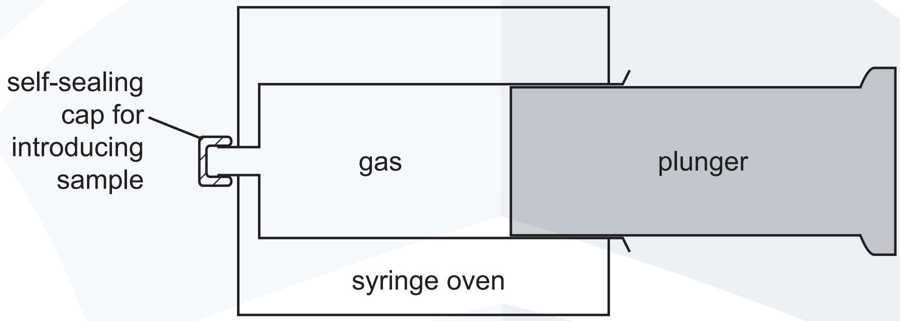
1 The +4 oxidation state of carbon is more stable than the +2 state.

2 The standard enthalpy change of formation of carbon dioxide is more negative than that of carbon monoxide.

3 The value of the equilibrium constant for the reaction, $2CO(g) + O_2(g) \rightleftharpoons 2CO_2(g)$, is likely to be high.

6 Phosphorus pentachloride is introduced into an empty gas syringe which has a movable, tightly-fitting plunger. The gas is allowed to expand until equilibrium is reached at a temperature at which the phosphorus pentachloride partially dissociates.

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$$



Which statements are correct?

1 The equilibrium pressure inside the syringe will be greater than atmospheric pressure.

2 When the plunger is pushed in the equilibrium adjusts to produce more $PCl_5(g)$.

3 The volume of gas in the syringe at equilibrium will be greater than if no dissociation had occurred.

7 Catalysts are used in many reversible reactions in the chemical industry. Vanadium(V) oxide is used in this way in the Contact process for the formation of SO_3.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

What effect does vanadium(V) oxide have on this equilibrium?

1 It speeds up the forward reaction.

2 It increases the value of K_p.

3 It increases the value of E_a for the reverse reaction.

8 Which statements about the Haber process for the industrial production of ammonia are correct?

1 The equilibrium constant K_p increases with pressure.

2 As the temperature increases, the equilibrium constant for the forward reaction becomes smaller.

3 The process is usually carried out at between 450 °C and 550 °C at a pressure of at least 150 atm.

9 Which equilibria, in which all species are gaseous, would have equilibrium constants, K_p, with no units?

1 sulfur dioxide and oxygen in equilibrium with sulfur trioxide

2 hydrogen and iodine in equilibrium with hydrogen iodide

3 carbon monoxide and steam in equilibrium with carbon dioxide and hydrogen

10 Which of the following can act as a Bronsted-Lowry acid?

1 H_3O^+

2 NH_4^+

3 H_2O

11 Which statements are correct in terms of the Brønsted-Lowry theory of acids and bases?

1 Water can act as either an acid or a base.

2 Sulfuric acid, H_2SO_4, does not behave as an acid when dissolved in ethanol, C_2H_5OH.

3 The ammonium ion acts as a base when dissolved in liquid ammonia.

12 Concentrated sulphuric acid behaves as a strong acid when it reacts with water.

$$H_2SO_4(l) + aq \rightarrow H^+(aq) + HSO_4^-(aq)$$

The HSO_4^- ion formed behaves as a weak acid.

$$HSO_4^-(aq) \rightleftharpoons H^+(aq) + SO_4^{2-}(aq)$$

Which statements are true for 1.0 mol dm^{-3} sulphuric acid?

1 $[H^+(aq)]$ is high

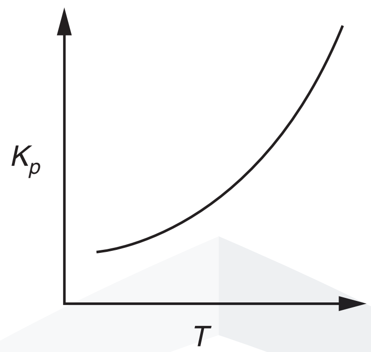
2 $[SO_4^{2-}(aq)]$ is high

3 $[HSO_4^-(aq)] = [SO_4^{2-}(aq)]$

13 The equilibrium constant K_p for the reaction

$$X(g) + Y(g) \rightleftharpoons Z(g)$$

varies with temperature as shown in the diagram below.



Which conclusions can be drawn from this information?

1 The reaction is exothermic in the forward direction.

2 The equilibrium mixture contains a greater proportion of Z at higher pressures.

3 The equilibrium mixture contains a greater proportion of Z at higher temperatures.

14 What are necessary properties of a dynamic equilibrium?

1 Equal amounts of reactants and products are present.

2 Concentrations of reactants and products remain constant.

3 The rate of the forward reaction is the same as the rate of the reverse reaction.

15 If N_2O_4 gas is placed in a sealed vessel the following equilibrium is established.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g)$$

The forward reaction is endothermic.

What happens when the temperature is increased?

1 The equilibrium constant increases.

2 The partial pressure of NO_2 increases.

3 The activation energy is unchanged.

EQUILIBRIA WS 4

1 Hydrogen iodide dissociates into its elements according to the equation below.

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

(a) Write the expression for the equilibrium constant, K_c.

[1]

(b) At 120 °C the equilibrium mixture contains 1.47 mol dm^{-3} of HI(g), 0.274 mol dm^{-3} each of H_2(g) and I_2(g).

Calculate the value of K_c for the equilibrium at 120 °C.

[1]

(c) Suggest and explain why it would be more difficult to determine K_c for this equilibrium at room temperature.

....

....

....

....[2]

2 NO is also formed when nitrosyl chloride, $NOCl$, dissociates according to the following equation.

$$2NOCl(g) \rightleftharpoons 2NO(g) + Cl_2(g)$$

Different amounts of the three gases were placed in a closed container and allowed to come to equilibrium at 230 °C. The experiment was repeated at 465 °C.

The equilibrium concentrations of the three gases at each temperature are given in the table below.

	concentration / mol dm^{-3}		
temperature / °C	$NOCl$	NO	Cl_2
230	2.33×10^{-3}	1.46×10^{-3}	1.15×10^{-2}
465	3.68×10^{-4}	7.63×10^{-3}	2.14×10^{-4}

(c) (i) Write the expression for the equilibrium constant, K_c, for this reaction. Give the units.

(ii) Calculate the value of K_c at each of the temperatures given.

230 °C

465 °C

(iii) Is the forward reaction endothermic or exothermic? Explain your answer.

....

....

[5]

3 **(b)** Ethanoic acid, CH_3CO_2H, reacts with ethanol, C_2H_5OH, to produce ethyl ethanoate and water. The reaction is an example of dynamic equilibrium.

$$CH_3CO_2H + C_2H_5OH \rightleftharpoons CH_3CO_2C_2H_5 + H_2O$$

(i) Explain what is meant by *dynamic equilibrium*.

....

....

(ii) Write an expression for the equilibrium constant, K_c, for this reaction.

[2]

(c) A mixture of 6.0 g of ethanoic acid and 6.0 g of ethanol was added to 4.4 g of ethyl ethanoate and the overall mixture allowed to reach equilibrium. It was found that 0.040 mol of ethanoic acid was present in the equilibrium mixture.

(i) Calculate the number of moles of each compound, both initially and at equilibrium. Place the results in the spaces provided.

	CH_3CO_2H	+	C_2H_5OH	$\rightleftharpoons$	$CH_3CO_2C_2H_5$	+	H_2O
initially	....		....		....		0.00
at equilibrium	0.040		....		....		....

(ii) Calculate the equilibrium constant, K_c, for the reaction.

(iii) Explain why K_c in this reaction has no units.

....[4]

4 The reaction of ethanoic acid with ethanol to form ethyl ethanoate and water is an example of dynamic equilibrium. It is catalysed by the presence of H^+ ions.

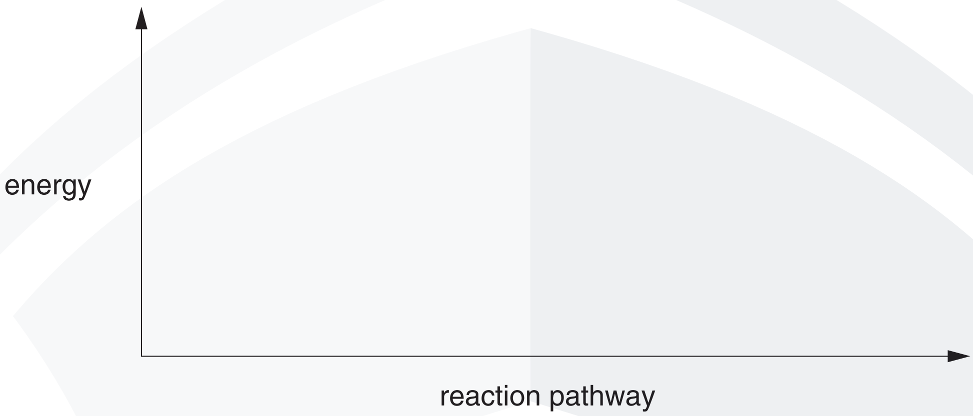
$$CH_3CO_2H(l) + C_2H_5OH(l) \rightleftharpoons CH_3CO_2C_2H_5(l) + H_2O(l)$$

$$\Delta H = +\ 14\,\text{kJ mol}^{-1}$$

(a) **(i)** Explain what is meant by *dynamic equilibrium*.

(ii) On the axes below, draw and label a reaction pathway/energy diagram for both the catalysed and uncatalysed reaction.

Also label your diagram with the ΔH value given.



[5]

(b) **(i)** State the expression for the equilibrium constant, K_c, for this reaction.

(ii) State why, in determining the value of K_c for this reaction, it is only necessary to know the number of moles rather than the concentrations of each substance.

[2]

(c) In an experiment to determine K_c, 1.00 mol of ethanoic acid was allowed to reach equilibrium at 60 °C with 1.00 mol of ethanol in the presence of 0.100 mol of H^+ dissolved in 1.00 mol of water. It forms an homogeneous mixture.

(i) At equilibrium, it was found that 0.43 mol of ethanoic acid was present.

How many moles of each of the following are present at equilibrium?

ethanol ....

ethyl ethanoate ....

water ....

(ii) Use these values to calculate the equilibrium constant, K_c.

[4]

5 Alcohols and esters are important organic compounds which are widely used as solvents.

Esters such as ethyl ethanoate can be formed by reacting carboxylic acids with alcohols.

$$CH_3CO_2H + C_2H_5OH \rightleftharpoons CH_3CO_2C_2H_5 + H_2O$$

This reaction is an example of a dynamic equilibrium.

(a) Explain what is meant by the term *dynamic equilibrium*.

....

....[1]

(b) Write the expression for the equilibrium constant for this reaction, K_c.

[1]

(c) For this equilibrium, the value of K_c is 4.0 at 298 K.
A mixture containing 0.5 mol of ethanoic acid, 0.5 mol ethanol, 0.1 mol ethyl ethanoate and 0.1 mol water was set up and allowed to come to equilibrium at 298 K. The final volume of solution was V dm^3.

Calculate the amount, in moles, of each substance present at equilibrium.

[4]

6 Ethanoic acid can be reacted with alcohols to form esters, an equilibrium mixture being formed.

$$CH_3CO_2H + ROH \rightleftharpoons CH_3CO_2R + H_2O$$

The reaction is usually carried out in the presence of an acid catalyst.

(a) Write an expression for the equilibrium constant, K_c, for this reaction, clearly stating the units.

K_c =

units .... [2]

In an experiment to determine K_c a student placed together in a conical flask 0.10 mol of ethanoic acid, 0.10 mol of an alcohol ROH, and 0.005 mol of hydrogen chloride catalyst.
The flask was sealed and kept at 25 °C for seven days.
After this time, the student titrated all of the contents of the flask with 2.00 mol dm^{-3} NaOH using phenolphthalein indicator.
At the end-point, 22.5 cm^3 of NaOH had been used.

(b) **(i)** Calculate the amount, in moles, of NaOH used in the titration.

(ii) What amount, in moles, of this NaOH reacted with the hydrogen chloride?

(iii) Write a balanced equation for the reaction between ethanoic acid and NaOH.

(iv) Hence calculate the amount, in moles, of NaOH that reacted with the ethanoic acid.

[4]

(c) **(i)** Use your results from **(b)** to calculate the amount, in moles, of ethanoic acid present at equilibrium. Hence complete the table below.

	CH_3CO_2H	ROH	CH_3CO_2R	H_2O
initial amount / mol	0.10	0.10	0	0
equilibrium amount / mol				

(ii) Use your results to calculate a value for K_c for this reaction.

[3]

(d) Esters are hydrolysed by sodium hydroxide. During the titration, sodium hydroxide reacts with ethanoic acid and the hydrogen chloride, but not with the ester.

Suggest a reason for this.

....

.... [1]

(e) What would be the effect, if any, on the amount of ester present if all of the water were removed from the flask and the flask kept for a further week at 25 °C?

Explain your answer.

....

....

.... [2]

7 Under certain conditions the equilibrium pressures of the three gases are

nitrogen	44.8 atm,
hydrogen	105.6 atm,
ammonia	37.2 atm.

(i) Write an expression for the equilibrium constant, K_p, for the Haber Process.

(ii) Calculate K_p from these data, giving the units.

[4]

8 Concern over the ever-increasing use of fossil fuels has led to many suggestions for alternative sources of energy. One of these, suggested by Professor George Olah, winner of a Nobel Prize in chemistry, is to use methanol, CH_3OH, which can be obtained in a number of different ways.

Methanol could be used instead of petrol in a conventional internal combustion engine or used to produce electricity in a fuel cell.

(a) Construct a balanced equation for the **complete** combustion of methanol.

.... [1]

When hydrocarbon fuels are completely burned in an internal combustion engine, several toxic pollutants may be formed.

(b) State **two toxic** pollutants that can be produced after **complete** combustion of a hydrocarbon fuel in an internal combustion engine.

....

.... [2]

Methanol may be manufactured catalytically from *synthesis gas*, a mixture of CO, CO_2 and H_2. The CO is reacted with H_2 to form methanol, CH_3OH.

$$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g) \qquad \Delta H = -91\ \text{kJ mol}^{-1}$$

(c) From your understanding of Le Chatelier's principle, state **two** conditions that could be used in order to produce a high yield of methanol.

In **each** case, explain why the yield would increase.

condition 1 ....

explanation ....

....

condition 2 ....

explanation ....

.... [4]

Carbon monoxide, which can be used to make methanol, may be formed by reacting carbon dioxide with hydrogen.

$$CO_2(g) + H_2(g) \rightleftharpoons CO(g) + H_2O(g) \qquad K_c = 1.44 \text{ at } 1200\text{ K}$$

(d) **(i)** It has been suggested that, on a large scale, this reaction could be helpful to the environment.

Explain, with reasons, why this would be the case.

....

....

(ii) A mixture containing 0.50 mol of CO_2, 0.50 mol of H_2, 0.20 mol of CO and 0.20 mol of H_2O was placed in a 1.0 dm^3 flask and allowed to come to equilibrium at 1200 K.

Calculate the amount, in moles, of each substance present in the equilibrium mixture at 1200 K.

	CO_2	+	H_2	$\rightleftharpoons$	CO	+	H_2O
initial moles	0.50		0.50		0.20		0.20

[6]

9 Methanol, CH_3OH, is considered to be a possible alternative to fossil fuels, particularly for use in vehicles.

Methanol can be produced from fossil fuels and from agricultural waste. It can also be synthesised from carbon dioxide and hydrogen.

$$CO_2(g) + 3H_2(g) \rightleftharpoons CH_3OH(g) + H_2O(g)$$

The synthesis of methanol is carried out at about 500 K with a pressure of between 40 and 100 atmospheres (between 4×10^6 Pa and 10×10^7 Pa) and using a catalyst. The use of such conditions will affect both the rate of reaction and the equilibrium yield.

In the spaces below, explain the effects of higher temperature, higher pressure, and the use of a catalyst on the **equilibrium yield** of methanol.

higher temperature

effect ....

explanation ....

....

higher pressure

effect ....

explanation ....

....

use of catalyst

effect ....

explanation ....

....

[6]

10 Methanol may be synthesised from carbon monoxide and hydrogen.

$$CO(g) + 2H_2(g) \rightarrow CH_3OH(g)$$

The operating conditions for this reaction are as follows.

pressure	200 atmospheres (2×10^7 Pa)
temperature	600 K
catalyst	oxides of Cr, Cu, and Zn

In the spaces below, explain how **each** of these conditions affects the **rate of formation** of methanol.

pressure

....

....

....

temperature

....

....

....

catalyst

....

....

....

[6]

11 Hydrogen iodide can be made by heating together hydrogen gas and iodine vapour. The reaction is incomplete.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$$

(b) Write an expression for K_c and state the units.

K_c = ... units .... [2]

(c) For this equilibrium, the numerical value of the equilibrium constant K_c is 140 at 500 K and 59 at 650 K.

Use this information to state and explain the effect of the following changes on the equilibrium position.

(i) increasing the pressure applied to the equilibrium

....

....

(ii) decreasing the temperature of the equilibrium

....

....
[4]

(d) A mixture of 0.02 mol of hydrogen and 0.02 mol of iodine was placed in a 1 dm^3 flask and allowed to come to equilibrium at 650 K.

Calculate the amount, in moles, of each substance present in the equilibrium mixture at 650 K.

	$H_2(g)$	+	$I_2(g)$	$\rightleftharpoons$	$2HI(g)$
initial moles	0.02		0.02		0

12 Hydrogen is the most abundant element in the Universe, although on Earth only very small quantities of molecular hydrogen have been found to occur naturally.

Hydrogen is manufactured on a large scale for use in the chemical industry and is also regarded as a possible fuel to replace fossil fuels in internal combustion engines.

(a) State **one** large scale use of hydrogen in the chemical industry.

.... [1]

One common way of producing hydrogen on a large scale for use in the chemical industry is by the steam 'reforming' of methane (natural gas), in which steam and methane are passed over a catalyst at 1000–1400 K to produce carbon monoxide and hydrogen.

$$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \qquad \Delta H = +206\,kJ\,mol^{-1}$$

(b) Use the information above to state and explain the effect on the equilibrium position of the following changes.

(i) increasing the pressure applied to the equilibrium

....

....

(ii) decreasing the temperature of the equilibrium

....

.... [4]

(c) What will be the effect on the rate of the reaction of increasing the pressure at which it is carried out? Explain your answer.

....

....

.... [2]

(d) Further hydrogen can be obtained by the 'water-gas shift' reaction in which the carbon monoxide produced is reacted with steam.

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g) \qquad K_c = 6.40 \times 10^{-1} \text{ at } 1100\,K$$

A mixture containing 0.40 mol of CO, 0.40 mol of H_2O, 0.20 mol of CO_2 and 0.20 mol of H_2 was placed in a 1 dm^3 flask and allowed to come to equilibrium at 1100 K

(i) Give an expression for K_c for this reaction.

(ii) Calculate the amount, in moles, of each substance present in the equilibrium mixture at 1100 K.

	$CO(g)$	+	$H_2O(g)$	$\rightleftharpoons$	$CO_2(g)$	+	$H_2(g)$
initial moles	0.40		0.40		0.20		0.20

[5]

13 Ammonium nitrate fertiliser is manufactured from ammonia. The first reaction in the manufacture of the fertiliser is the catalytic oxidation of ammonia to form nitrogen monoxide, NO. This is carried out at about 1×10^3 kPa (10 atmospheres) pressure and a temperature of 700 to 850 °C.

$$4NH_3(g) + 5O_2(g) \rightleftharpoons 4NO(g) + 6H_2O(g) \qquad \Delta H^{\ominus} = -906\,\text{kJ mol}^{-1}$$

(a) Write the expression for the equilibrium constant, K_p, stating the units.

K_p =

units .... [2]

(b) What will be the effect on the yield of NO of **each** of the following?
In each case, explain your answer.

(i) increasing the temperature

....

....

....

(ii) decreasing the applied pressure

....

....

....

[4]

14 Methanol, CH_3OH, can be produced industrially by reacting carbon monoxide, CO, with hydrogen, H_2.

$$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g) \qquad \Delta H = -91\,kJ\,mol^{-1}$$

The process is carried out at 4×10^3 kPa (40 atmospheres) and 1150 K.

(a) **(i)** State Le Chatelier's Principle.

....

....

.... [2]

(ii) From your understanding of Le Chatelier's Principle, state the conditions of temperature and pressure that could be used in order to produce an increased yield of methanol in this process.
In **each** case, explain why the yield would increase.

temperature ....

explanation ....

....

pressure ....

explanation ....

....

[4]

(b) The carbon monoxide for use in the production of methanol may be formed by reacting carbon dioxide with hydrogen.

$$CO_2(g) + H_2(g) \rightleftharpoons CO(g) + H_2O(g) \qquad K_c = 1.44 \text{ at } 1200\,K$$

A mixture containing 0.70 mol of CO_2, 0.70 mol of H_2, 0.30 mol of CO and 0.30 mol of H_2O was placed in a 1 dm^3 flask and allowed to come to equilibrium at 1200 K.

Calculate the amount, in moles, of each substance present in the equilibrium mixture at 1200 K.

	CO_2	+	H_2	$\rightleftharpoons$	CO	+	H_2O
initial moles	0.70		0.70		0.30		0.30

[4]

15 Nitrogen dioxide, NO_2, can enter the atmosphere in a variety of ways.

(a) **(i)** State one natural and one man-made source of atmospheric NO_2.

natural ....

man-made ....
[1]

(ii) Write an equation to show how NO_2 leads to the formation of nitric acid in acid rain.

.... [1]

(iii) Use equations to illustrate the catalytic role of NO_2 in the formation of sulfuric acid in acid rain.

....

....

.... [3]

(b) Nitrogen dioxide exists in equilibrium with dinitrogen tetroxide, N_2O_4.

$$2NO_2(g) \rightleftharpoons N_2O_4(g)$$

2.00 mol of dinitrogen tetroxide was sealed in a container at 350 K. After equilibrium had been established the total pressure was 140 kPa and the mixture of gases contained 1.84 mol of dinitrogen tetroxide.

(i) Give the expression for the equilibrium constant, K_p, for this equilibrium.

K_p =

[1]

(ii) Calculate the number of moles of NO_2 present at equilibrium.

[1]

(iii) Calculate the total number of moles of gas present at equilibrium and hence the mole fraction of each gas present at equilibrium.

[2]

(iv) Calculate the partial pressure of each gas present at equilibrium.

[2]

(v) Calculate the value of the equilibrium constant, K_p, at 350 K.
Give your answer to **three** significant figures and include the units.

K_p = ...

units = ...
[2]

16 The Contact process for the manufacture of sulfuric acid was originally patented in the 19th century and is still in use today.

The key step in the overall process is the reversible conversion of sulfur dioxide to sulfur trioxide in the presence of a vanadium(V) oxide catalyst.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H = -196\,kJ\,mol^{-1}$$

(a) One way in which the sulfur dioxide for this reaction is produced is by heating the sulfide ore iron pyrites, FeS_2, in air. Iron(III) oxide is also produced. Write an equation for this reaction.

.... [2]

(d) The conversion of sulfur dioxide into sulfur trioxide is carried out at a temperature of 400 °C.

(i) With reference to Le Chatelier's Principle and reaction kinetics, state and explain one advantage and one disadvantage of using a higher temperature.

....

....

....

....

....

.... [4]

(ii) State the expression for the equilibrium constant, K_p, for the formation of sulfur trioxide from sulfur dioxide.

K_p =

[1]

(iii) 2.00 moles of sulfur dioxide and 2.00 moles of oxygen were put in a flask and left to reach equilibrium.
At equilibrium, the pressure in the flask was 2.00×10^5 Pa and the mixture contained 1.80 moles of sulfur trioxide.

Calculate K_p. Include the units.

K_p = ...

units = ...

[5]

17 The Haber process for the manufacture of ammonia, NH_3, was originally devised at the start of the 20th century and was developed into a full-scale industrial process by Carl Bosch in 1913.

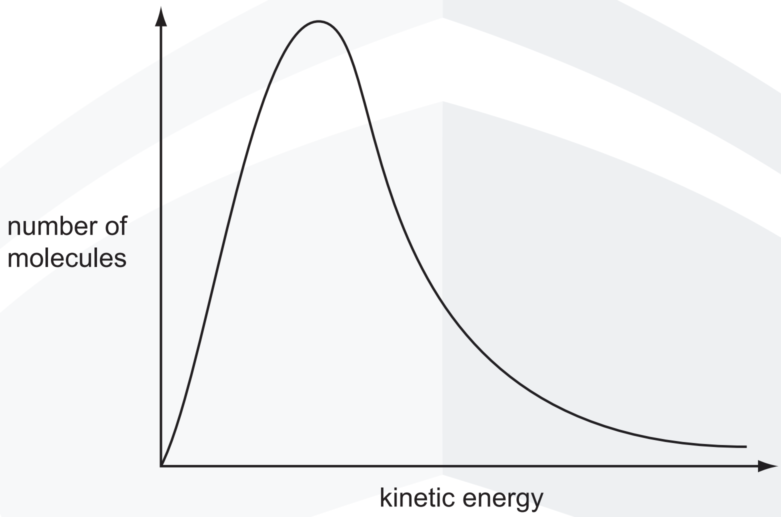
The key step in the process is the reversible reaction of nitrogen and hydrogen in the presence of an iron catalyst.

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

(a) The hydrogen for this reaction can be formed by reacting methane with steam, during which carbon monoxide is also produced. Write an equation for this reaction.

.... [1]

(b) Use the Boltzmann distribution shown to explain why a catalyst increases the rate of this reaction.



....

....

....

.... [4]

(c) Draw a three-dimensional diagram to show the shape of an ammonia molecule. Name this shape and state the bond angle.

shape .... bond angle .... [3]

(d) The Haber process is typically carried out at a temperature of 400 °C.

(i) With reference to Le Chatelier's Principle and reaction kinetics, state and explain one advantage and one disadvantage of using a higher temperature.

....

....

....

....

....

.... [4]

(ii) State the expression for the equilibrium constant, K_p, for the formation of ammonia from nitrogen and hydrogen in the Haber process.

K_p =

[1]

(iii) 2.00 moles of nitrogen and 3.00 moles of hydrogen were put in a vessel and left to reach equilibrium.

At equilibrium, the pressure was 2.00×10^7 Pa and the mixture contained 1.60 moles of ammonia.

Calculate K_p. Include the units.

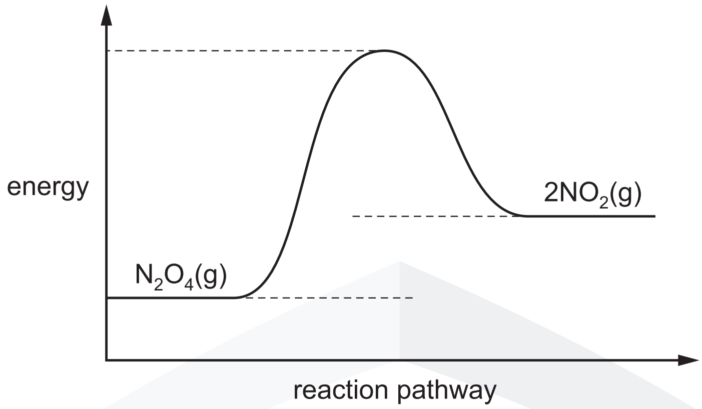
K_p = ...

units = ...
[5]

18 Dinitrogen tetraoxide, N_2O_4, and nitrogen dioxide, NO_2, exist in dynamic equilibrium with each other.

$$N_2O_4(g) \rightleftharpoons 2NO_2(g) \qquad \Delta H = +54\,kJ\,mol^{-1}$$

The energy profile for this reaction is shown.



(a) Add labelled arrows to the energy profile to indicate

- the enthalpy change of the reaction, ΔH,
- the activation energy of the forward reaction, E_a.

[2]

(b) 0.0500 mol of N_2O_4 was placed in a sealed vessel of volume 1.00 dm^3, at a temperature of 50 °C and a pressure of 1.68×10^5 Pa. The mass of the resulting equilibrium mixture was 4.606 g.

(i) Calculate the average molecular mass, M_r, of the resulting equilibrium mixture. Give your answer to **three** significant figures.

M_r = ... [2]

(ii) The number of moles of N_2O_4 that dissociated can be represented by n.

State, in terms of n, the amount, in moles, of NO_2 in the equilibrium mixture.

moles of NO_2 = ... [1]

The number of moles of N_2O_4 remaining at equilibrium is (0.05 – *n*).

(iii) State, in terms of *n*, the total amount, in moles, of gas in the equilibrium mixture.

[1]

(iv) State, in terms of *n*, the mole fraction of NO_2 in the equilibrium mixture.

[1]

In this equilibrium mixture, the mole fraction of NO_2 is 0.400.

(v) Use your answers to **(ii)** and **(iv)** to calculate the amount in moles of each gas in the equilibrium mixture. Give your answers to **three** significant figures.

amount of N_2O_4 = ... mol

amount of NO_2 = ... mol

[2]

(vi) Write the expression for the equilibrium constant, K_p, for this equilibrium.

K_p =

[1]

(vii) Use the total pressure of the mixture, 1.68×10^5 Pa, to calculate the value of the equilibrium constant, K_p, and give its units.

K_p = ...

units = ...

[3]

[Total: 13]

Reaction kinetics

The investigation of the factors that affect the rate of a chemical reaction is important in the study of physical chemistry. The temperature and the addition of a catalyst can both affect the progression of a chemical reaction.

a explain and use the term rate of reaction ☐

b explain qualitatively, in terms of collisions, the effect of concentration changes on the rate of a reaction ☐

c explain and use the term activation energy, including reference to the Boltzmann distribution ☐

d explain qualitatively, in terms both of the Boltzmann distribution and of collision frequency, the effect of temperature change on the rate of a reaction ☐

e

REACTION KINETICS

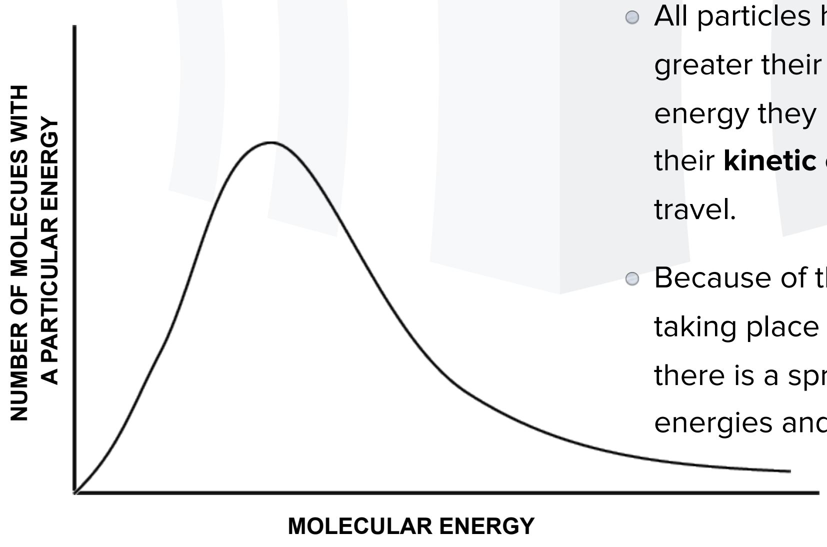
8 Reaction kinetics

The investigation of the factors that affect the rate of a chemical reaction is important in the study of physical chemistry. The temperature and the addition of a catalyst can both affect the progression of a chemical reaction.

	Learning outcomes Candidates should be able to:
8.1 Simple rate equations; orders of reaction; rate constants	a) explain and use the term *rate of reaction* b) explain qualitatively, in terms of collisions, the effect of concentration changes on the rate of a reaction **c) explain and use the terms *rate equation, order of reaction, rate constant, half-life of a reaction, rate-determining step*** **d) construct and use rate equations of the form rate = $k[A]^m[B]^n$ (for which *m* and *n* are 0, 1 or 2), including:** **(i) deducing the order of a reaction, or the rate equation for a reaction, from concentration-time graphs or from experimental data relating to the initial rates method and half-life method** **(ii) interpreting experimental data in graphical form, including concentration-time and rate-concentration graphs** **(iii) calculating an initial rate using concentration data** **(integrated forms of rate equations are not required)** **e) (i) show understanding that the half-life of a first-order reaction is independent of concentration** **(ii) use the half-life of a first-order reaction in calculations** **f) calculate the numerical value of a rate constant, for example by using the initial rates or half-life method** **g) for a multi-step reaction:** **(i) suggest a reaction mechanism that is consistent with the rate equation and the equation for the overall reaction** **(ii) predict the order that would result from a given reaction mechanism (and vice versa)** **h) devise a suitable experimental technique for studying the rate of a reaction, from given information**
8.2 Effect of temperature on reaction rates and rate constants; the concept of activation energy	a) explain and use the term *activation energy*, including reference to the Boltzmann distribution b) explain qualitatively, in terms both of the Boltzmann distribution and of collision frequency, the effect of temperature change on the rate of a reaction **c) explain qualitatively the effect of temperature change on a rate constant and hence the rate of a reaction**

REACTION KINETICS

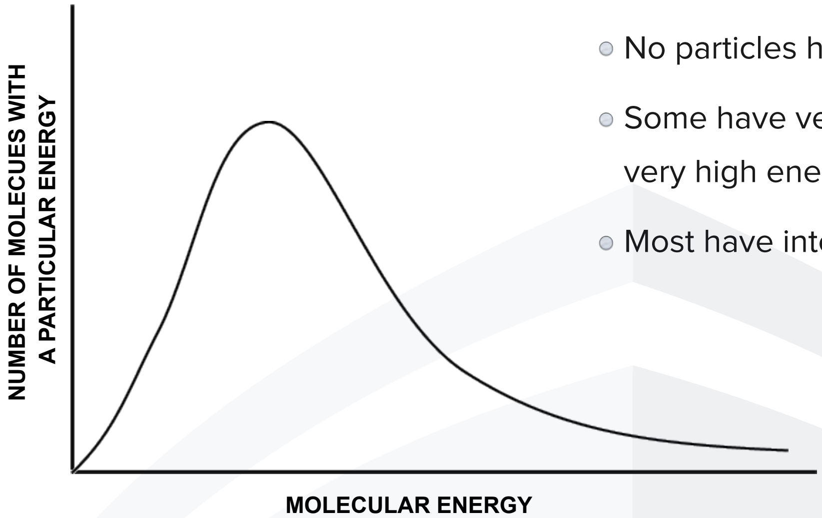
BOLTZMANN DISTRIBUTION OF MOLECULAR ENERGY



- All particles have energy - the greater their temperature, the more energy they possess. The greater their **kinetic energy** the faster they travel.
- Because of the many collisions taking place between molecules, there is a spread of molecular energies and velocities.

2

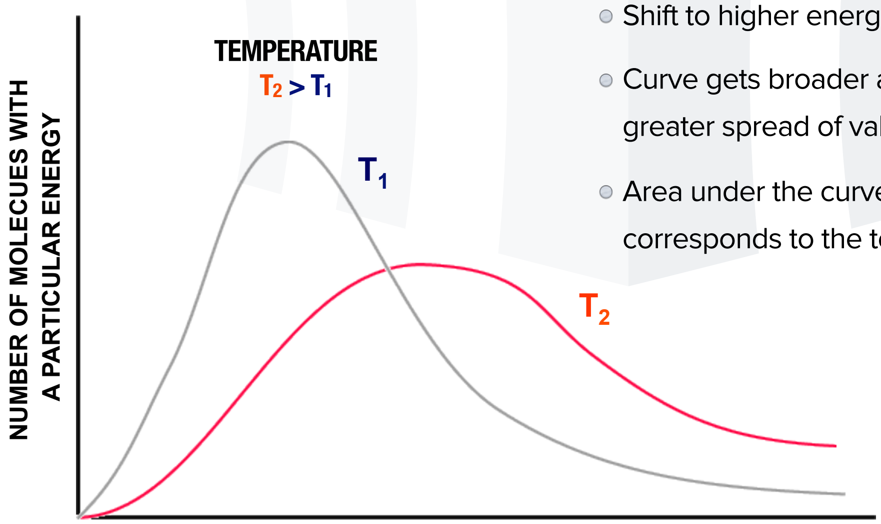
BOLTZMANN DISTRIBUTION OF MOLECULAR ENERGY



- No particles have zero energy/velocity
- Some have very low and some have very high energies/velocities
- Most have intermediate velocities.

3

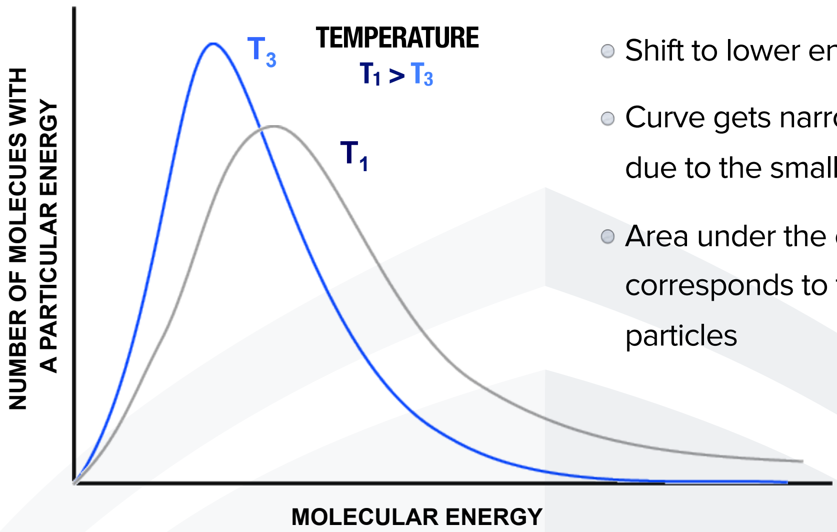
INCREASING TEMPERATURE



- Shift to higher energies/velocities
- Curve gets broader and flatter due to the greater spread of values
- Area under the curve stays constant - it corresponds to the total number of particles

4

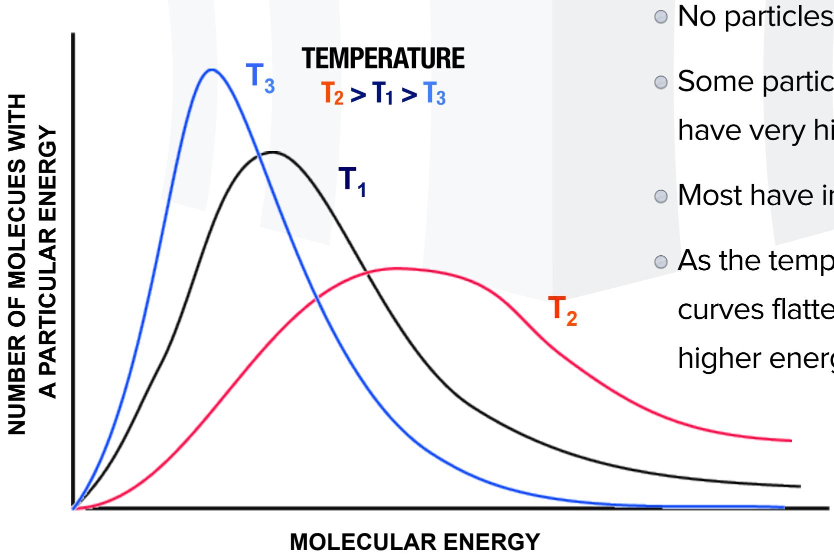
DECREASING TEMPERATURE



- Shift to lower energies/velocities
- Curve gets narrower and more pointed due to the smaller spread of values
- Area under the curve stays constant - it corresponds to the total number of particles

5

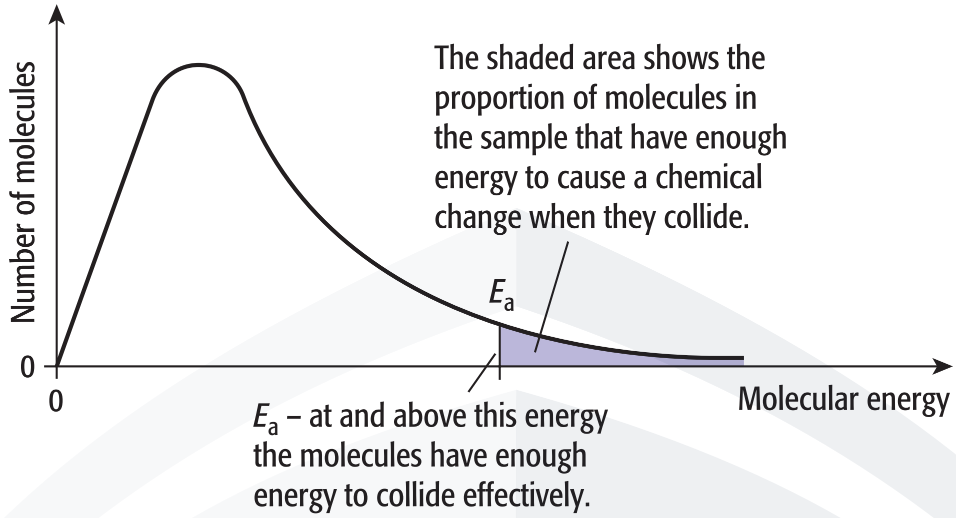
REVIEW



- No particles have zero energy/velocity
- Some particles have very low and some have very high energies/velocities
- Most have intermediate velocities
- As the temperature increases the curves flatten, broaden and shift to higher energies

6

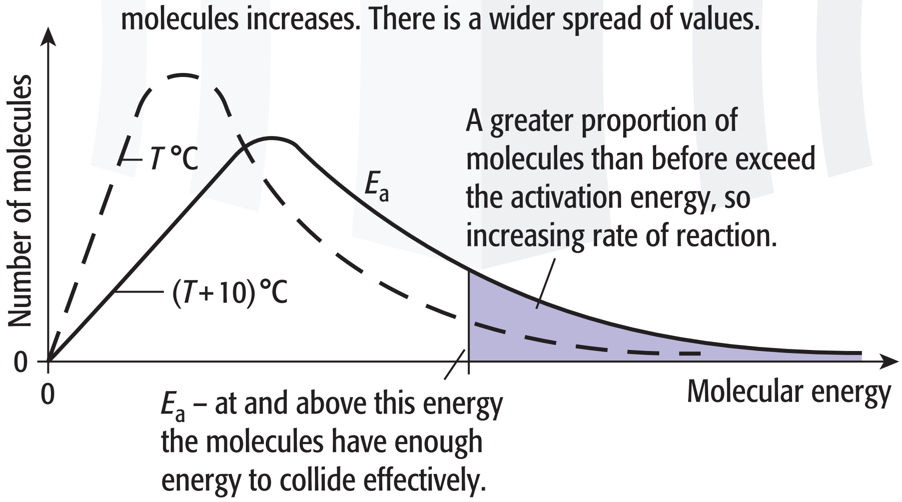
ACTIVATION ENERGY - E_A



7

INCREASING TEMPERATURE

When the sample is heated, the mean energy of the molecules increases. There is a wider spread of values.



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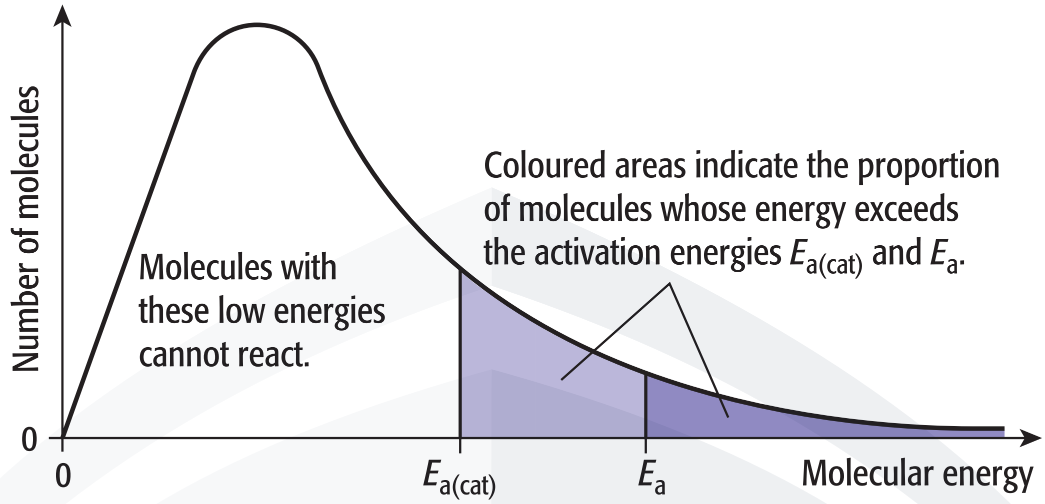
CATALYSTS



9

CATALYSIS

Catalysts increase the rate of a chemical reaction. They do this by providing an alternative pathway for the reaction with lower activation energy.

We can divide catalysts into two main classes.

Catalysis

Homogeneous Catalysis
Occurs when the catalyst is in the same phase as the reaction mixture. For example: hydrogen ions catalyse the hydrolysis of esters.

Heterogeneous Catalysis
Occurs when the catalyst is in a different phase to the reaction mixture. For example, decomposition of aqueous hydrogen peroxide catalysed by manganese(IV) oxide.

10

HOMOGENEOUS CATALYSIS

Homogeneous catalysis often involves changes in oxidation number of the ions involved in catalysis.

Ions of transition elements are often good catalysts because of their ability to change oxidation number.

Examples:

1. The catalytic role of atmospheric oxides of nitrogen in the oxidation of atmospheric sulfur dioxide.
2. Catalytic role of Fe^{3+} in the $I^-/S_2O_8^{2-}$ reaction.

11

HETEROGENEOUS CATALYSIS

The mechanism of this catalysis can be explained using the theory of adsorption. Chemical adsorption (also called chemisorption) occurs when molecules become bonded to atoms on the surface of a solid.

You must be careful to distinguish between the words **adsorb** and **absorb**. Adsorb means to bond to the surface of a substance. Absorb means to move right into the substance – rather like a sponge absorbs water.

Examples:

1. Iron in the Haber Process
2. Transition elements in catalytic converters
3. Vanadium (V) oxide in the contact process

12

REACTION KINETICS WS 1

SECTION A

1 Ammonia is made by the Haber process. The reactants are nitrogen and hydrogen.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H \text{ –ve}$$

What will increase the rate of the forward reaction?

A adding argon to the mixture but keeping the total volume constant

B decreasing the temperature

C increasing the total pressure by reducing the total volume at constant temperature

D removing ammonia as it is made but keeping the total volume of the mixture the same

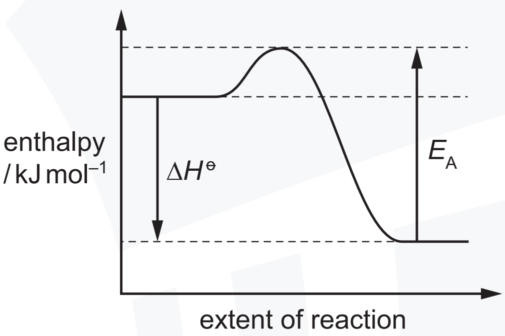
2 Nitric oxide, NO, and bromine vapour react together according to the following equation.

$$2NO(g) + Br_2(g) \rightarrow 2NOBr(g) \qquad \Delta H^{\ominus} = -23\,\text{kJ mol}^{-1}$$

The reaction has an activation energy of $+5.4\,\text{kJ mol}^{-1}$.

What is the correct reaction pathway diagram for this reaction?

A



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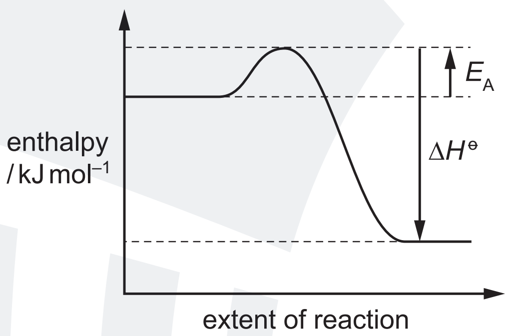
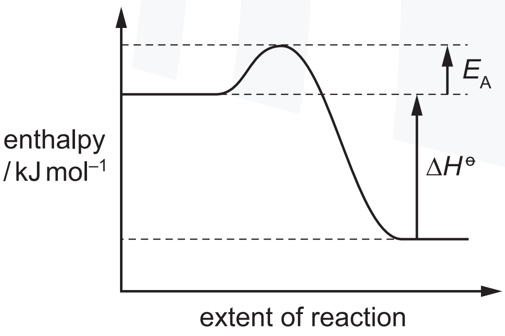
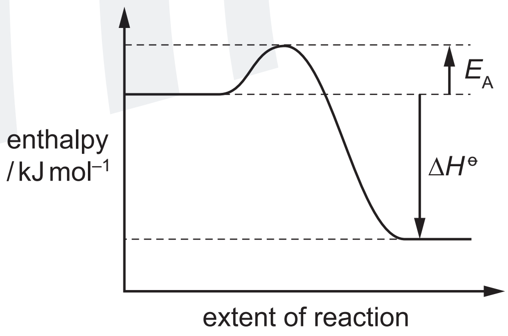


C



D



3 Enzymes are biological catalysts. Many enzymes show specificity. An example of an enzyme which shows specificity is glucokinase. Glucokinase is involved in the metabolism of glucose.

What does specificity mean in this context?

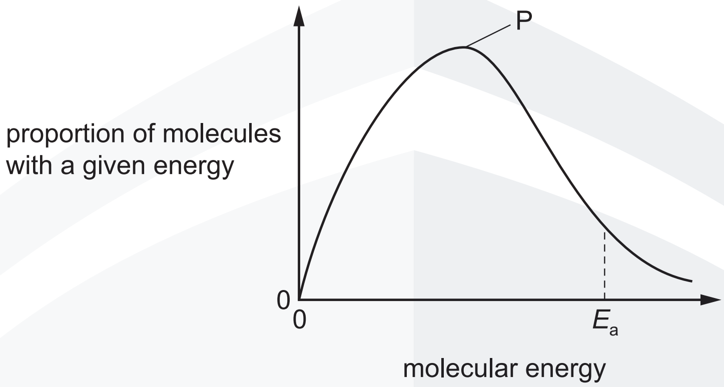
A Glucokinase is most effective as a catalyst over a narrow pH range.

B Glucokinase is most effective as a catalyst over a narrow range of temperatures.

C Glucokinase only operates on a narrow range of substrate molecules.

D Glucokinase provides an alternative route for the reactions it catalyses.

4 The diagram shows the Boltzmann distribution of energies in 1 mole of a gas. The gas can take part in a reaction with an activation energy, E_a.



Which statement correctly describes the effect of an increase in temperature?

A Peak P will be higher and fewer molecules will have energy > E_a.

B Peak P will be higher and more molecules will have energy > E_a.

C Peak P will be lower and fewer molecules will have energy > E_a.

D Peak P will be lower and more molecules will have energy > E_a.

5 Which change alters the activation energy of a given reaction?

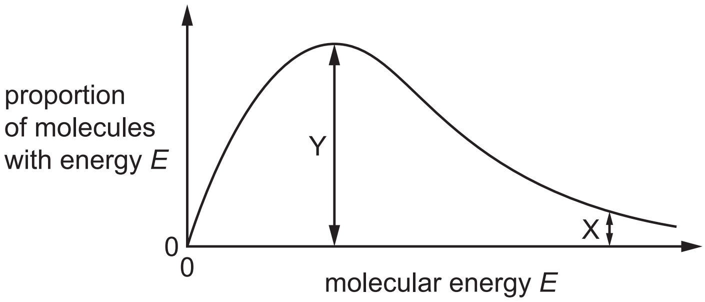
A adding a suitable catalyst

B changing the particle size of the reactants

C changing the pressure at which the reaction is carried out

D changing the temperature at which the reaction is carried out

6 The diagram shows the Boltzmann distribution of the energy of gaseous molecules at a particular temperature.



Which statement is correct?

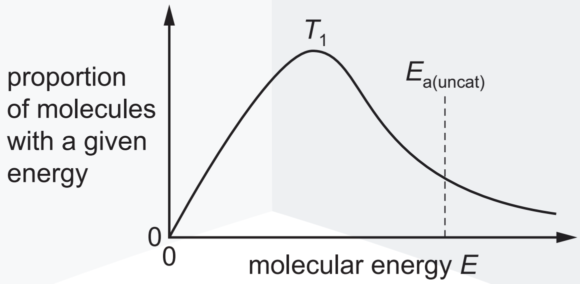
A If the temperature of the gas is raised, the height of the maximum of the curve increases.

B If the temperature of the gas is raised, the maximum of the curve moves to the right.

C The length of the line labelled X shows the activation energy for the reaction.

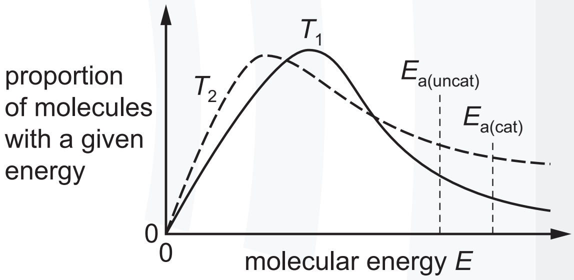
D The length of the line labelled Y shows the enthalpy change of the reaction.

7 The diagram shows the distribution of molecular energies in a sample of gas at a temperature T_1. The activation energy for an uncatalysed reaction of this gas, $E_{a(uncat)}$, is shown.

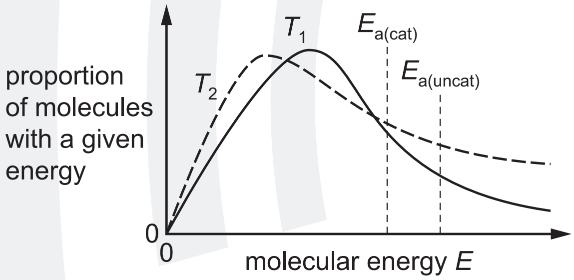


Which diagram correctly shows the new distribution and new activation energy, $E_{a(cat)}$, when the temperature is increased to T_2, and a catalyst is used that increases the rate of the reaction?

A



B



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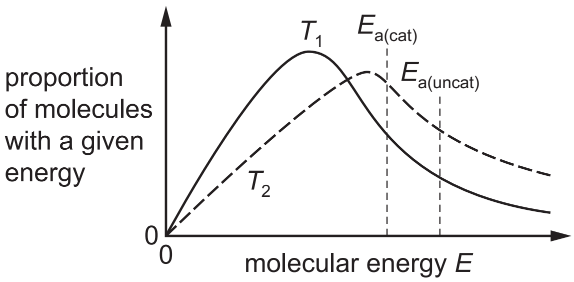
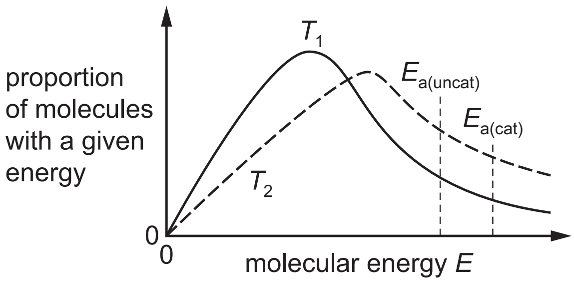


D



8 Methanol can be produced from hydrogen and carbon monoxide.

$$2H_2(g) + CO(g) \rightleftharpoons CH_3OH(g)$$

What is the expression for K_p for this reaction?

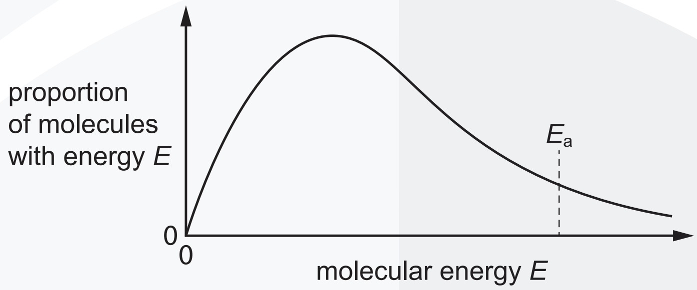
A $K_p = \dfrac{(2p_{H_2})^2 \times p_{CO}}{p_{CH_3OH}}$

B $K_p = \dfrac{(p_{H_2})^2 \times p_{CO}}{p_{CH_3OH}}$

C $K_p = \dfrac{p_{CH_3OH}}{(p_{H_2})^2 \times p_{CO}}$

D $K_p = \dfrac{p_{CH_3OH}}{p_{CO} \times (2p_{H_2})^2}$

9 The Boltzmann distribution for the hydrogenation of an alkene at a particular temperature in the absence of a catalyst is shown.



Which row correctly describes the effects of adding nickel to the reaction vessel?

	the shape of the Boltzmann distribution	activation energy, E_a
A	changes	decreases
B	changes	increases
C	does not change	decreases
D	does not change	increases

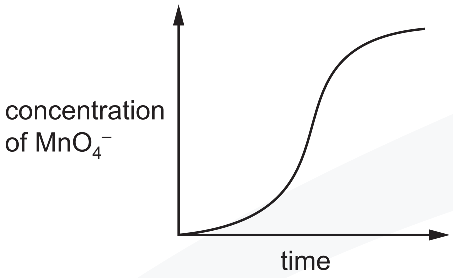
10 Oxidation of ethanedioate ions by acidified manganate(VII) ions is very slow at room temperature.

$$2MnO_4^- + 5C_2O_4^{2-} + 16H^+ \rightarrow 2Mn^{2+} + 10CO_2 + 8H_2O$$

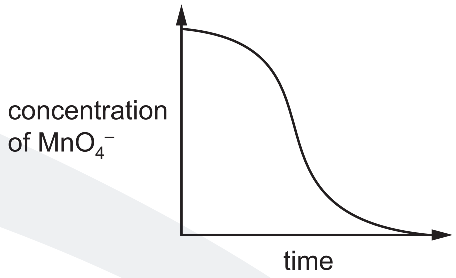
Mn^{2+} ions catalyse this reaction.

Which graph shows how the concentration of acidified manganate(VII) ions varies after ethanedioate ions are added?

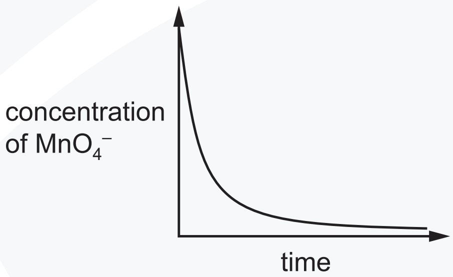
A



B



C



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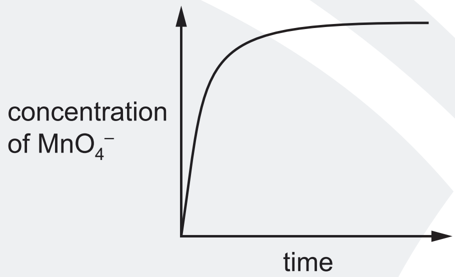


11 A large excess of marble chips was reacted with 25 cm^3 of 1.0 mol dm^{-3} hydrochloric acid at 40 °C.

How will the result be different when the reaction is repeated with 60 cm^3 of 0.5 mol dm^{-3} hydrochloric acid at 40 °C?

A The reaction is faster and less of the products are made.

B The reaction is faster and more of the products are made.

C The reaction is slower and less of the products are made.

D The reaction is slower and more of the products are made.

[W'17 2 Q11]

12 Which change alters the activation energy of a given reaction?

A adding a suitable catalyst

B changing the particle size of the reactants

C changing the pressure at which the reaction is carried out

D changing the temperature at which the reaction is carried out

[W'17 2 Q12]

13 Which statement about the effect of a catalyst on a reversible reaction is correct?

A The activation energy of the forward reaction stays the same.

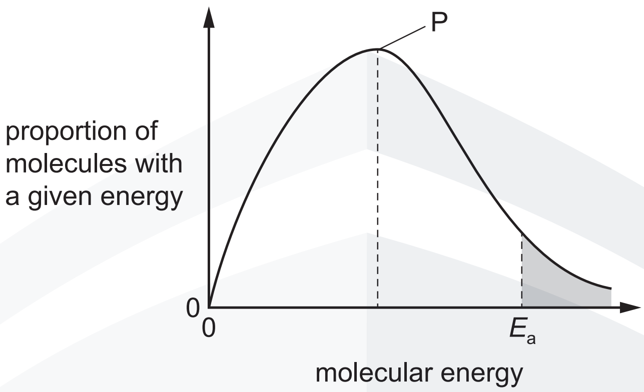
B The composition of the equilibrium mixture stays the same.

C The rate of the backward reaction stays the same.

D The value of the equilibrium constant changes.

[M'18 P12 Q12]

14 The diagram shows the Boltzmann distribution of energies in a gas. The gas can take part in a reaction with an activation energy, E_a. The gas is maintained at a constant temperature.



Which statement is correct?

A If a catalyst is added, peak P will be lower and E_a will move to the left.

B If a catalyst is added, peak P will be lower and E_a will move to the right.

C If a catalyst is added, peak P will be the same and E_a will move to the left.

D If a catalyst is added, peak P will be the same and E_a will move to the right.

[J'18 P11 Q4]

15 A chemical company used a catalyst in a chemical process. The company has now decided not to use the catalyst but to increase the temperature so that the rate of the reaction is the same as it was when the catalyst was used.

Which statement about the new conditions compared to the original conditions is correct?

A The activation energy has been decreased.

B The activation energy has been increased.

C There are fewer successful collisions per unit time.

D There are more successful collisions per unit time.

[J'18 P12 Q10]

16 Elements and their compounds are important as catalysts.

In which process is a compound used, rather than an element?

A catalytic converters

B Contact process

C Haber process

D hydrogenation of alkenes

[J'18 P13 Q18]

17 Two reactions are shown.

reaction 1 $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

reaction 2 $2O_3(g) \rightleftharpoons 3O_2(g)$

In reaction 1, a finely powdered iron catalyst is used.

In reaction 2, a vaporised tetrachloromethane catalyst in ultraviolet light is used.

Which statement about the catalysts used is correct?

A Both reaction 1 and reaction 2 use a heterogeneous catalyst.

B Both reaction 1 and reaction 2 use a homogeneous catalyst.

C Reaction 1 uses a heterogeneous catalyst and reaction 2 uses a homogeneous catalyst.

D Reaction 1 uses a homogeneous catalyst and reaction 2 uses a heterogeneous catalyst.

[N'18 P11 Q11]

18 Reaction 1: chlorine reacts with cold aqueous sodium hydroxide to form solution Z.

Reaction 2: solution Z is heated and forms $ClO_3^-(aq)$ and $Cl^-(aq)$.

Which equations represent reaction 1 and reaction 2?

A reaction 1 $2Cl_2 + 4OH^- \rightarrow ClO_2^- + 3Cl^- + 2H_2O$

reaction 2 $3ClO_2^- \rightarrow 2ClO_3^- + Cl^-$

B reaction 1 $2Cl_2 + 4OH^- \rightarrow ClO_2^- + 3Cl^- + 2H_2O$

reaction 2 $3ClO^- \rightarrow ClO_3^- + 2Cl^-$

C reaction 1 $Cl_2 + 2OH^- \rightarrow ClO^- + Cl^- + H_2O$

reaction 2 $2ClO^- + 2OH^- \rightarrow ClO_3^- + Cl^- + H_2O$

D reaction 1 $Cl_2 + 2OH^- \rightarrow ClO^- + Cl^- + H_2O$

reaction 2 $3ClO^- \rightarrow ClO_3^- + 2Cl^-$

[N'18 P11 Q17]

19 Transition elements and their compounds are widely used as catalysts.

What is the identity and what is the oxidation number of the element present in the catalyst used in the Contact process?

	element	oxidation number
A	iron	0
B	iron	+3
C	vanadium	0
D	vanadium	+5

[N'18 P11 Q19]

20 In a chemical system the particles involved have a range of energies. This can be shown on a graph called the Boltzmann distribution.

Which statement correctly explains the effect of a catalyst on the particles in a chemical system?

A A catalyst enables particles with a lower energy to collide successfully.

B A catalyst increases the number of particles with higher energies.

C A catalyst increases the number of particles with the most probable energy value.

D A catalyst increases the value of the most probable particle energy.

[N'18 P12 Q10]

21 Nitrogen and hydrogen can react together to form ammonia.

The formation of ammonia is exothermic.

The rate and yield of the reaction can be altered by changing the conditions under which the reaction is carried out.

Which row shows the effects of adding iron to the mixture **and** increasing the temperature?

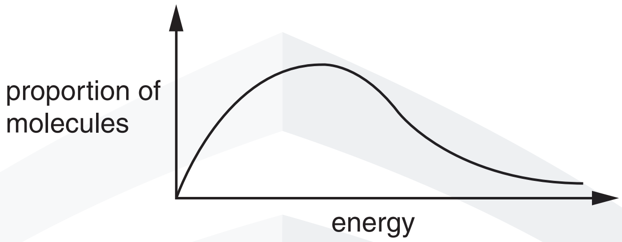
	adding iron	increasing the temperature
A	has no effect on the equilibrium yield	reduces the equilibrium yield
B	increases the equilibrium yield	increases the equilibrium yield
C	increases the equilibrium yield	increases the rate
D	increases the rate	has no effect on the equilibrium yield

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 The diagram represents the Boltzmann distribution of molecular energies at a given temperature.



As temperature increases, which statements are correct?

1 The maximum of the curve is displaced to the right.

2 The proportion of molecules with energies **above** any given value increases.

3 The proportion of molecules **with** any given energy increases.

2 Why does a mixture of hydrogen gas and bromine gas react together faster at a temperature of 500 K than it does at a temperature of 400 K?

1 A higher proportion of effective collisions occurs at 500 K.

2 Hydrogen molecules and bromine molecules collide more frequently at 500 K.

3 The activation energy of the reaction is lower at 500 K.

3 Which statements about the properties of a catalyst are correct?

1 A catalyst increases the average kinetic energy of the reacting particles.

2 A catalyst increases the rate of the reverse reaction.

3 A catalyst has no effect on the enthalpy change of the reaction.

4 Ethanol is manufactured by reacting ethene gas and steam in the presence of phosphoric(V) acid.

$$C_2H_4(g) + H_2O(g) \rightleftharpoons C_2H_5OH(g) \qquad \Delta H = -45\,\text{kJ mol}^{-1}$$

The reaction is carried out at 570 K and 60 atm.

What would be the consequences of carrying out the reaction at the same temperature but at a pressure of 200 atm?

1 The manufacturing costs would increase.

2 The maximum yield at equilibrium would be higher.

3 The reaction would proceed at a faster rate.

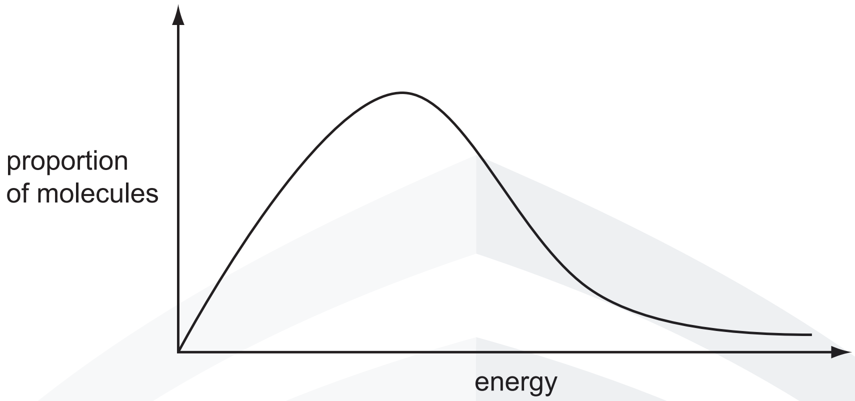
5 Which statements are correct about the activation energy of a reaction?

1 It is different for the forward and back reactions in an exothermic process.

2 It is low for a reaction that takes place slowly.

3 It is unaffected by the presence of a catalyst.

6 The diagram represents the Boltzmann distribution of molecular energies at a given temperature.



Which of the factors that affect the rate of a reaction can be explained using such a Boltzmann distribution?

1 increasing the concentration of reactants

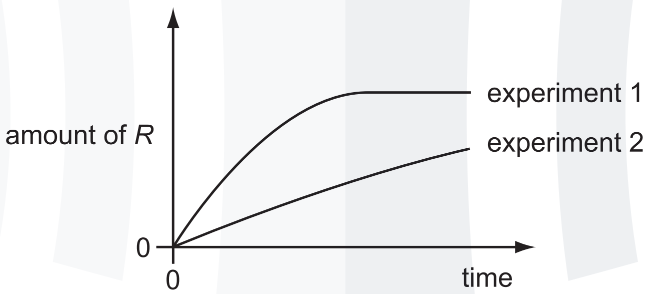
2 increasing the temperature

3 the addition of a catalyst

7 The stoichiometry of a catalysed reaction is shown by the equation below.

$$P(g) + Q(g) \rightleftharpoons R(g) + S(g)$$

Two experiments were carried out in which the production of *R* was measured against time. The results are shown in the diagram below.



Which changes in the conditions from experiment 1 to experiment 2 might explain the results shown?

1 Less of *P* was used.

2 A different catalyst was used.

3 Product *S* was continuously removed from the reaction vessel.

8 Which statements about the properties of a catalyst are correct?

1 A catalyst increases the average kinetic energy of the reacting particles.

2 A catalyst increases the rate of the reverse reaction.

3 A catalyst has no effect on the enthalpy change $\Delta H^{\ominus}$ of the reaction.

9 What factors can affect the value of the activation energy of a reaction?

1 the presence of a catalyst

2 changes in temperature

3 changes in concentration of the reactants

10 A student puts 10 cm^3 of 0.100 mol dm^{-3} sulfuric acid into one test-tube and 10 cm^3 of 0.100 mol dm^{-3} ethanoic acid into another test-tube. He then adds 1.0 g (an excess) of magnesium ribbon to each test-tube and takes suitable measurements. Both acids have the same starting temperature.

Neither reaction is complete after 2 minutes, but both are complete after 20 minutes.

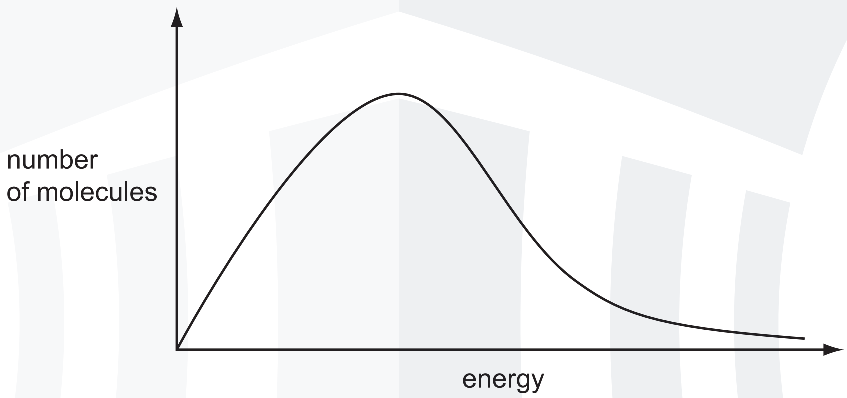
Which statements are correct?

1 After 2 minutes, the sulfuric acid is at a higher temperature than the ethanoic acid.

2 After 2 minutes, the sulfuric acid has produced more gas than the ethanoic acid.

3 After 20 minutes, the sulfuric acid has produced more gas than the ethanoic acid.

11 The diagram represents the Boltzmann distribution of molecular energies at a given temperature.



Which of the factors that affect the rate of a reaction can be explained using such a Boltzmann distribution?

1 increasing the concentration of reactants

2 increasing the temperature

3 the addition of a catalyst

12 The reaction

$$E + F \rightleftharpoons G + H$$

is catalysed by platinum.

Which statements about the properties of the catalyst are correct?

1 The catalyst has no effect on the enthalpy change of the reaction.

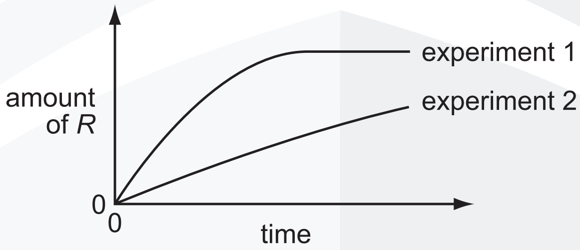
2 The catalyst increases the rate of the reverse reaction.

3 The catalyst increases the average kinetic energy of the reacting particles.

13 The stoichiometry of a catalysed reaction is shown by the equation below.

$$P(g) + Q(g) \rightleftharpoons R(g) + S(l)$$

Two experiments were carried out in which the rate of production of *R* was measured. The results are shown in the diagram below.



Which changes in the conditions might explain the results shown?

1 A lower pressure was used in experiment 2.

2 A different catalyst was used in experiment 2.

3 Product *S* was continuously removed from the reaction vessel in experiment 2.

14 A reversible reaction is catalysed.

Which statements about the effects of the catalyst on this system are correct?

1 The catalyst alters the mechanism of the reaction.

2 The catalyst reduces the activation energy for both the forward and the backward reaction.

3 The catalyst alters the composition of the equilibrium mixture.

15 Why does raising the pressure of a fixed mass of gaseous reactants at a constant temperature cause an increase in the rate of reaction?

1 More collisions occur per second when the pressure is increased.

2 More molecules have energy greater than the activation energy at the higher pressure.

3 Raising the pressure lowers the activation energy.

REACTION KINETICS WS 2

1 The hydrogen halides, HCl, HBr and HI, can undergo thermal decomposition.
In a sealed container an equilibrium is established according to the equation shown.

$$2HX(g) \rightleftharpoons H_2(g) + X_2(g) \qquad \text{(where X = C}l\text{, Br or I)}$$

(a) Some bond energies are shown in the table.

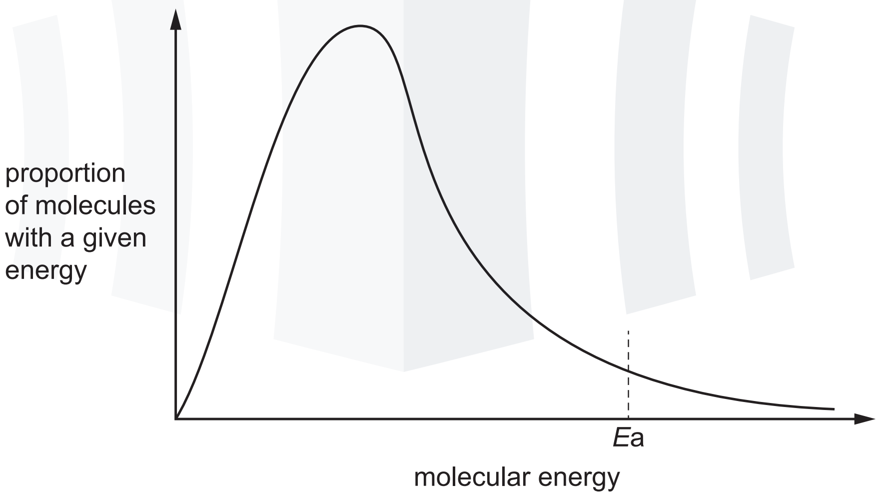
	bond energy / $kJ\,mol^{-1}$
H–Br	366
H–H	436
Br–Br	193

Use these data to calculate a value for the enthalpy change, ΔH, for the thermal decomposition of hydrogen bromide, HBr, according to the equation shown.

ΔH = ... $kJ\,mol^{-1}$ [1]

(b) At a temperature of 700 K a sample of HBr is approximately 10% decomposed. Changing the temperature affects both the rate of decomposition of HBr and the percentage that decomposes.

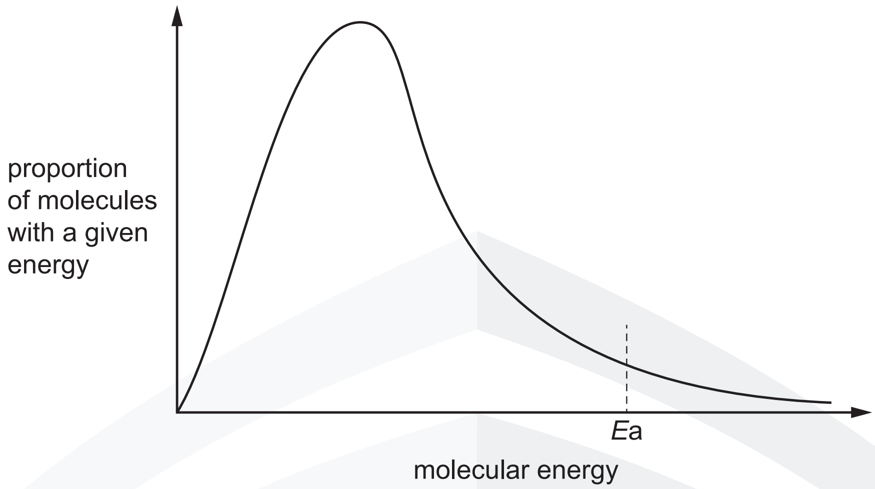
The Boltzmann distribution for a sample of HBr at 700 K is shown. *E*a represents the activation energy for the reaction.



(i) Using the same axes, sketch a second curve to indicate the Boltzmann distribution at a higher temperature. [2]

(b) The Haber process is usually carried out at a temperature of approximately 400 °C in the presence of a catalyst. Changing the temperature affects both the rate of production of ammonia and the yield of ammonia.

The Boltzmann distribution for a mixture of nitrogen and hydrogen at 400 °C is shown.
*E*a represents the activation energy for the reaction.



(i) Using the same axes, sketch a second curve to indicate the Boltzmann distribution at a higher temperature. [2]

(ii) **With reference to the Boltzmann distribution**, state and explain the effect of increasing temperature on the rate of production of ammonia.

....

....

....

.... [3]

(iii) State and explain the effect of increasing temperature on the yield of ammonia.
Use Le Chatelier's principle to explain your answer.

....

....

....

.... [3]

2 **(c)** Hydrogen chloride undergoes a reversible reaction with oxygen.

$$4HCl(g) + O_2(g) \rightleftharpoons 2Cl_2(g) + 2H_2O(g)$$

The reaction is carried out at 400 °C in the presence of a copper(II) chloride catalyst.

(i) Use the data in the table to calculate the overall enthalpy change of reaction.

compound	enthalpy change of formation / kJ mol^{-1}
$HCl(g)$	–92
$H_2O(g)$	–242

enthalpy change of reaction = ... kJ mol^{-1} [2]

(ii) State the **type** of catalyst used in this reaction. Explain how a catalyst is able to increase the rate of a chemical reaction.

....

....

....

.... [2]

3 Sulfuric acid is manufactured by the Contact process.

One stage in this process is the conversion of sulfur dioxide into sulfur trioxide in the presence of a heterogeneous catalyst of vanadium(V) oxide, V_2O_5.

$$2\,O{=}S{=}O(g) \;+\; O{=}O(g) \rightleftharpoons 2\,O{=}\overset{\overset{\displaystyle O}{\|}}{S}{=}O(g) \qquad \Delta H = -196\,\text{kJ}\,\text{mol}^{-1}$$

(a) **(i)** State the effect of a catalyst on a reaction.
Explain how a catalyst causes this effect.

....

....

....

.... [2]

(ii) State the meaning of the term *heterogeneous* as applied to catalysts.

....

....

.... [1]

4 **(c)** SO_3 is produced by the reaction between SO_2 and O_2 in the Contact process. A dynamic equilibrium is established.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H = -196\,kJ\,mol^{-1}$$

(i) Explain why increasing the total pressure, at constant temperature, increases the rate of production of SO_3 and increases the yield of SO_3.

rate ....

....

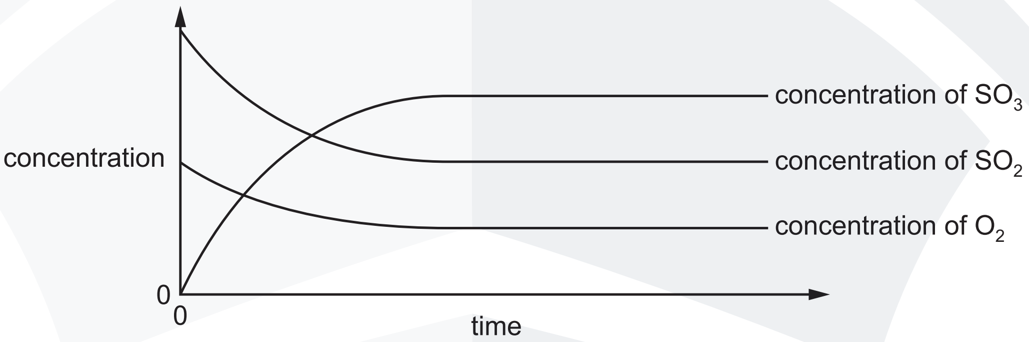
....

yield ....

....

.... [4]

The graph shows how the concentrations of all three species in the system change with time for a typical reaction mixture. The gradients of all three lines decrease with time and then level off in this dynamic equilibrium.



(ii) Explain why the gradients of the SO_2 and O_2 lines decrease with time.

....

.... [2]

(iii) Explain why all three lines become horizontal.

....

.... [1]

(iv) Suggest a reason why the initial gradient of the SO_2 line is steeper than that of the O_2 line.

....

....

.... [1]

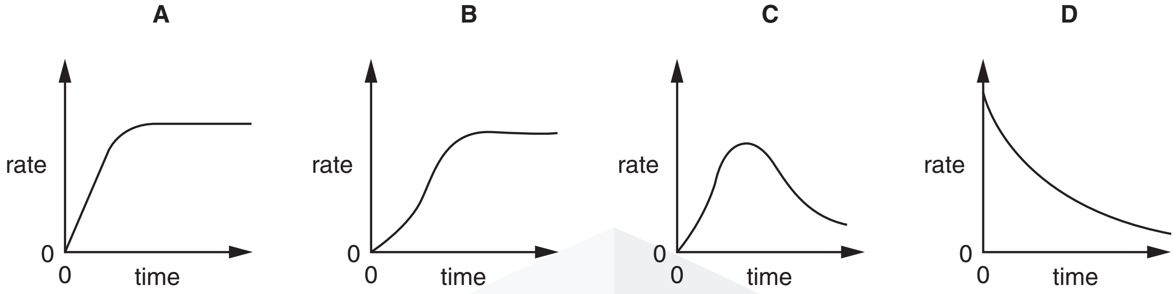
[J'18 P23 Q1]

5

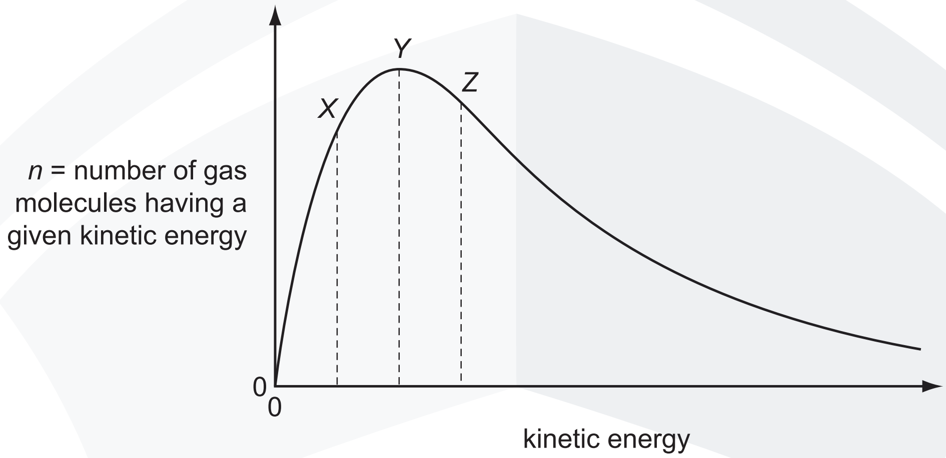
REACTION KINETICS WS 3

SECTION A

1 Which curve is obtained if the rate of reaction is plotted against time for an autocatalytic reaction (i.e. a reaction in which one of the products catalyses the reaction)?



2 The Boltzmann distribution for a gas at constant temperature is shown below.



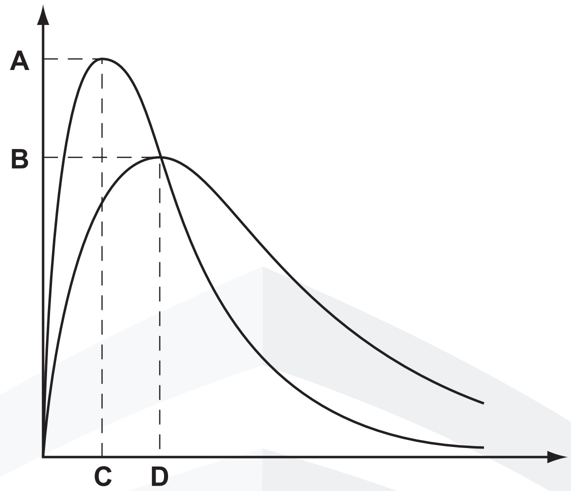
If the temperature of the gas is **reduced** by 10 °C the graph changes shape.

What happens to the values of *n* for the points marked *X*, *Y* and *Z*?

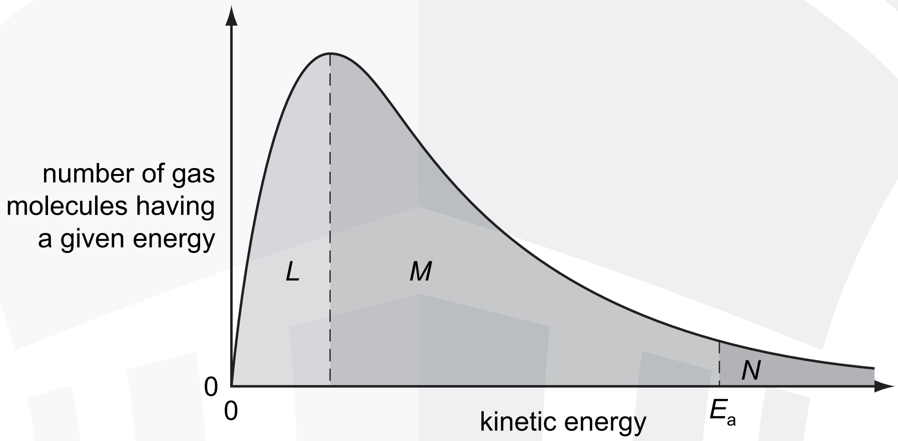
	X	*Y*	*Z*
A	higher	lower	higher
B	higher	lower	lower
C	lower	higher	lower
D	lower	lower	lower

3 The diagram shows the Maxwell-Boltzmann energy distribution curves for molecules of a sample of a gas at two different temperatures.

Which letter on the axes represents the most probable energy of the molecules at the lower temperature?



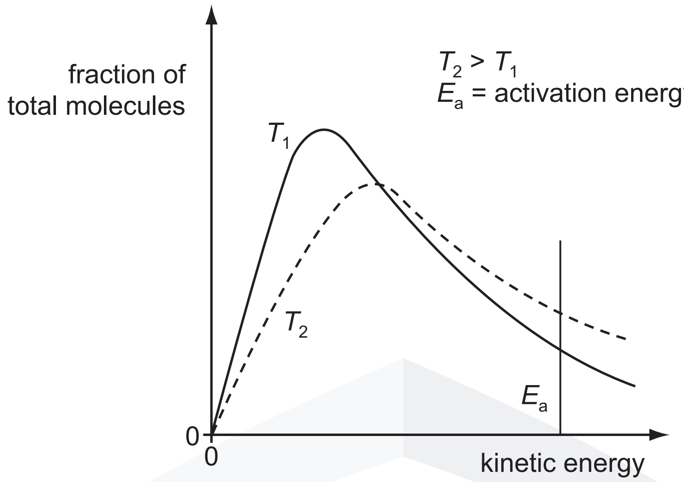
4 The Boltzmann distribution shows the number of molecules having a particular kinetic energy at constant temperature.



If the temperature is decreased by 10 °C, what happens to the size of the areas labelled *L*, *M* and *N*?

	L	*M*	*N*
A	decreases	decreases	decreases
B	decreases	increases	decreases
C	increases	decreases	decreases
D	increases	decreases	increases

5 The distribution of molecular kinetic energies within a gas at temperature T_1 and T_2 are shown in the diagram.



Which statement correctly explains why a small increase in temperature leads to a significant increase in the rate of a gaseous reaction?

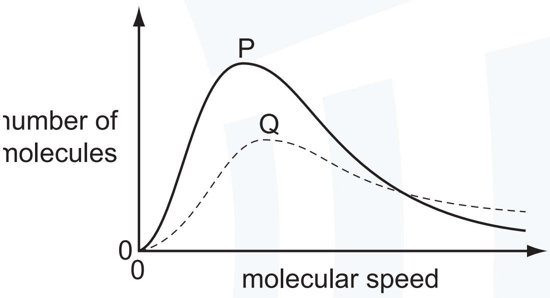
A The frequency of collisions between molecules is greater at a higher temperature.

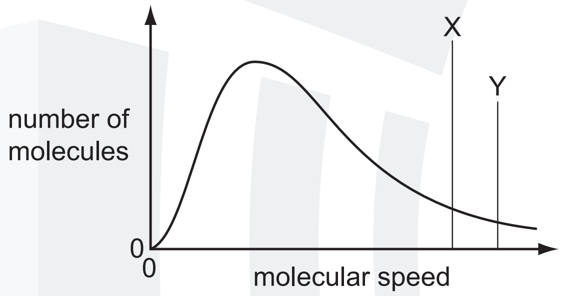
B The activation energy of the reaction is less when the gases are at a higher temperature.

C The frequency of collisions between molecules with kinetic energy greater than the activation energy is greater at higher temperature.

D The proportion of molecules with more kinetic energy than the activation energy is lower at a higher temperature.

6 Different Boltzmann distributions are shown in the diagrams.





In diagram 1, one curve P or Q corresponds to a temperature higher than that of the other curve.

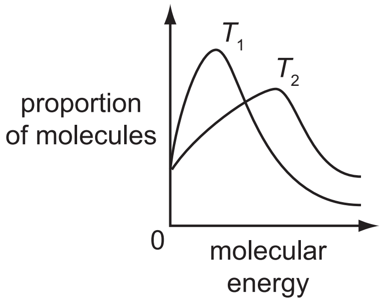
In diagram 2, one line X or Y corresponds to the activation energy for a catalysed reaction and the other line corresponds to the activation energy of the same reaction when uncatalysed.

Which combination gives the correct curve and line?

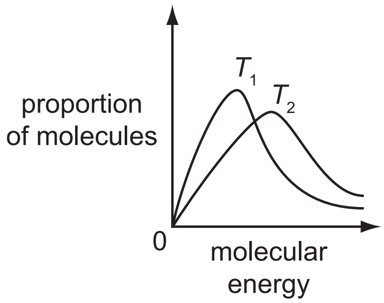
	higher temperature	presence of catalyst
A	P	X
B	P	Y
C	Q	X
D	Q	Y

7 Which diagram correctly represents the Boltzmann distribution of molecular energies at two temperatures T_1 and T_2, where T_1 = 300 K and T_2 = 310 K?

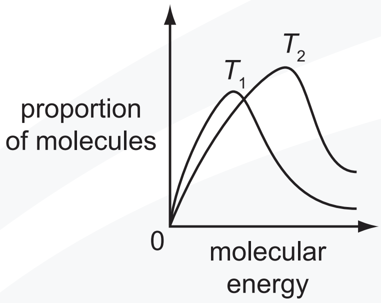
A



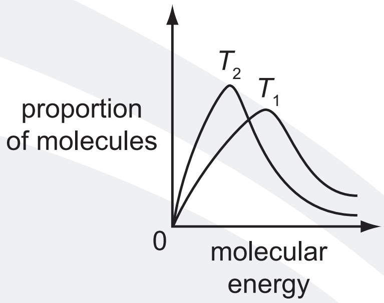
B



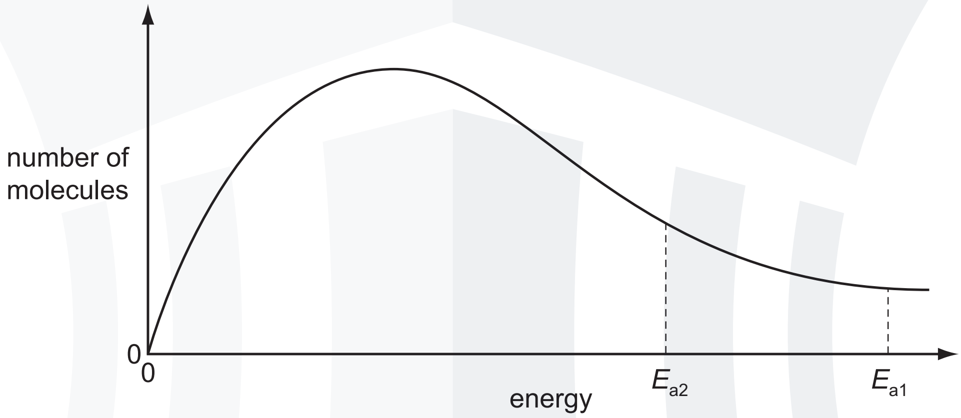
C



D



8 The diagram shows the Maxwell-Boltzmann energy distribution curve for molecules of a mixture of two gases at a given temperature. For a reaction to occur the molecules must collide together with sufficient energy.

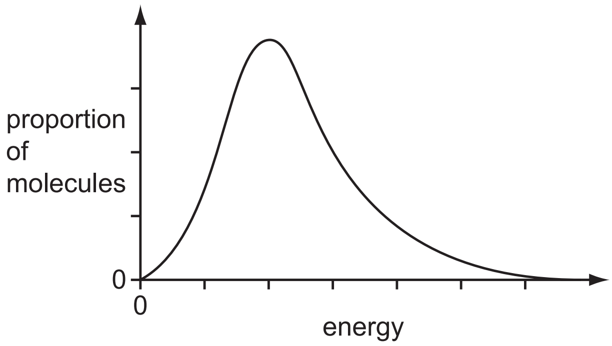


E_a is the activation energy for the reaction between the gases. Of the two values shown, one is for a catalysed reaction, the other for an uncatalysed one.

Which pair of statements is correct when a catalyst is used?

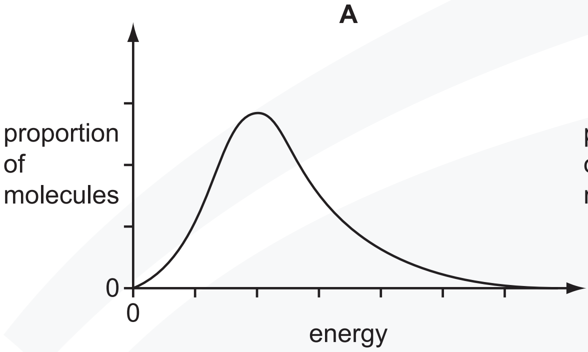
A	E_{a1} catalysed reaction fewer effective collisions	E_{a2} uncatalysed reaction more effective collisions
B	E_{a1} uncatalysed reaction fewer effective collisions	E_{a2} catalysed reaction more effective collisions
C	E_{a1} catalysed reaction more effective collisions	E_{a2} uncatalysed reaction fewer effective collisions
D	E_{a1} uncatalysed reaction more effective collisions	E_{a2} catalysed reaction fewer effective collisions

9 The molecular energy distribution curve represents the variation in energy of the molecules of a gas at room temperature.

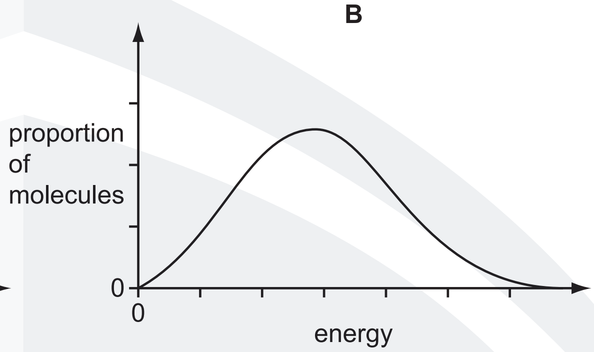


Which curve applies for the same gas at a lower temperature?

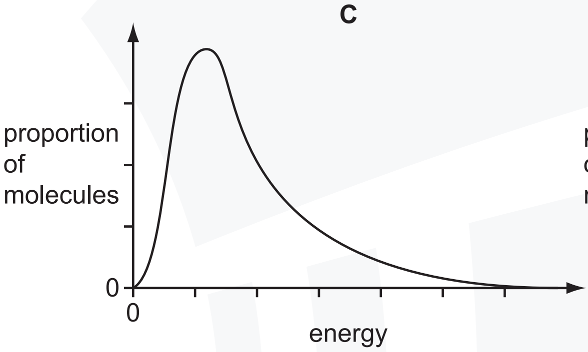
A



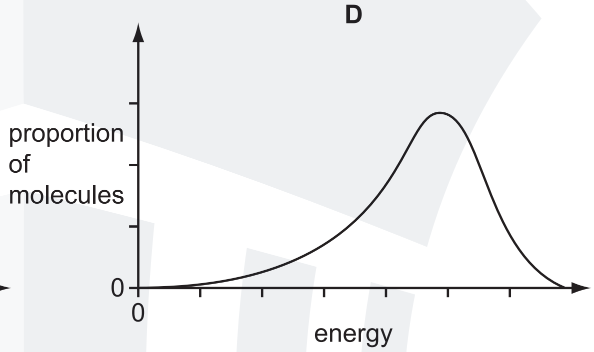
B



C



D

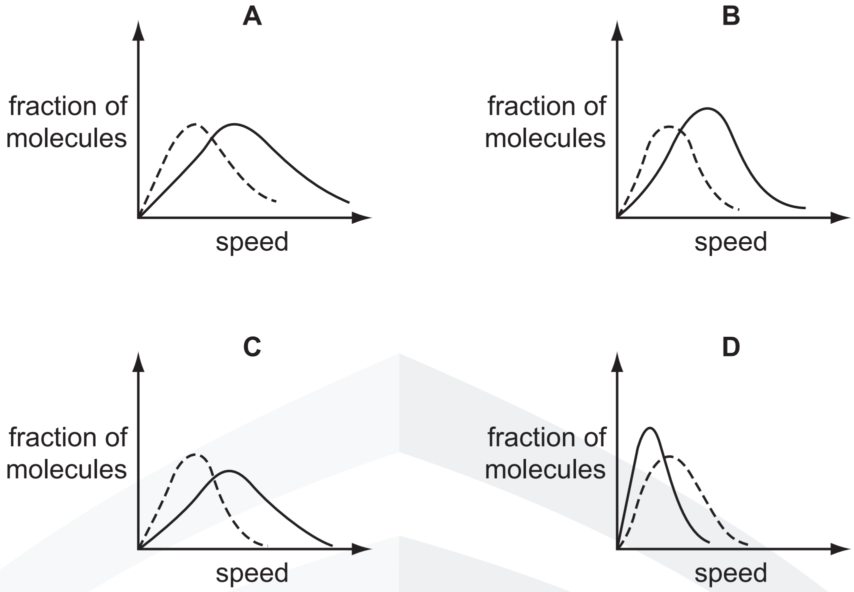


10 A piece of zinc foil dissolved completely in 20 cm^3 of a dilute sulphuric acid solution and the volume of hydrogen evolved was noted at equal, short time intervals. Another piece of zinc foil of the same surface area and mass was added to 40 cm^3 of the same solution of dilute sulphuric acid.

How will the initial rate of reaction and the total volume of hydrogen evolved in this second experiment compare to the first experiment?

	initial rate of reaction	*total volume of hydrogen evolved*
A	no change	decrease
B	no change	no change
C	increase	no change
D	increase	increase

11 Which solid-line curve most accurately represents the distribution of molecular speeds in a gas at 500 K if the dotted-line curve represents the corresponding distribution for the same gas at 300 K?



12 Crotonaldehyde, $CH_3CH{=}CHCHO$, can be obtained by oxidising butadiene, $CH_2{=}CHCH{=}CH_2$, using air or oxygen. One method is to pass a mixture of butadiene and oxygen through a hot aqueous solution of palladium(II) ions, $Pd^{2+}(aq)$, which catalyse the reaction.

Which statement is **not** correct about the action of the $Pd^{2+}(aq)$ ions?

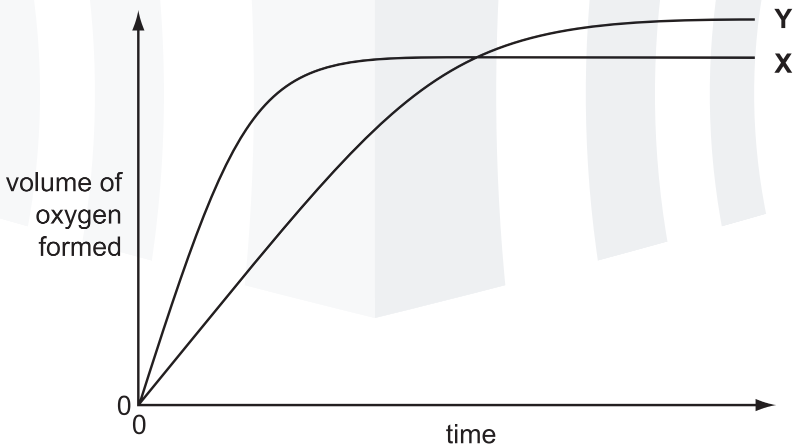
A Changing the concentration of the $Pd^{2+}(aq)$ will have an effect on the rate of the reaction.

B $Pd^{2+}(aq)$ increases the energy of the reacting molecules.

C $Pd^{2+}(aq)$ lowers the activation energy for the reaction.

D When $Pd^{2+}(aq)$ is used, the reaction proceeds by a different route.

13 In the diagram, curve **X** was obtained by observing the decomposition of 100 cm^3 of 1.0 $mol\,dm^{-3}$ hydrogen peroxide, catalysed by manganese(IV) oxide.



Which alteration to the original experimental conditions would produce curve **Y**?

A adding water

B adding some 0.1 $mol\,dm^{-3}$ hydrogen peroxide

C using less manganese(IV) oxide

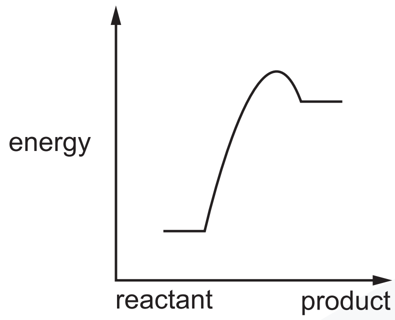
D lowering the temperature

14 Four reactions of the type shown are studied at the same temperature.

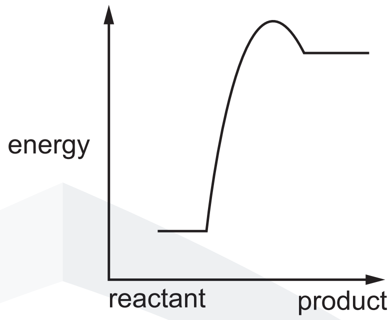
$$X(g) + Y(g) \rightarrow Z(g)$$

Which is the correct reaction pathway diagram for the reaction that would proceed most rapidly and with good yield?

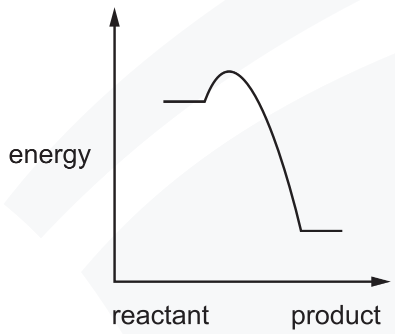
A



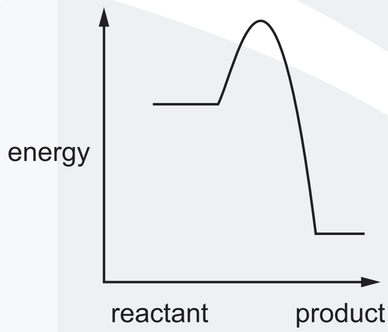
B



C



D



15 It is often said that the rate of a typical reaction is roughly doubled by raising the temperature by 10 °C.

What explains this observation?

A Raising the temperature by 10 °C doubles the average energy of each molecule.

B Raising the temperature by 10 °C doubles the average velocity of the molecules.

C Raising the temperature by 10 °C doubles the number of molecular collisions in a given time.

D Raising the temperature by 10 °C doubles the number of molecules having more than a certain minimum energy.

16 Crotonaldehyde, $CH_3CH{=}CHCHO$, can be obtained by oxidising butadiene, $CH_2{=}CHCH{=}CH_2$, using air or oxygen. One method is to pass a mixture of butadiene and oxygen through a hot aqueous solution of palladium(II) ions, $Pd^{2+}(aq)$, which catalyse the reaction.

Which statement is **not** correct about the action of the $Pd^{2+}(aq)$ ions?

A Changing the concentration of the $Pd^{2+}(aq)$ will have an effect on the rate of the reaction.

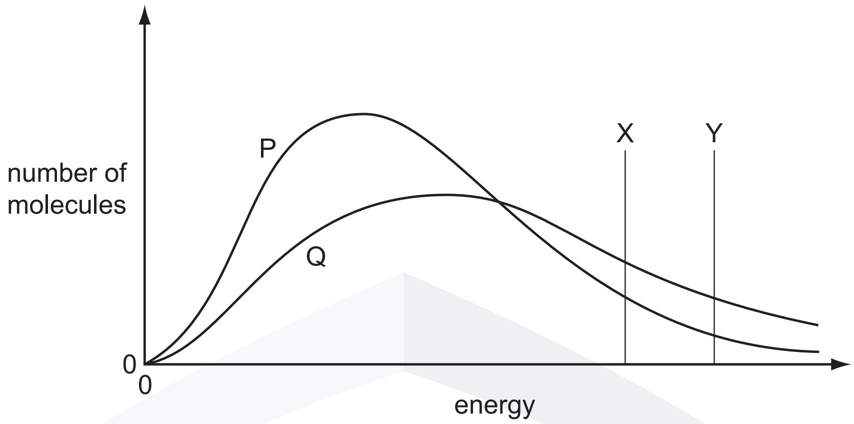
B $Pd^{2+}(aq)$ increases the energy of the reacting molecules.

C $Pd^{2+}(aq)$ lowers the activation energy for the reaction.

D $Pd^{2+}(aq)$ provides a different route for the reaction.

17 The gaseous compound Z decomposes on heating.

In the diagram below, Boltzmann distributions for Z at two different temperatures P and Q are shown. The lines X and Y indicate activation energies for the decomposition of Z with and without a catalyst.



Which curve and which line describe the decomposition of Z at a higher temperature and with a catalyst present?

	higher temperature	catalyst present
A	P	X
B	P	Y
C	Q	X
D	Q	Y

18 Why does the rate of a gaseous reaction increase when the pressure is increased at a constant temperature?

A More particles have energy that exceeds the activation energy.

B The particles have more space in which to move.

C The particles move faster.

D There are more frequent collisions between particles.

19 Which factor can affect the value of the activation energy of a reaction?

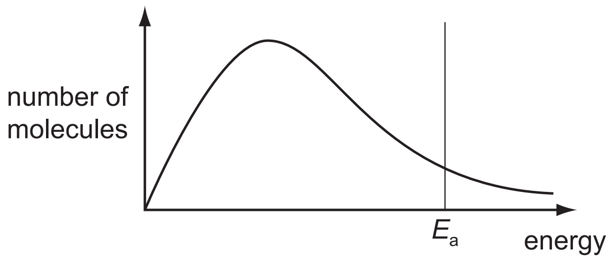
A changes in concentration of the reactants

B decrease in temperature

C increase in temperature

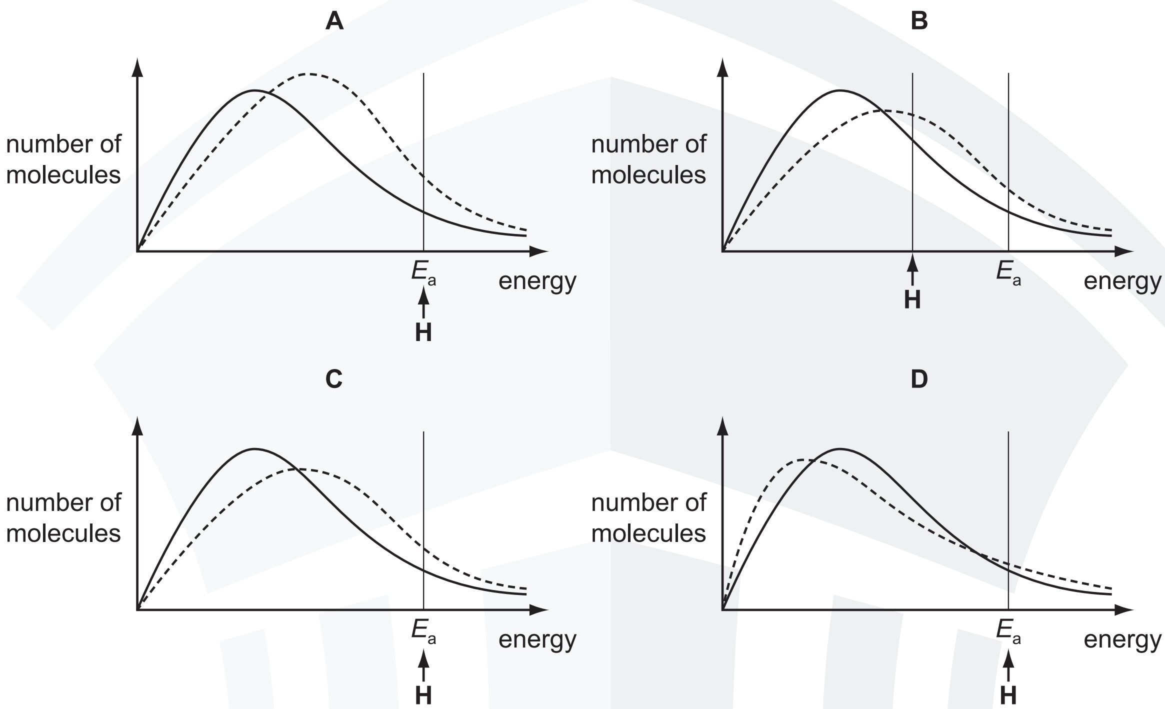
D the presence of a catalyst

20 The diagram represents, for a given temperature, the Boltzmann distribution of the kinetic energies of the molecules in a mixture of two gases that will react together. The activation energy for the reaction, E_a , is marked.



The dotted curves below show the Boltzmann distribution for the same reaction at a higher temperature. On these diagrams, **H** represents the activation energy at the higher temperature.

Which diagram is correct?



21 Butanedioate ions can be dehydrogenated to form *trans*-butenedioate ions. The enzyme fumarase speeds up this reaction.

Why does fumarase speed up this reaction?

A Fumarase is a protein.

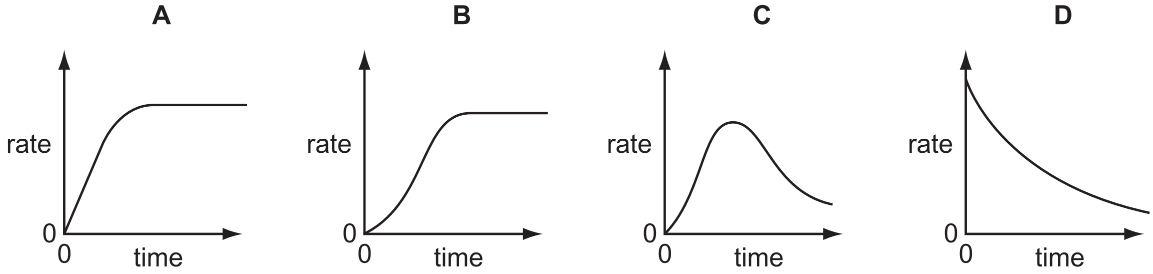
B Fumarase is effective at body temperature.

C Fumarase lowers the activation energy of the dehydrogenation reaction.

D The enzyme fumarase is specific for this dehydrogenation reaction.

22 An autocatalytic reaction is a reaction in which one of the products catalyses the reaction.

Which curve was obtained if the rate of reaction was plotted against time for an autocatalytic reaction?

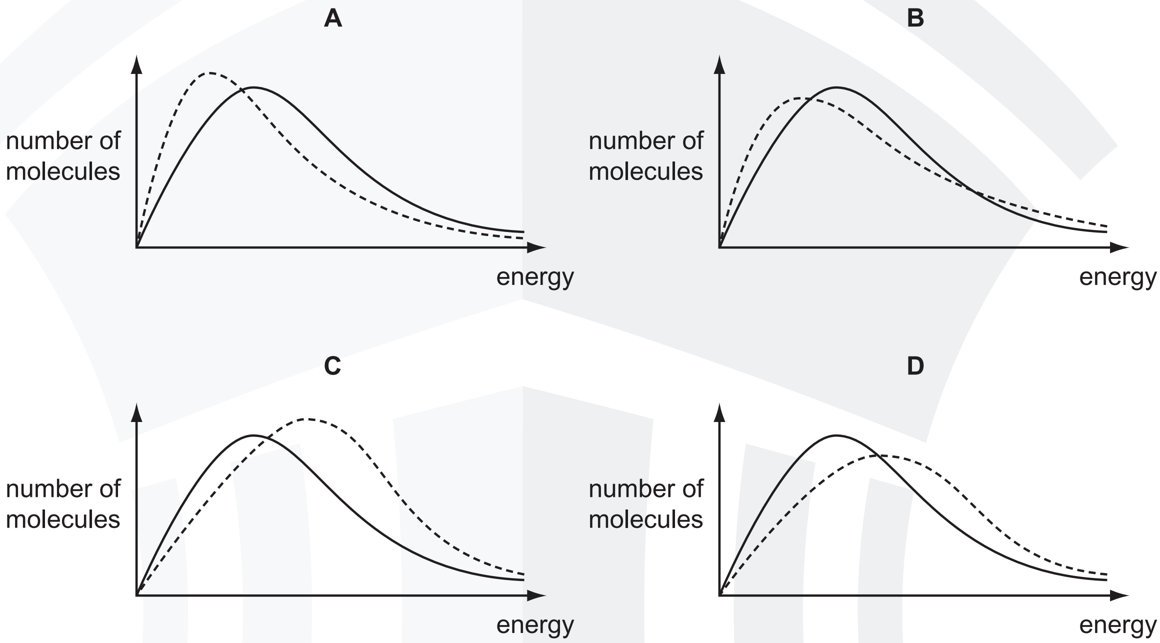


23 The diagrams below show the Boltzmann distribution for air at two temperatures.

The solid line represents the distribution at –20 °C.

The dotted line represents the distribution at –10 °C.

Which diagram is correct?



24 $Na_2S_2O_3$ reacts with dilute HC*l* to give a pale yellow precipitate. If 1 cm^3 of 0.1 mol dm^{-3} HC*l* is added to 10 cm^3 of 0.02 mol dm^{-3} $Na_2S_2O_3$ the precipitate forms slowly.

If the experiment is repeated with 1 cm^3 of 0.1 mol dm^{-3} HC*l* and 10 cm^3 of 0.05 mol dm^{-3} $Na_2S_2O_3$ the precipitate forms more quickly.

Why is this?

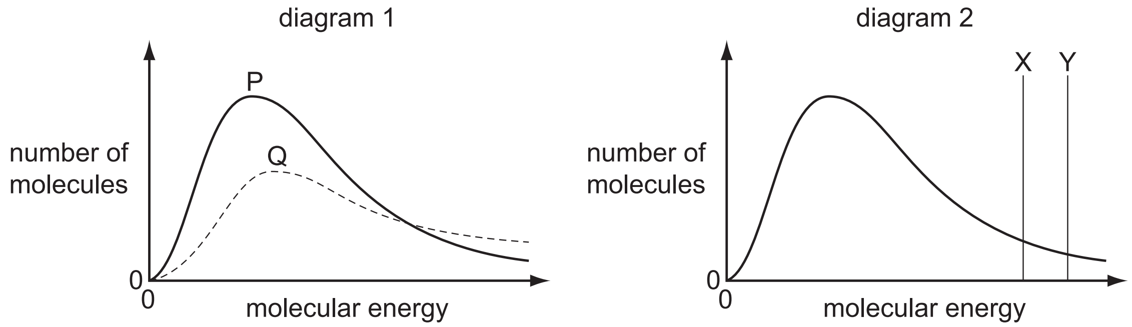
A The activation energy of the reaction is lower when 0.05 mol dm^{-3} $Na_2S_2O_3$ is used.

B The collisions between reactant particles are more violent when 0.05 mol dm^{-3} $Na_2S_2O_3$ is used.

C The reactant particles collide more frequently when 0.05 mol dm^{-3} $Na_2S_2O_3$ is used.

D The reaction proceeds by a different pathway when 0.05 mol dm^{-3} $Na_2S_2O_3$ is used.

25 Boltzmann distributions are shown in the diagrams.



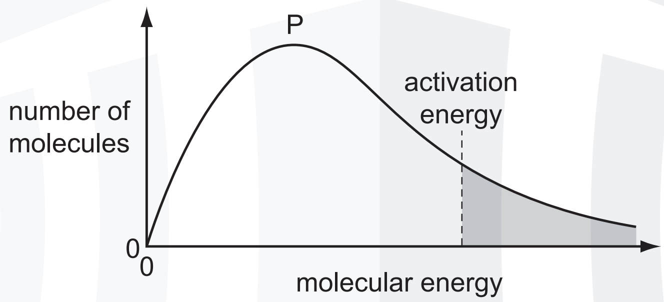
In diagram 1, one curve, P or Q, corresponds to a temperature higher than that of the other curve.

In diagram 2, one line, X or Y, corresponds to the activation energy in the presence of a catalyst and the other line corresponds to the activation energy of the same reaction in the absence of a catalyst.

Which combination gives the correct curve and line?

	higher temperature	presence of catalyst
A	P	X
B	P	Y
C	Q	X
D	Q	Y

26 The diagram shows a Boltzmann distribution of molecular energies for a gaseous mixture. The distribution has a peak, labelled P on the diagram.



What happens when the temperature of the mixture increases?

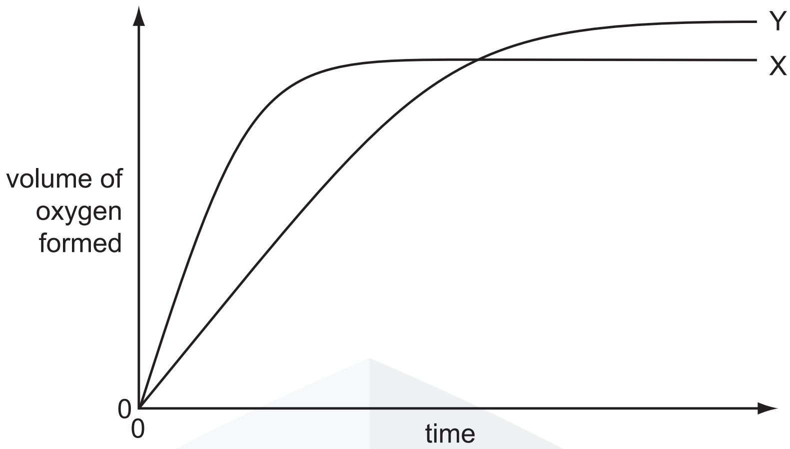
A The height of the peak, P, decreases and the activation energy moves to the left.

B The height of the peak, P, decreases and the activation energy moves to the right.

C The height of the peak, P, decreases and the activation energy does not change.

D The height of the peak, P, increases and the activation energy moves to the left.

27 In the diagram, curve X was obtained by observing the decomposition of $100\,cm^3$ of $1.0\,mol\,dm^{-3}$ hydrogen peroxide, catalysed by manganese(IV) oxide.



Which alteration to the original experimental conditions would produce curve Y?

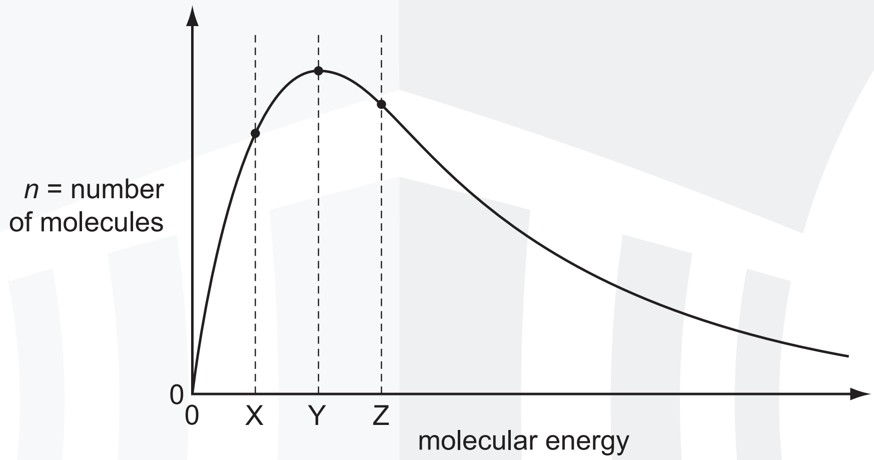
A adding more manganese(IV) oxide

B adding some $0.1\,mol\,dm^{-3}$ hydrogen peroxide

C adding water

D raising the temperature

28 The Boltzmann distribution for a gas at constant temperature is shown below.



If the temperature of the gas is **reduced** by 10 °C the graph changes shape.

What happens to the values of *n* for the molecular energies X, Y and Z?

	X	Y	Z
A	higher	lower	higher
B	higher	lower	lower
C	lower	higher	lower
D	lower	lower	lower

29 Hydrazine, N_2H_4, is used as a rocket fuel because it reacts with oxygen as shown, producing 'environmentally friendly' gases.

$$N_2H_4(l) + O_2(g) \rightarrow N_2(g) + 2H_2O(g) \qquad \Delta H = -534\,kJ\,mol^{-1}$$

Despite its use as a rocket fuel, hydrazine does not burn spontaneously in oxygen.

Which statement explains why hydrazine does **not** burn spontaneously?

A Hydrazine is a liquid.

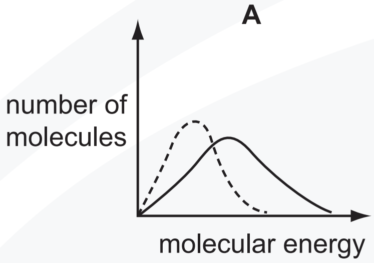
B The activation energy is too high.

C The N≡N bond is very strong.

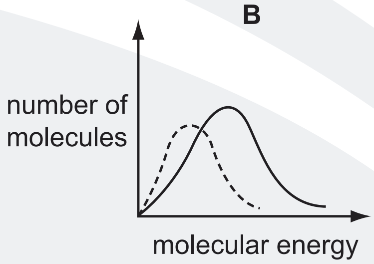
D The reaction is exothermic.

30 Which solid-line curve most accurately represents the distribution of molecular energies in a gas at 500 K if the dotted-line curve represents the corresponding distribution for the same gas at 300 K?

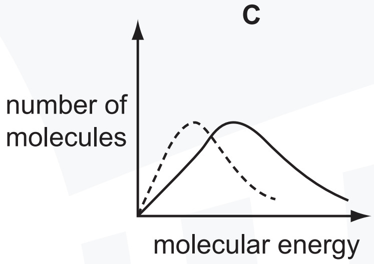
A



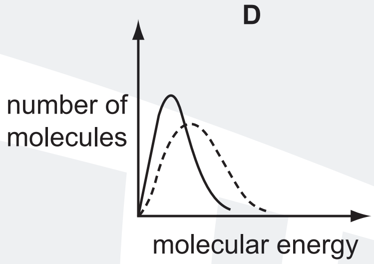
B



C



D

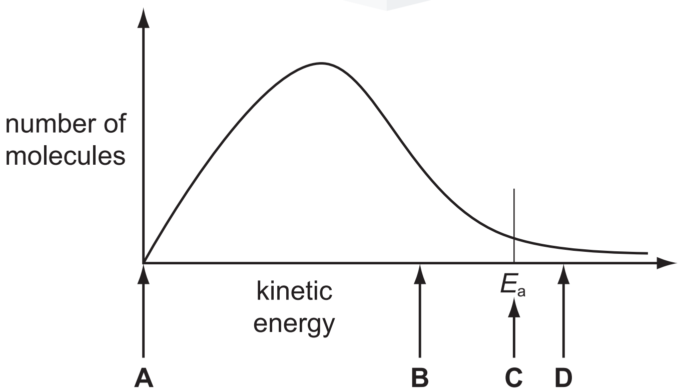


31 The diagram below represents, for a given temperature, the Boltzmann distribution of the kinetic energy of the molecules in a mixture of two gases that react slowly together.

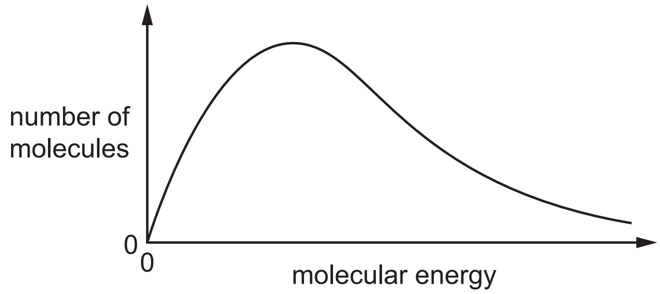
The activation energy for the reaction, E_a, is marked.

When the reaction is catalysed, the rate of reaction increases a little.

What will be the position of E_a for the catalysed reaction?



32 The Boltzmann distribution below shows the distribution of molecular energies in a sample of a gas at a given temperature.



Which statement correctly describes the change in such a distribution if the temperature is increased?

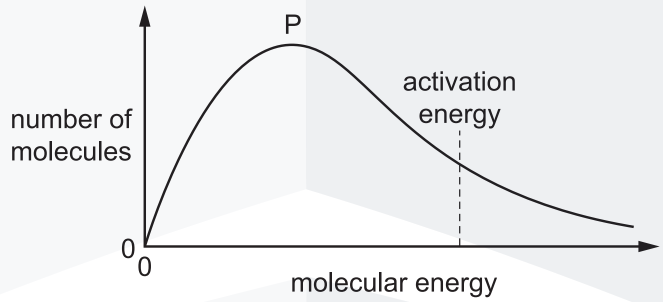
A Fewer molecules possess the most probable energy value and this value shifts to the left.

B Fewer molecules possess the most probable energy value and this value shifts to the right.

C More molecules possess the most probable energy value and this value shifts to the left.

D The area under the curve of the distribution increases.

33 The diagram shows a Boltzmann distribution of molecular energies for a gaseous mixture. The distribution has a peak, labelled P on the diagram.



What happens when an effective catalyst is added to the mixture?

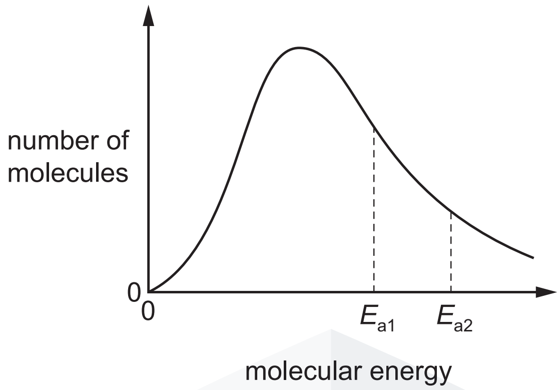
A The height of the peak decreases and the activation energy moves to the right.

B The height of the peak decreases and the activation energy moves to the left.

C The height of the peak remains the same and the activation energy moves to the right.

D The height of the peak remains the same and the activation energy moves to the left.

34 The diagram shows the Boltzmann energy distribution curve for molecules of a mixture of two gases at a given temperature. For a reaction to occur the molecules must collide together with sufficient energy.



E_a is used to represent the activation energy for the reaction between the gases. Of the two values shown, one is the activation energy for a catalysed reaction, the other for an uncatalysed reaction.

Which statement about $\boldsymbol{E_{a1}}$ is correct?

A E_{a1} corresponds to a catalysed reaction with fewer effective collisions than the uncatalysed reaction.

B E_{a1} corresponds to an uncatalysed reaction with fewer effective collisions than the catalysed reaction.

C E_{a1} corresponds to a catalysed reaction with a greater number of effective collisions than the uncatalysed reaction.

D E_{a1} corresponds to an uncatalysed reaction with a greater number of effective collisions than the catalysed reaction.

35 Which row correctly describes what happens when the temperature of a chemical reaction is **decreased**?

	activation energy (E_a)	number of successful collisions
A	decreases	decreases
B	decreases	increases
C	remains the same	decreases
D	remains the same	increases

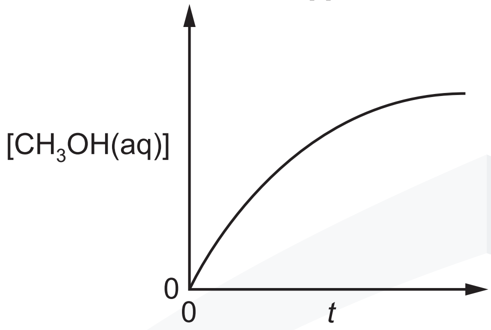
36 The following reaction was carried out.

$$HCO_2CH_3(aq) + NaOH(aq) \rightarrow HCO_2Na(aq) + CH_3OH(aq)$$

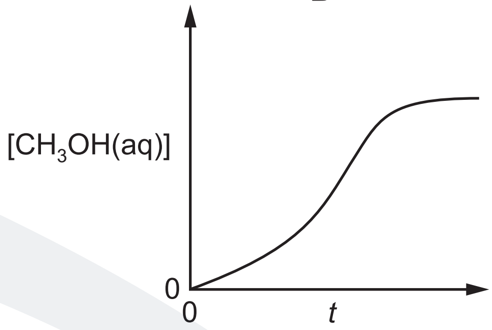
The concentration of methanol, $[CH_3OH(aq)]$, was measured with time, t.

Which graph shows the relationship between $[CH_3OH(aq)]$ and t?

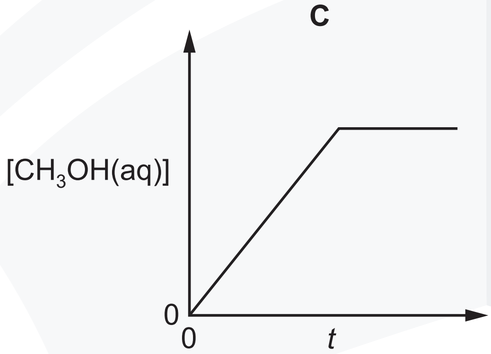
A



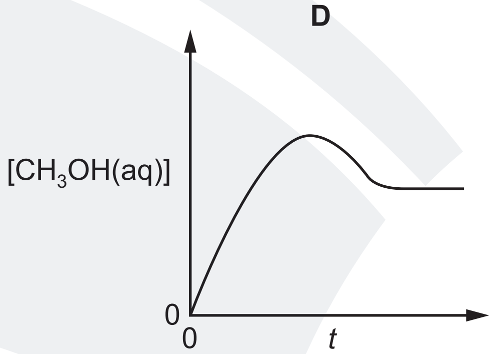
B



C



D



37 Which set of conditions gives the highest yield of ammonia at equilibrium?

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

	catalyst	pressure	temperature
A	absent	high	low
B	absent	low	high
C	present	high	high
D	present	low	low

38 Ammonia is made by the Haber process. The reactants are nitrogen and hydrogen.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H \text{ –ve}$$

What will increase the rate of the forward reaction?

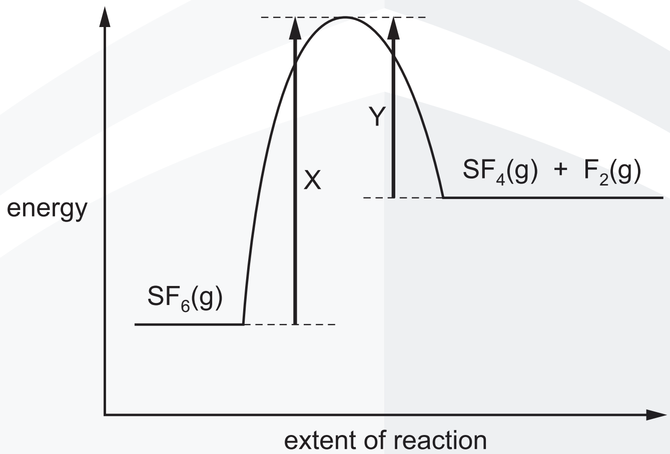
A adding argon to the mixture but keeping the total volume constant

B decreasing the temperature

C increasing the total pressure by reducing the total volume at constant temperature

D removing ammonia as it is made but keeping the total volume of the mixture the same

39 The decomposition reaction $SF_6(g) \rightarrow SF_4(g) + F_2(g)$ can be described by the reaction pathway diagram shown.



What are the values of ΔH° and E_a for this reaction?

	ΔH°	E_a
A	X	X + Y
B	X	Y
C	X – Y	X
D	Y – X	X

40 Which row correctly describes what happens when the temperature of a chemical reaction is **decreased**?

	activation energy (E_a)	number of successful collisions
A	decreases	decreases
B	decreases	increases
C	remains the same	decreases
D	remains the same	increases

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 Which statements correctly describe an effect of a rise in temperature on a gas-phase reaction?

1 More particles now have energies greater than the activation energy.

2 The energy distribution profile changes with more particles having the most probable energy.

3 The activation energy of the reaction is decreased.

2 A chemist puts a sample of dilute aqueous hydrochloric acid into beaker 1. She adds a sample of zinc and measures the rate of production of hydrogen gas.

She then puts a different sample of dilute aqueous hydrochloric acid into beaker 2. She adds a different sample of zinc and measures the rate of production of hydrogen gas.

The rate of the reaction in beaker 2 is greater than the rate of the reaction in beaker 1.

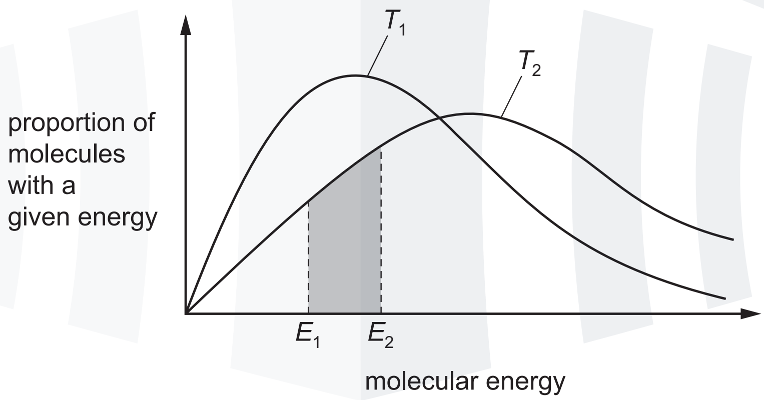
Which factors **could** help to explain this observation?

1 The reaction in beaker 1 has a higher activation energy than the reaction in beaker 2.

2 The zinc in beaker 1 is in larger pieces than the zinc in beaker 2.

3 The acid in beaker 1 is at a lower concentration than the acid in beaker 2.

3 The diagram shows the Boltzmann distribution of molecular energies in one mole of a gas at two temperatures, T_1 and T_2.



Which statements are correct?

1 The shaded area represents the proportion of molecules with energies between E_1 and E_2 at temperature T_2.

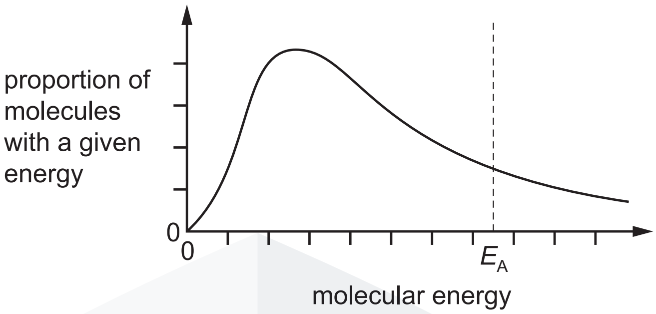
2 No particles have zero energy at either temperature.

3 T_2 is a lower temperature than T_1.

4 The equation shows a gas phase reaction.

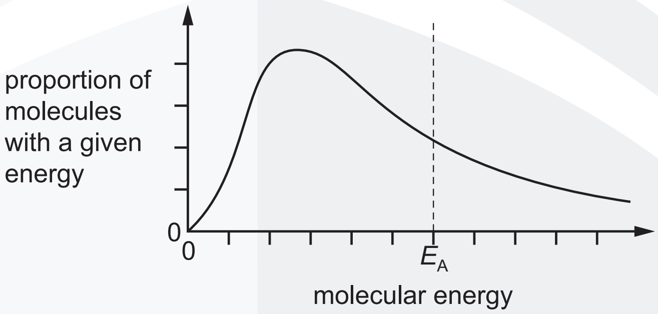
$$X(g) \rightarrow 2Y(g)$$

The diagram shows the Boltzmann distribution of a fixed mass of X(g) at temperature T in the absence of a catalyst. The line E_A indicates the activation energy.

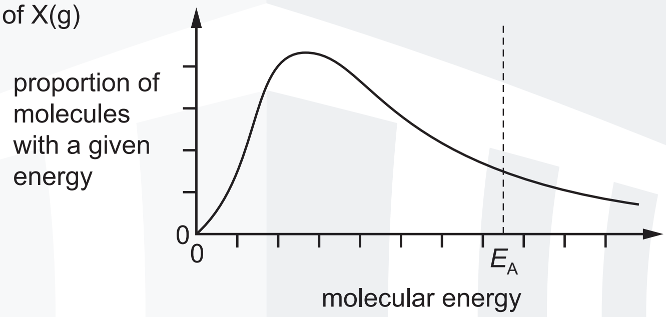


Which diagrams correctly show the effect of the following changes made separately and independently?

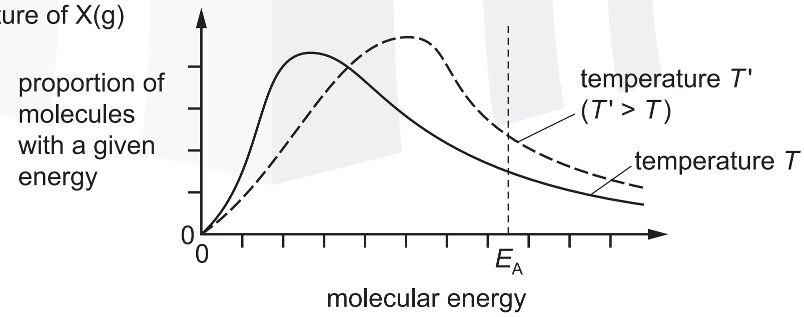
1 adding a catalyst



2 increasing the pressure of X(g)



3 increasing the temperature of X(g)



5 Three test-tubes, X, Y, and Z, each contain a small amount of water.

- A small amount of $NaCl$ is added to test-tube X.
- A small amount of $SiCl_4$ is added to test-tube Y.
- A small amount of $AlCl_3$ is added to test-tube Z.

After a short time, two drops of Universal Indicator solution are added to each test-tube.

Which observations are made?

1 The indicator added to test-tube X stays green.

2 The indicator added to test-tube Y turns red.

3 The indicator added to test-tube Z turns red.

6 Sulfur dioxide and oxygen react in the gas phase.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H = -197\,kJ\,mol^{-1}$$

Which statements are correct?

1 Increasing the pressure increases the equilibrium yield of SO_3.

2 Increasing the temperature lowers the value of the equilibrium constant K_p.

3 The presence of a vanadium(V) oxide catalyst increases the equilibrium yield of SO_3.

7 The rate of chemical reactions can be increased by the addition of a suitable catalyst.

For which reactions can a heterogeneous catalyst be used?

1 $N_2 + 3H_2 \rightleftharpoons 2NH_3$

2 $2SO_2 + O_2 \rightleftharpoons 2SO_3$

3 $2NO + 2CO \rightleftharpoons N_2 + 2CO_2$

8 A container is partially filled with hot water, sealed and left to cool.

Which statements are correct?

1 As the temperature decreases, water molecules lose kinetic energy.

2 As the temperature decreases, more water molecules move from vapour to liquid.

3 As the temperature decreases, the vapour pressure of the water decreases.

[M'18 P12 Q13]

9 The temperature of a reversible gas phase reaction is increased.

Which statements are **always** correct?

1 More product is present at equilibrium.

2 The average speed of the particles increases.

3 There are more successful collisions per unit time.

[J'18 P12 Q34]

REACTION KINETICS WS 4

1 **(a)** Draw a diagram to show the Boltzmann distribution of molecular energies. Label the axes.

[2]

(b) Comment on the shape of the distribution curve.

....

....

....

....[1]

(c) **(i)** Explain the meaning of the term *activation energy*.

....

....

....

....

(ii) Insert and label the activation energy in your diagram in **(a)**. [2]

(d) **(i)** Use a dotted line added to your diagram in **(a)** to show how the distribution of molecular energies changes at a slightly higher temperature (label this curve $+\delta T$).

(ii) Use this new line to explain why reactions are faster at a higher temperature.

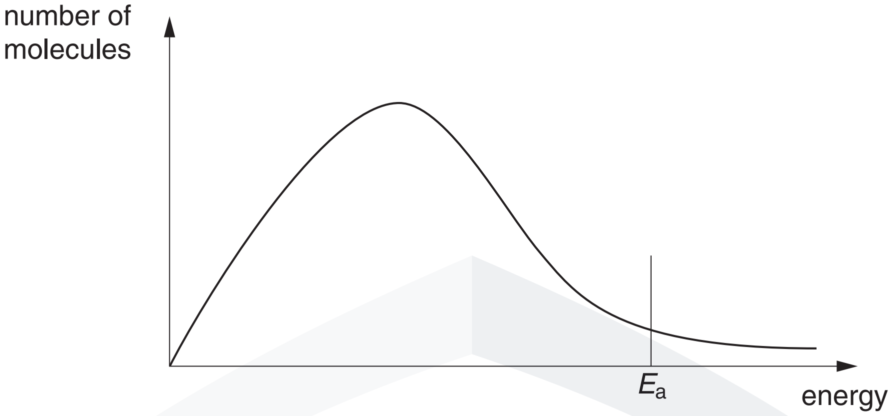
....

....

....

....[3]

2 The diagram below shows, for a given temperature T, a Boltzmann distribution of the kinetic energy of the molecules of a mixture of two gases that will react together, such as nitrogen and hydrogen.
The activation energy for the reaction, E_a, is marked.



(a) **On the graph above,**

(i) draw a new distribution curve, **clearly labelled T′**, for the same mixture of gases at a higher temperature, **T′**;

(ii) **mark clearly, as H**, the position of the activation energy of the reaction at the higher temperature, **T′**.

[3]

(b) Explain the meaning of the term *activation energy*.

....

....

....

.... [2]

The reaction between nitrogen and hydrogen to produce ammonia in the Haber process is an example of a large-scale gaseous reaction that is catalysed.

(c) **(i)** State the catalyst used and give the operating temperature and pressure of the Haber process.

catalyst ....

temperature ....

pressure ....

(ii) **On the energy axis of the graph opposite**, mark the position, **clearly labelled C**, of the activation energy of the reaction when a catalyst is used.

(iii) Use your answer to **(ii)** to explain how the use of a catalyst results in reactions occurring at a faster rate.

....

....

....

[3]

(d) Two reactions involving aqueous NaOH are given below.

$CH_3CHBrCH_3 + NaOH \rightarrow CH_3CH(OH)CH_3 + NaBr$ **reaction 1**

$HCl + NaOH \rightarrow NaCl + H_2O$ **reaction 2**

In order for **reaction 1** to occur, the reagents must be heated together for some time. On the other hand, **reaction 2** is almost instantaneous at room temperature.

Suggest brief explanations why the rates of these two reactions are very different.

reaction 1 ....

....

....

reaction 2 ....

....

.... [4]

3 The Haber process for the manufacture of ammonia, NH_3, was originally devised at the start of the 20th century and was developed into a full-scale industrial process by Carl Bosch in 1913.

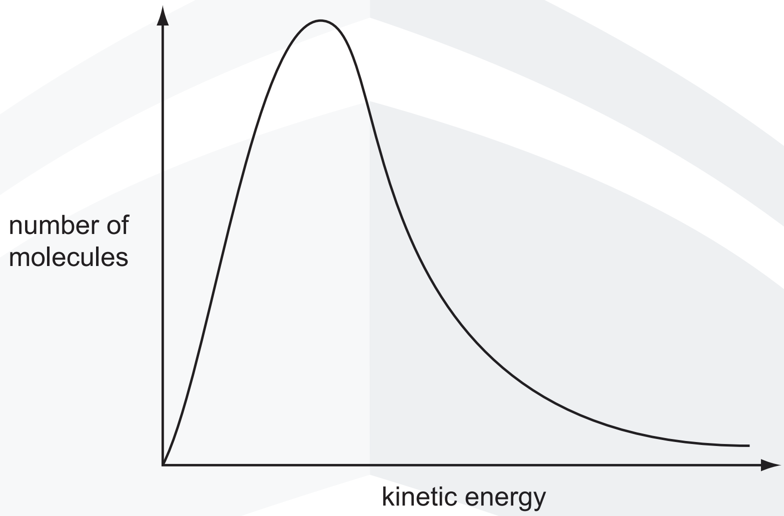
The key step in the process is the reversible reaction of nitrogen and hydrogen in the presence of an iron catalyst.

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

(a) The hydrogen for this reaction can be formed by reacting methane with steam, during which carbon monoxide is also produced. Write an equation for this reaction.

.... [1]

(b) Use the Boltzmann distribution shown to explain why a catalyst increases the rate of this reaction.



....

....

....

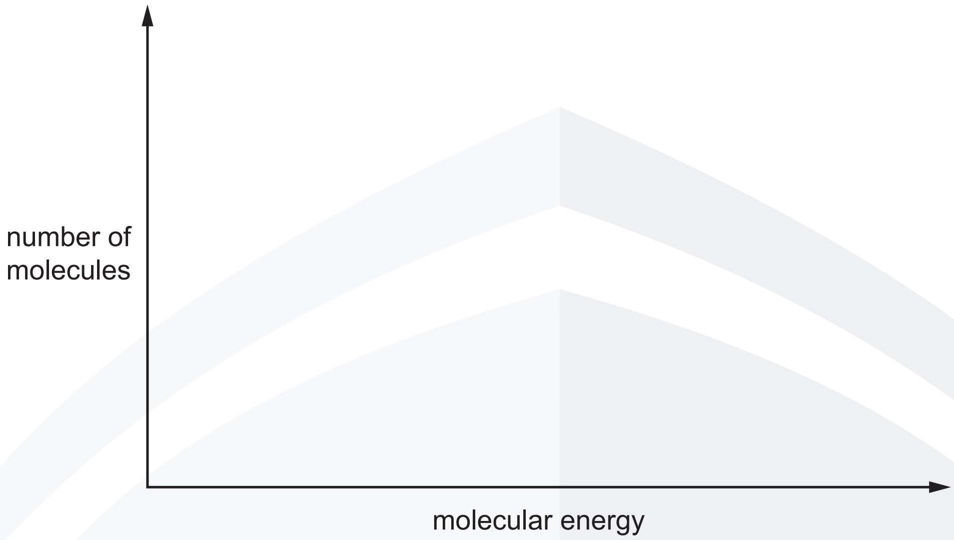
.... [4]

4 Over one million tonnes of hydrogen cyanide, HCN, are produced each year using the Andrussow process. The overall equation for the reaction is shown.

$$CH_4(g) + NH_3(g) + 1\tfrac{1}{2}O_2(g) \rightleftharpoons HCN(g) + 3H_2O(g)$$

The process uses a platinum catalyst, which increases the rate of reaction.

Sketch a Boltzmann distribution on the axes given below and use your diagram to explain how the platinum catalyst increases the rate of the reaction.



....

....

....

.... [3]

5 Ammonium nitrate is an important fertiliser made by the acid-base reaction between ammonia and nitric acid.

(a) Write an equation for the production of ammonium nitrate from ammonia and nitric acid.

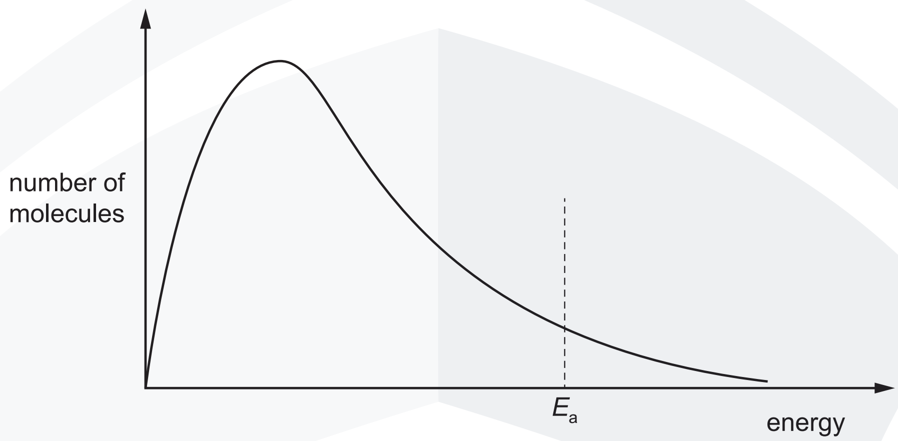
.... [1]

The ammonia for this reaction is produced by the Haber process and the nitric acid is produced by oxidation of ammonia.

(b) The Haber process involves a reaction between nitrogen and hydrogen at a temperature of 450 °C and a pressure of 20 000 kPa. At a higher reaction temperature, the rate of production of ammonia would be greater.

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

The Boltzmann distribution curve shows the distribution of energies in a mixture of nitrogen and hydrogen at 450 °C.



(i) Sketch a second line onto the axes above to show the distribution of energies in the same mixture of gases at a higher temperature. [2]

(ii) With reference to the two curves, explain why the rate of production of ammonia would be greater at a higher temperature.

....

....

.... [2]

(iii) Add a suitable label to the horizontal axis above and use it to explain why a catalyst is used in the Haber process.

....

....

.... [2]

(iv) Explain why a higher temperature is **not** used despite the fact that it would increase the rate of production of ammonia.

....

....

.... [2]

(c) The first stage in the production of nitric acid involves the reaction of ammonia with oxygen to form nitrogen monoxide, NO, and water.

Suggest an equation for this reaction and use oxidation numbers to show that it is a redox reaction.

....

....

....

.... [3]

Period 3

This topic illustrates the regular patterns in chemical and physical properties of the elements in the Periodic Table.

a describe the reactions, if any, of the elements with oxygen (to give Na_2O, MgO, Al_2O_3, P_4O_{10}, SO_2, SO_3), chlorine (to give $NaCl$, $MgCl_2$, Al_2Cl_6, $SiCl_4$, PCl_5) and water (Na and Mg only) ☐

b state and explain the variation in oxidation number of the oxides (sodium to sulfur only) and chlorides (sodium to phosphorus only) in terms of their valence shell electrons ☐

c describe the reactions of the oxides with water (treatment of peroxides and superoxides is not required) ☐

d describe and explain the acid/base behaviour of oxides and hydroxides including, where relevant, amphoteric behaviour in reaction with acids and bases (sodium hydroxide only) ☐

e describe and explain the reactions of the chlorides with water ☐

f interpret the variations and trends in 9.2(b), (c), (d) and (e) in terms of bonding and electronegativity ☐

g suggest the types of chemical bonding present in chlorides and oxides from observations of their chemical and physical properties ☐

h predict the characteristic properties of an element in a given Group by using knowledge of chemical periodicity ☐

i deduce the nature, possible position in the Periodic Table and identity of unknown elements from given information about physical and chemical properties ☐

PERIOD 3

9 The Periodic Table: chemical periodicity

This topic illustrates the regular patterns in chemical and physical properties of the elements in the Periodic Table.

Learning outcomes
Candidates should be able to:

9.2 Periodicity of chemical properties of the elements in the third period

a) describe the reactions, if any, of the elements with oxygen (to give Na_2O, MgO, Al_2O_3, P_4O_{10}, SO_2, SO_3), chlorine (to give $NaCl$, $MgCl_2$, Al_2Cl_6, $SiCl_4$, PCl_5) and water (Na and Mg only)

b) state and explain the variation in oxidation number of the oxides (sodium to sulfur only) and chlorides (sodium to phosphorus only) in terms of their valence shell electrons

c) describe the reactions of the oxides with water

(treatment of peroxides and superoxides is *not* required)

d) describe and explain the acid/base behaviour of oxides and hydroxides including, where relevant, amphoteric behaviour in reaction with acids and bases (sodium hydroxide only)

e) describe and explain the reactions of the chlorides with water

f) interpret the variations and trends in 9.2(b), (c), (d) and (e) in terms of bonding and electronegativity

g) suggest the types of chemical bonding present in chlorides and oxides from observations of their chemical and physical properties

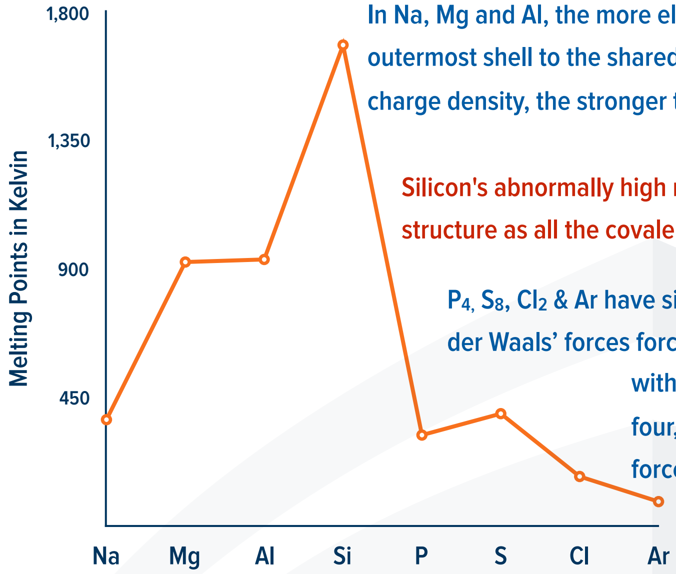
PERIOD III

PHYSICAL PROPERTIES

ELEMENT	Na	Mg	Al	Si	P	S	Cl	Ar
STRUCTURE	metallic lattice			macromolecular	simple covalent molecules			
SPECIES	Na^+	Mg^{2+}	Al^{3+}	Si atoms	P_4	S_8	Cl_2	Ar atoms
MELTING POINT	low	high			low			
MELTING POINT (°C)	98	649	660	1410	44	119	—101	—189
ELECTRICAL CONDUCTIVITY	high			moderate	low			

2

MELTING POINTS



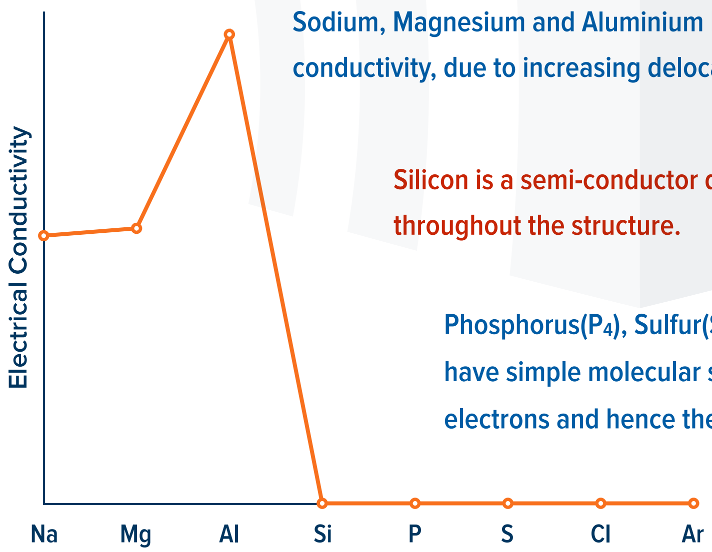
In Na, Mg and Al, the more electrons an atom contributes from its outermost shell to the shared delocalised electrons, greater the cation's charge density, the stronger the bonding and the higher the melting point.

Silicon's abnormally high melting point is due to its giant covalent structure as all the covalent bonds have to be broken.

P_4, S_8, Cl_2 & Ar have simple molecular structures held by weak van der Waals' forces forces resulting in low melting points, with S_8 having the highest melting point of the four, due to the strongest induced van der Waals' forces as it has the most electrons.

3

ELECTRICAL CONDUCTIVITY



Sodium, Magnesium and Aluminium have a trend of increasing conductivity, due to increasing delocalized electrons.

Silicon is a semi-conductor due to delocalized electrons present throughout the structure.

Phosphorus(P_4), Sulfur(S_8), Chlorine(Cl_2) and Argon(Ar) have simple molecular structures with no delocalized electrons and hence they do not conduct electricity.

4

REACTIONS OF ELEMENTS WITH OXYGEN

All the elements in Period 3 except chlorine and argon react with oxygen directly forming their respective oxides.

Oxygen being highly electronegative brings out the highest oxidation number of the elements.

The oxidation number of the element in their oxides is always positive and the maximum oxidation number in the oxide is the same as the Group number, corresponding to the number of electrons in the outermost shell.

ELEMENT	Na	Mg	Al	Si	P	S
FORMULA	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_{10}	SO_2, SO_3
OXIDATION #	+1	+2	+3	+4	+5	+4, +6

5

REACTIONS OF ELEMENTS WITH OXYGEN

Sodium burns vigorously in air with a yellow flame to form sodium oxide.

$$2Na\,(s) + \tfrac{1}{2}\,O_2\,(g) \longrightarrow Na_2O\,(s)$$

Magnesium also reacts vigorously when heated in oxygen with a bright white flame, forming magnesium oxide.

$$Mg\,(s) + \tfrac{1}{2}\,O_2\,(g) \longrightarrow MgO\,(s)$$

Aluminium metal is protected by a layer of aluminium oxide, but powdered aluminium does react well with oxygen burn with a bright white flame.

$$4Al\,(s) + 3\,O_2\,(g) \longrightarrow 2\,Al_2O_3\,(s)$$

6

REACTIONS OF ELEMENTS WITH OXYGEN

Silicon reacts with oxygen slowly when heated to form silicon (IV) oxide.

$$Si\ (s) + O_2\ (g) \longrightarrow SiO_2\ (s)$$

Phosphorus on heating burns with a yellow flame giving out white smokes of phosphorus(V) oxide.

$$P_4\ (s) + 5\ O_2\ (g) \longrightarrow P_4O_{10}\ (s)$$

Sulphur on heating burns with a blue flame forming sulphur dioxide.

$$S\ (s) + O_2\ (g) \longrightarrow SO_2\ (g)$$

Sulphur dioxide may be converted to sulphur trioxide by reacting the gas with air in the presence of a catalyst.

$$SO_2\ (g) + \tfrac{1}{2}\ O_2\ (g) \longrightarrow SO_3\ (g)$$

7

REACTIONS OF ELEMENTS WITH CHLORINE

When heated with chlorine, sodium, magnesium and aluminium react vigorously to form the respective solid white chlorides, aluminium chloride forming the dimer (Al_2Cl_6).

Silicon and phosphorus react slowly forming liquid products, silicon forming silicon (IV) chloride and phosphorus forming phosphorus pentachloride.

8

REACTIONS WITH WATER

Sodium reacts vigorously with cold water, giving off hydrogen gas. It quickly dissolves, leaving a strongly alkaline solution of sodium hydroxide behind:

$$2Na(s) + 2H_2O(l) \longrightarrow 2NaOH(aq) + H_2(g)$$

Magnesium only reacts very slowly with cold water, to produce of hydrogen gas very weakly alkaline solution.

$$Mg(s) + 2H_2O(l) \longrightarrow Mg(OH)_2(aq) + H_2(g)$$

Magnesium reacts vigorously steam to make MgO and hydrogen gas:

$$Mg(s) + H_2O(g) \longrightarrow MgO(s) + H_2(g)$$

9

PERIOD 3 OXIDES

ELEMENT	Na	Mg	Al	Si	P	S
FORMULA	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_{10}	SO_2, SO_3
OXIDATION #	+1	+2	+3	+4	+5	+4, +6
TYPE	BASIC		AMPHOTERIC	ACIDIC		
BONDING	IONIC			COVALENT		
STRUCTURE	GIANT IONIC				SIMPLE COVALENT	
MELTING POINT	HIGH				LOW	

10

PERIOD 3 OXIDES

	Na	Mg	Al	Si	P	S	Cl
Name of oxide	sodium oxide	magnesium oxide	aluminium oxide	silicon(IV) oxide	phosphorus(III) oxide	sulfur(IV) oxide	chlorine(I) oxide
					phosphorus(V) oxide	sulfur(VI) oxide	chlorine(VII) oxide
Formula of oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_6	SO_2	Cl_2O
					P_4O_{10}	SO_3	Cl_2O_7
Physical state at 25 °C	solid				liquid	gas	gas
					solid	liquid	liquid
Bonding in oxide	ionic			covalent			
Structure	giant				simple molecular		
Species present in liquid state	Na^+ and O^{2-} ions	Mg^{2+} and O^{2-} ions	Al^{3+} and O^{2-} ions	Si and O atoms	P_4O_6 molecules	SO_2 molecules	Cl_2O molecules
					P_4O_{10} molecules	SO_3 molecules	Cl_2O_7 molecules
Electrical conductivity when molten	good			none			
	liquid oxides conduct electricity as mobile ions present in liquid state			do not conduct electricity in liquid state as no ions present.			

11

PERIOD 3 OXIDES

	Sodium	Magnesium	Aluminium	Silicon	Phosphorus	Sulfur	Chlorine
Formula of oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_6	SO_2	Cl_2O
					P_4O_{10}	SO_3	Cl_2O_7
Nature of element	metal			non-metal			
Bonding in oxide	ionic			giant covalent	covalent molecular		
Nature of oxide	basic		amphoteric	acidic			
Reaction with water	soluble and reacts	sparingly soluble, some reaction	insoluble		soluble and reacts		
Solution formed	alkaline	slightly alkaline	–		acidic		

12

BASIC OXIDES

Sodium and magnesium oxides produce alkaline solutions with water

$$Na_2O\,(s) + H_2O\,(l) \longrightarrow 2NaOH\,(aq)$$

$$MgO\,(s) + H_2O\,(l) \longrightarrow Mg(OH)_2\,(s)$$

$Mg(OH)_2$ is not very soluble in water resulting solution less alkaline solution.

Both basic oxides dissolve in acids to form salt and water.

$$Na_2O(s) + 2HCl\,(aq) \longrightarrow 2NaCl\,(aq) + H_2O\,(l)$$

$$MgO(s) + 2HCl\,(aq) \longrightarrow MgCl_2\,(aq) + H_2O\,(l)$$

13

ALUMINIUM OXIDE

The insoluble oxide of aluminium shows its amphoteric nature by reacting and dissolving in both acidic and alkaline solutions.

$$Al_2O_3(s) + 6H^+ \longrightarrow 2Al^{3+} + 3H_2O$$

$$Al_2O_3(s) + 6HCl \longrightarrow 2AlCl_3 + 3H_2O$$

$$Al_2O_3(s) + 2OH^- + 3H_2O \longrightarrow 2Al(OH)_4^-$$

$$Al_2O_3(s) + 2NaOH + 3H_2O \longrightarrow 2NaAl(OH)_4$$

14

NON-METAL OXIDES

The covalently bonded non-metal oxides of phosphorus and sulfur dissolve and react in water to form acidic solutions.

$$P_4O_{10}(s) + 6H_2O \longrightarrow 4H_3PO_4$$

$$SO_2\,(g) + H_2O \longrightarrow H_2SO_3$$

$$SO_3\,(g) + H_2O \longrightarrow H_2SO_4$$

These oxides also neutralise alkalis.

$$P_4O_{10}(s) + 12NaOH \longrightarrow 4Na_3PO_4 + 6H_2O$$

$$SO_2\,(g) + 2NaOH \longrightarrow Na_2SO_3 + H_2O$$

$$SO_3\,(g) + 2NaOH \longrightarrow Na_2SO_4 + H_2O$$

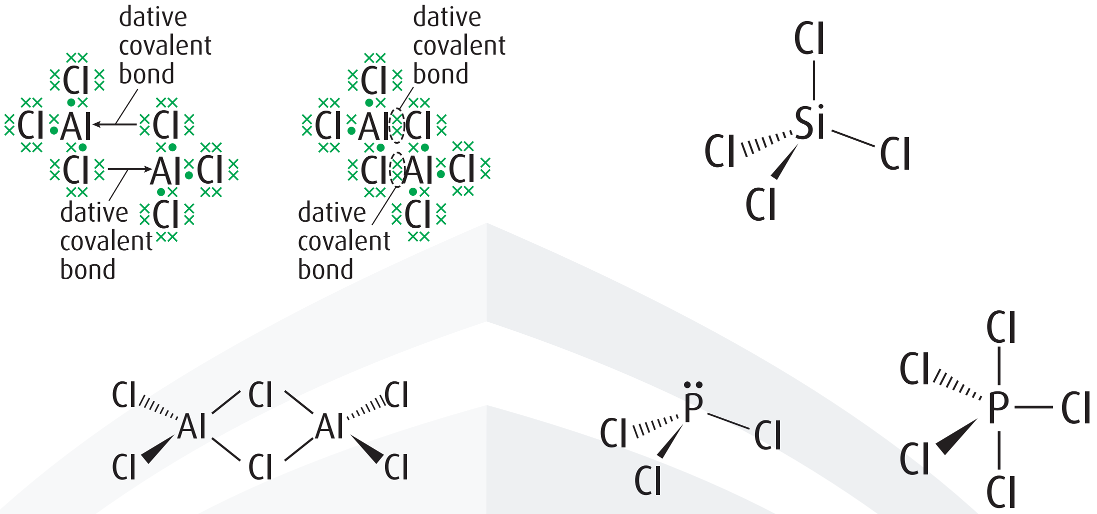
15

PERIOD 3 CHLORIDES

ELEMENT	Na	Mg	Al	Si	P
FORMULA	NaCl	$MgCl_2$	Al_2Cl_6	$SiCl_4$	PCl_5
STRUCTURE	GIANT IONIC		SIMPLE COVALENT		
OXIDATION #	+1	+2	+3	+4	+5
STATE at RTP	solid	solid	solid	liquid	solid
PH	7	6.5	3	2	2
OBSERVATIONS WITH WATER	white solids dissolve to form colourless solutions			white fumes of HCl gas	

16

PERIOD 3 CHLORIDES



17

FORMATION OF PERIOD 3 CHLORIDES

When sodium metal is heated with chlorine gas there is a vigorous reaction and a yellow flame is seen:

$$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$$

Magnesium and aluminium also react vigorously with chlorine gas:

$$Mg(s) + Cl_2(g) \longrightarrow MgCl_2(s)$$

$$2Al(s) + 3Cl_2(g) \longrightarrow Al_2Cl_6(s)$$

18

FORMATION OF PERIOD 3 CHLORIDES

Silicon reacts slowly with chlorine giving silicon(IV) chloride:

$$Si(s) + 2Cl_2(g) \longrightarrow SiCl_4(l)$$

Phosphorus also reacts slowly with excess chlorine gas:

$$P_4(s) + 10Cl_2(g) \longrightarrow 4PCl_5(l)$$

19

PERIOD 3 CHLORIDES WITH WATER

	Sodium	Magnesium	Aluminium	Silicon	Phosphorus	Chlorine
Formula of chloride	NaCl	$MgCl_2$	'$AlCl_3$' = Al_2Cl_6	$SiCl_4$	PCl_3, PCl_5	Cl_2
Reaction with water	dissolves, no reaction	dissolves, very slight reaction	fairly vigorous reaction with water; fumes in moist air	vigorous reaction	vigorous reaction	dissolves and reacts slightly
pH (aqueous solution)*	7	6.2	3	1	1	2
Acidity	**neutral**	**slightly acidic**	**acidic**	**acidic**	**acidic**	**acidic**

20

PERIOD 3 CHLORIDES WITH WATER

The ionic chlorides of sodium and magnesium do not react with water; they just dissolve.

On adding Al_2Cl_6 to water, it breaks down forming Al^{3+} and Cl^- ions.

Al^{3+} is small and is highly charged (high charge density), causing the water molecules bonded to it to lose one H^+ ion, making the resulting solution acidic.

$$[Al(H_2O)_6]^{3+}{}_{(aq)} \longrightarrow [Al(H_2O)_5OH]^{2+}{}_{(aq)} + H^+{}_{(aq)}$$

21

PERIOD 3 CHLORIDES WITH WATER

The liquid chlorides, $SiCl_4$ and PCl_5, are hydrolysed in water, releasing white fumes of hydrogen chloride gas in a rapid reaction

$$SiCl_{4\,(l)} + 2H_2O_{(l)} \longrightarrow SiO_{2\,(s)} + 4HCl_{(g)}$$

The SiO_2 is a white/off-white precipitate. Some of the HCl dissolves in the water, giving an acidic solution.

$$PCl_{5\,(l)} + 4H_2O_{(l)} \longrightarrow H_3PO_{4(aq)} + 5HCl_{(g)}$$

Both H_3PO_4 and HCl are soluble in water and are highly acidic

22

PERIOD 3 WS 1

SECTION A

1 Which oxide does **not** react with cold dilute sodium hydroxide to produce a salt?

A Al_2O_3 **B** P_4O_{10} **C** SO_2 **D** SiO_2

2 Ferrochrome is an alloy of iron and chromium. Ferrochrome can be dissolved in dilute sulfuric acid to produce a mixture of $FeSO_4$ and $Cr_2(SO_4)_3$. The $FeSO_4$ reacts with $K_2Cr_2O_7$ in acid solution according to the following equation.

$$14H^+ + 6Fe^{2+} + Cr_2O_7^{2-} \rightarrow 2Cr^{3+} + 6Fe^{3+} + 7H_2O$$

When 1.00 g of ferrochrome is dissolved in dilute sulfuric acid, and the resulting solution titrated, 13.1 cm^3 of 0.100 mol dm^{-3} $K_2Cr_2O_7$ is required for complete reaction.

What is the percentage by mass of Fe in the sample of ferrochrome?

A 1.22 **B** 4.39 **C** 12.2 **D** 43.9

3 What is the **ionic** equation for the reaction between aqueous sodium carbonate and dilute nitric acid?

A $2HNO_3(aq) + CO_3^{2-}(aq) \rightarrow H_2O(l) + CO_2(g) + 2NO_3^-(aq)$

B $2H^+(aq) + CO_3^{2-}(aq) \rightarrow CO_2(g) + H_2O(l)$

C $2HNO_3(aq) + Na_2CO_3(aq) \rightarrow 2NaNO_3(aq) + CO_2(g) + H_2O(l)$

D $2HNO_2(aq) + CO_3^{2-}(aq) \rightarrow H_2O(l) + CO_2(g) + 2NO_2^-(aq)$

4 An element **Y** reacts according to the following sequence.

$$\text{Y} \xrightarrow{\text{burns in } O_2} \text{white solid} \xrightarrow{\text{HC}l\text{(aq)}} \text{solution} \xrightarrow{\text{NaOH(aq)}} \text{white precipitate} \xrightarrow{\text{an excess of NaOH(aq)}} \text{solution}$$

What could be element **Y**?

A Al **B** Ca **C** Mg **D** P

5 One molecule of the oxide of element **Z** reacts with six molecules of water to produce an acidic compound.

What is element **Z**?

A aluminium

B phosphorus

C sodium

D sulfur

6 A student examines two semi-precious stones; one is agate, SiO_2, and the other is calcite, $CaCO_3$.

How could they be distinguished?

A Add a fixed amount of cold aqueous sodium hydroxide to each separately and measure any temperature change.

B Heat each separately over a gentle Bunsen flame and note which one melts first.

C Shake each separately with dilute hydrochloric acid and test any gas formed.

D Shake each separately with distilled water and add a few drops of Universal Indicator.

7 In oxygen difluoride, OF_2, fluorine has an oxidation number of –1. OF_2 will react with sulfur dioxide according to the following equation.

$$OF_2 + SO_2 \rightarrow SO_3 + F_2$$

What is oxidised and what is reduced in this reaction?

	fluorine	oxygen in OF_2	sulfur
A	oxidised	oxidised	reduced
B	oxidised	reduced	oxidised
C	reduced	oxidised	reduced
D	reduced	reduced	oxidised

8 Mohr's salt is a pale green crystalline solid which is soluble in water. It contains two cations, one of which is Fe^{2+}, and one anion which is SO_4^{2-}.

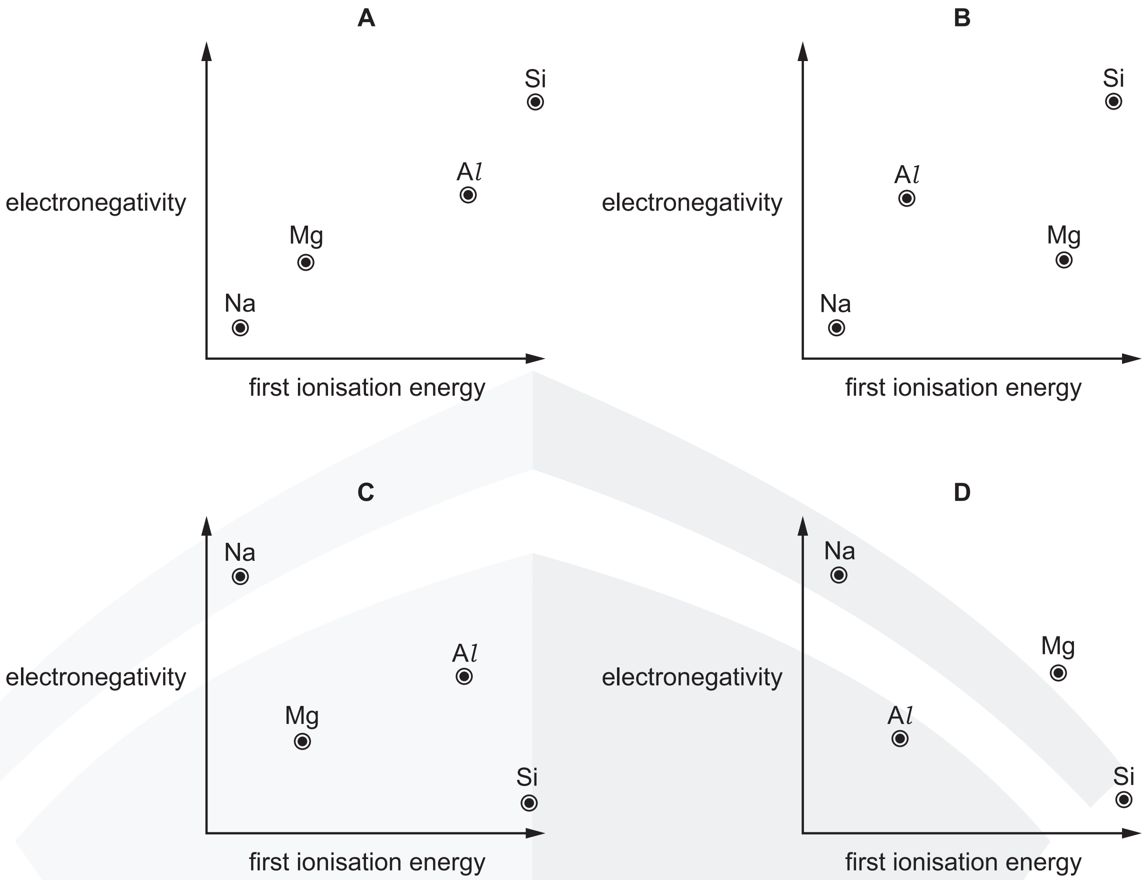
The identity of the second cation was determined by heating Mohr's salt with aqueous sodium hydroxide. A colourless gas was evolved which readily dissolved in water giving an alkaline solution.

A green precipitate was also formed.

What are the identities of the gas and the precipitate?

	gas	precipitate
A	NH_3	$Fe(OH)_2$
B	NH_3	Na_2SO_4
C	SO_2	$Fe(OH)_2$
D	SO_2	Na_2SO_4

9 Which diagram correctly shows the electronegativity of the elements Na, Mg, Al and Si plotted against their first ionisation energies?



10 In which reaction does an element have the largest change in oxidation number?

A $Cr_2O_7^{2-} + 6Fe^{2+} + 14H^+ \rightarrow 2Cr^{3+} + 6Fe^{3+} + 7H_2O$

B $3OCl^- \rightarrow ClO_3^- + 2Cl^-$

C $5Fe^{2+} + MnO_4^- + 8H^+ \rightarrow 5Fe^{3+} + Mn^{2+} + 4H_2O$

D $PbO_2 + Sn^{2+} + 4H^+ \rightarrow Sn^{4+} + Pb^{2+} + 2H_2O$

11 Which oxide will produce the solution with the highest pH when it is mixed with water?

A Al_2O_3 **B** CO_2 **C** Na_2O **D** SO_2

12 The labels had become detached from four bottles in the laboratory. A student realised that the contents of one of them could easily be identified, because on addition of water it would **not** give fumes of hydrogen chloride.

Which did **not** give the HCl fumes?

A Al_2Cl_6 **B** $MgCl_2$ **C** PCl_5 **D** $SiCl_4$

13 Which of the elements sodium, magnesium, aluminium, silicon, phosphorus, sulfur and chlorine

- has a lower first ionisation energy than the preceding element in the Periodic Table,
- conducts electricity and
- has a lower atomic radius than the preceding element in the Periodic Table?

A aluminium

B magnesium

C phosphorus

D sulfur

14 The melting points of the Period 3 elements sodium to aluminium are shown in the table.

element	Na	Mg	A*l*
mp / K	371	923	932

Which factor explains the **increase** in melting points from sodium to aluminium?

A the changes in first ionisation energy from sodium to aluminium

B the increase in electronegativity from sodium to aluminium

C the increase in the A_r of the elements from sodium to aluminium

D the increase in the number of outer electrons in each atom from sodium to aluminium

15 **X** is the oxide of a Period 3 element. **X** reacts with water to give an acidic solution.

A solution is prepared by reacting 0.100 g of **X** with excess water. This solution was neutralised by exactly 25.0 cm^3 of 0.100 $mol\,dm^{-3}$ sodium hydroxide solution.

What could be the identity of **X**?

A Al_2O_3 **B** MgO **C** P_4O_{10} **D** SO_3

16 Arsenic chloride, $AsCl_3$, reacts with sodium borohydride, $NaBH_4$.

$$\mathbf{p}AsCl_3 + \mathbf{q}NaBH_4 \rightarrow \mathbf{r}AsH_3 + \mathbf{s}NaCl + \mathbf{t}BCl_3$$

What are the numbers **p**, **q**, **r**, **s** and **t** when this equation is balanced correctly?

	p	q	r	s	t
A	2	3	2	3	1
B	3	3	3	3	2
C	4	3	4	3	3
D	4	4	4	4	3

17 Which chloride of a Period 3 element dissolves in water to form a solution with a pH of 7?

A aluminium chloride

B phosphorus(V) chloride

C silicon(IV) chloride

D sodium chloride

18 Which row correctly compares the electrical conductivity and first ionisation energy of magnesium and aluminium?

	higher electrical conductivity	higher first ionisation energy
A	aluminium	aluminium
B	aluminium	magnesium
C	magnesium	aluminium
D	magnesium	magnesium

19 Consecutive elements **X**, **Y** and **Z** are in Period 3 of the Periodic Table. Element **Y** has the highest first ionisation energy and the lowest melting point of these three elements.

What are the identities of **X**, **Y** and **Z**?

A sodium, magnesium, aluminium

B magnesium, aluminium, silicon

C aluminium, silicon, phosphorus

D silicon, phosphorus, sulfur

20 A white powder is known to be a mixture of magnesium oxide and aluminium oxide.

$100\,cm^3$ of $2\,mol\,dm^{-3}$ NaOH(aq) is just sufficient to cause the aluminium oxide in *x* grams of the mixture to dissolve.

The reaction occurring is $Al_2O_3 + 2OH^- + 3H_2O \rightarrow 2Al(OH)_4^-$.

$800\,cm^3$ of $2\,mol\,dm^{-3}$ HCl(aq) is just sufficient to cause **all** of the oxide in *x* grams of the mixture to dissolve.

The reactions occurring are $Al_2O_3 + 6H^+ \rightarrow 2Al^{3+} + 3H_2O$
and $MgO + 2H^+ \rightarrow Mg^{2+} + H_2O$.

How many moles of each oxide are present in *x* grams of the mixture?

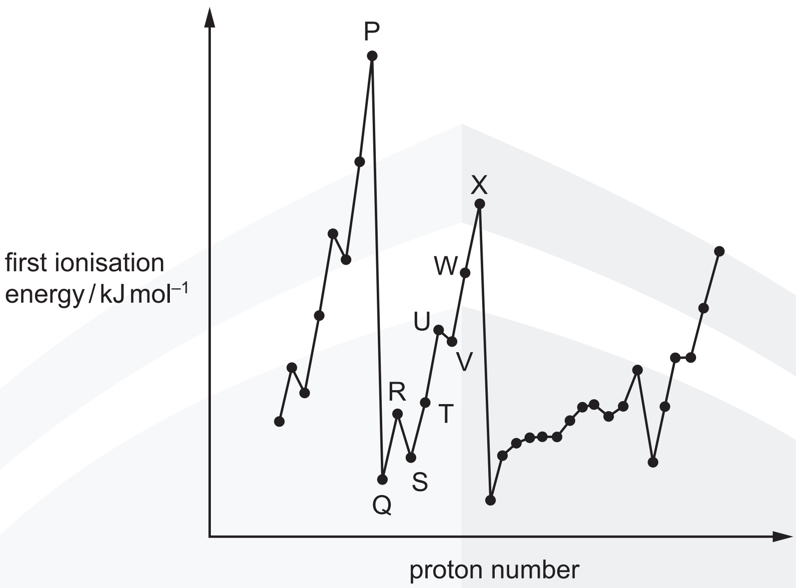
	aluminium oxide	magnesium oxide
A	0.05	0.25
B	0.05	0.50
C	0.10	0.25
D	0.10	0.50

21 Elements D and E are both in Period 3. Element D has the smallest atomic radius in Period 3. There are only two elements in Period 3 which have a lower melting point than element E. Elements D and E react together to form compound L.

Which compound could be L?

A $MgCl_2$ **B** MgS **C** Na_2S **D** PCl_3

22 The graph below shows the variation of the first ionisation energy with proton number for some elements. The letters used are not the usual symbols for the elements.



Which statement about the elements is correct?

A P and X are in the same period in the Periodic Table.

B The general increase from Q to X is due to increasing atomic radius.

C The small decrease from R to S is due to decreased shielding.

D The small decrease from U to V is due to repulsion between paired electrons.

23 Elements Y and Z are both in Period 3.

When the chloride of Y is added to water, it reacts and a solution of pH 2 is produced.

When the chloride of Z is added to water, it dissolves and a solution of pH 7 is produced.

Which statement explains these observations?

A Both chlorides hydrolyse in water.

B Y is magnesium and Z is sodium.

C Y is phosphorus and Z is aluminium.

D Y is silicon and Z is sodium.

24 Element Z has a giant structure.

The chloride of Z reacts with water to give a solution with a pH less than 5.

Which row shows two elements which could be Z?

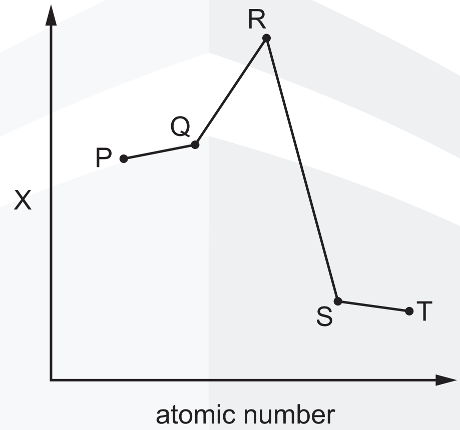
A aluminium, magnesium

B aluminium, silicon

C phosphorus, magnesium

D phosphorus, silicon

25 The relative magnitude of the property X of five elements is shown. P, Q, R, S and T are all in Period 3 and have consecutive atomic numbers.



Which row shows a correct pairing of property X and element R?

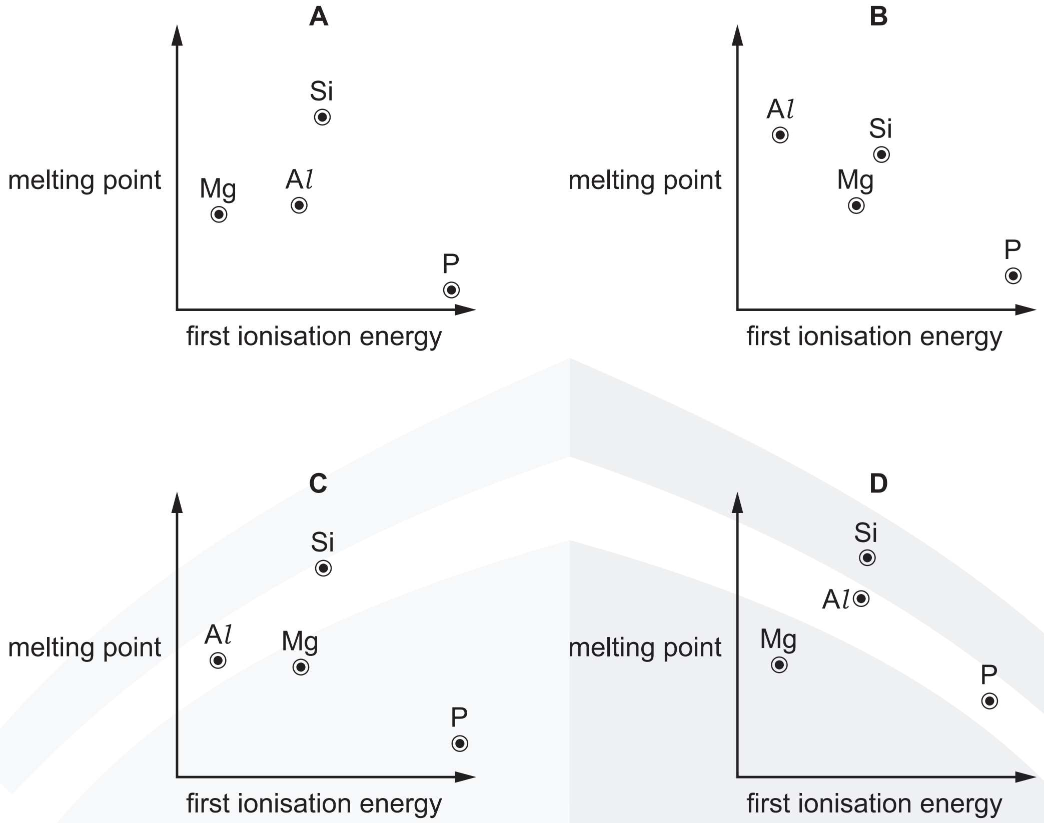
	property X	element R
A	electrical conductivity	Al
B	electronegativity	Si
C	melting point	Al
D	second ionisation energy	Si

26 The elements Cl, Mg, Si and S are all in Period 3.

What is the correct sequence of the melting points of these elements, from lowest to highest?

	lowest melting point	→		highest melting point
A	Cl	S	Mg	Si
B	Cl	S	Si	Mg
C	Mg	Si	S	Cl
D	Si	Mg	S	Cl

27 Which graph correctly shows the relative melting points of the elements Mg, Al, Si and P plotted against their relative first ionisation energies?

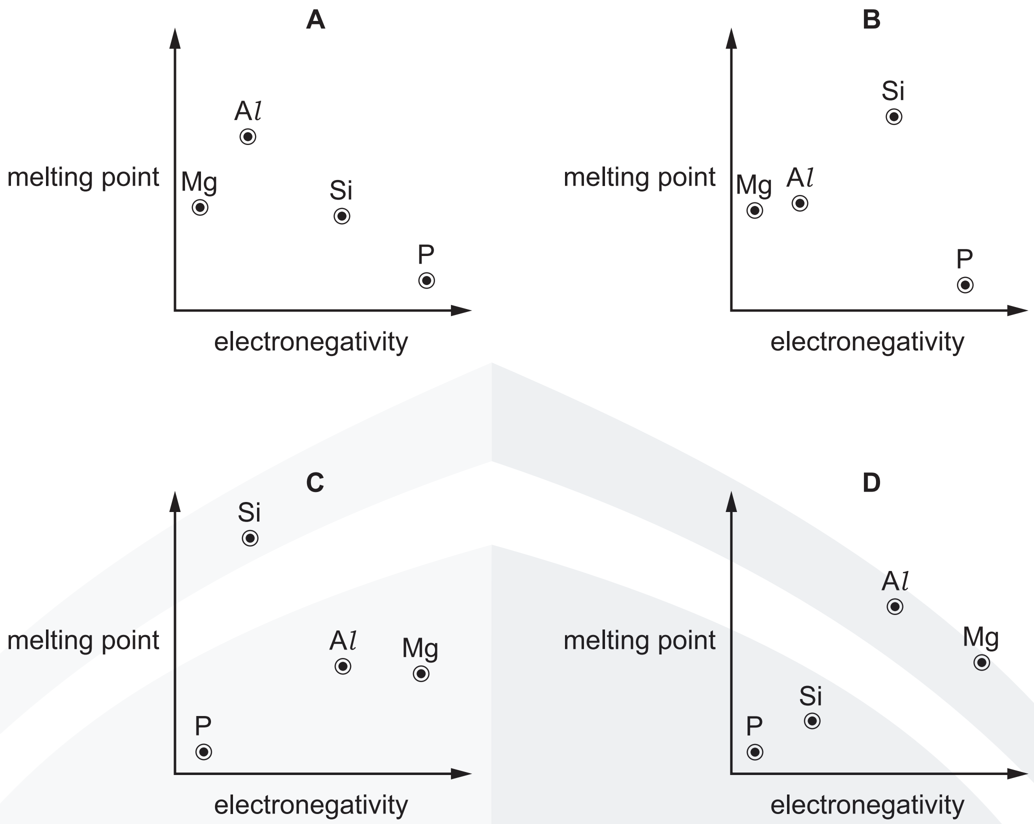


28 Magnesium chloride, $MgCl_2$, and silicon tetrachloride, $SiCl_4$, are separately added to water.

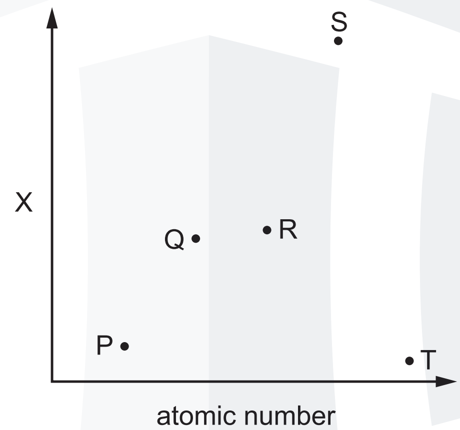
What are the approximate pH values of the solutions formed?

	$MgCl_2$	$SiCl_4$
A	0–3	0–3
B	0–3	6–7
C	6–7	0–3
D	6–7	6–7

29 Which graph correctly shows the relative melting points of the elements Mg, Al, Si and P plotted against their relative electronegativities?



30 The magnitude of property X of five elements from the third period of the Periodic Table, P, Q, R, S and T is shown. P, Q, R, S and T have consecutive atomic numbers. The letters do not represent the symbols of the elements.



Which row correctly identifies property X and element R?

	property X	element R
A	electrical conductivity	Al
B	electronegativity	Si
C	melting point	Al
D	melting point	Si

31 The electrical conductivities of two compounds, Y and Z, are shown in the table.

	Y	Z
conductivity of the compound in the liquid state	good	does not conduct
conductivity of the mixture obtained by adding the compound to water	good	good

What could compounds Y and Z be?

	Y	Z
A	Al_2O_3	$SiCl_4$
B	NaF	Al_2O_3
C	NaF	$SiCl_4$
D	$SiCl_4$	Al_2O_3

32 Elements D and E are both in Period 3. Element D has the smallest atomic radius in Period 3. There are only two elements in Period 3 which have a lower melting point than element E. Elements D and E react together to form compound L.

Which compound could be L?

A $MgCl_2$ **B** MgS **C** Na_2S **D** PCl_3

[S'16 1 Q13]

33 Which row correctly compares the electrical conductivity and first ionisation energy of magnesium and aluminium?

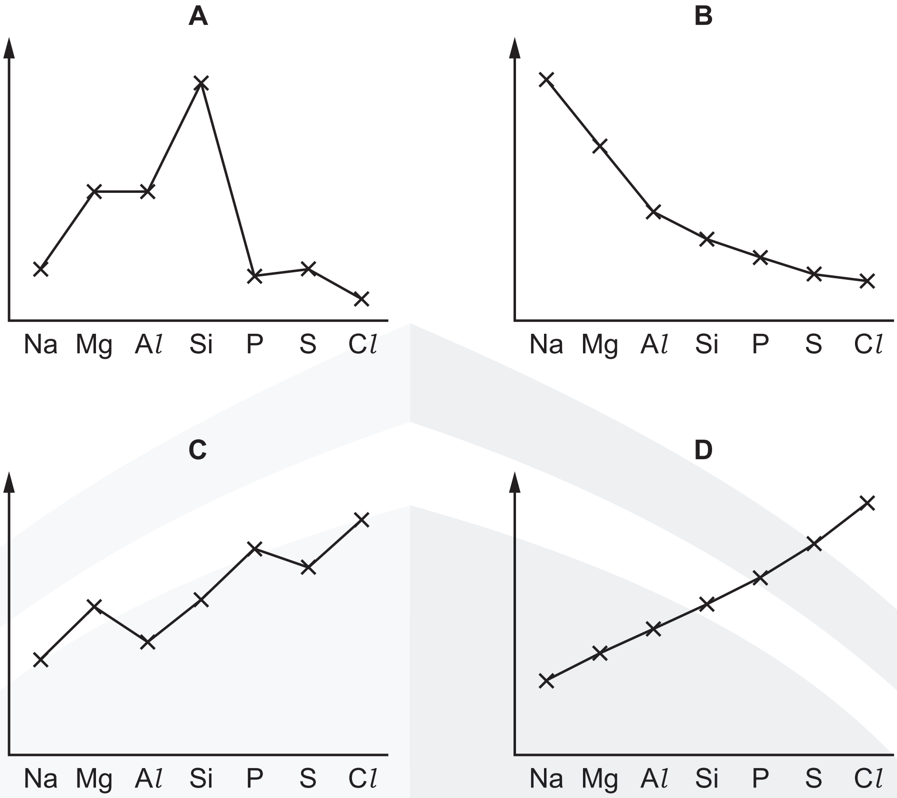
	higher electrical conductivity	higher first ionisation energy
A	aluminium	aluminium
B	aluminium	magnesium
C	magnesium	aluminium
D	magnesium	magnesium

[W'15 2 Q15]

34

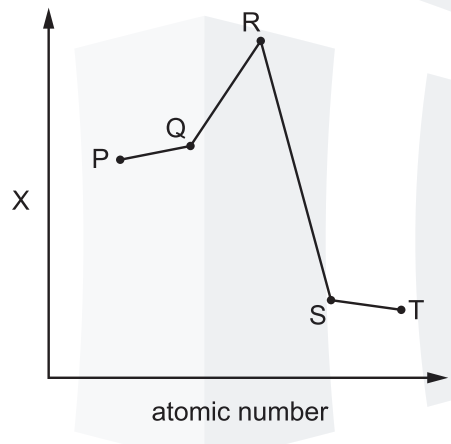
35 The graphs show trends in four physical properties of elements in Period 3, excluding argon.

Which graph has electronegativity on the *y*-axis?



[S'18 2 Q13]

36 The relative magnitude of the property X of five elements is shown. P, Q, R, S and T are all in Period 3 and have consecutive atomic numbers.



Which row shows a correct pairing of property X and element R?

	property X	element R
A	electrical conductivity	Al
B	electronegativity	Si
C	melting point	Al
D	second ionisation energy	Si

[W'17 2 Q12]

37 Element Z has a giant structure.

The chloride of Z reacts with water to give a solution with a pH less than 5.

Which row shows two elements which could be Z?

A aluminium, magnesium

B aluminium, silicon

C phosphorus, magnesium

D phosphorus, silicon

38 Which oxide is insoluble in aqueous sodium hydroxide?

A MgO **B** Al_2O_3 **C** P_4O_{10} **D** SO_2

[M'18 P12 Q13]

39 X, Y and Z are three elements in the third period.

- X reacts with chlorine to give a liquid product.
- Y reacts with chlorine to give a solid product that dissolves in water to give a solution of pH 7.
- Z reacts with chlorine to give a solid product that dissolves in water to give a solution of pH 6.

Which elements are good conductors of electricity?

A X and Y **B** Y and Z **C** Y only **D** Z only

[M'18 P12 Q13]

40 Silicon is heated in an excess of chlorine, producing compound J.

Excess water is added to the sample of J produced.

Which row is correct?

	structure of J	Is HCl produced when water is added to J?
A	giant molecular	no
B	giant molecular	yes
C	simple molecular	no
D	simple molecular	yes

[J'18 P11 Q12]

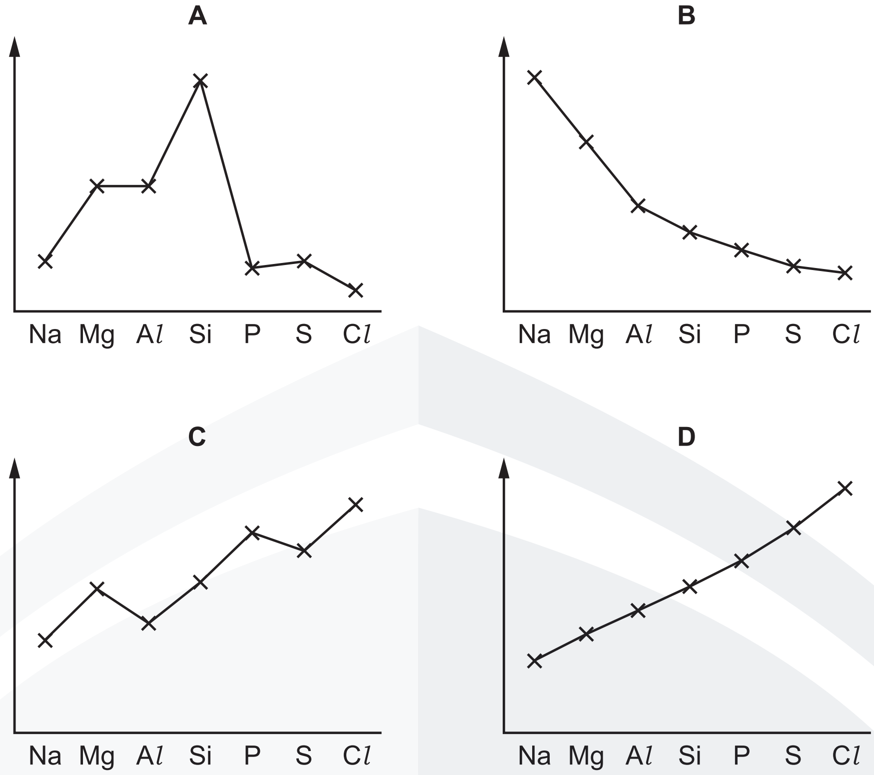
41 Which oxide does **not** react with cold, dilute sodium hydroxide to produce a salt?

A Al_2O_3 **B** P_4O_{10} **C** SO_2 **D** SiO_2

[J'18 P12 Q12]

42 The graphs show trends in four physical properties of elements in Period 3, excluding argon.

Which graph has electronegativity on the *y*-axis?



[J'18 P12 Q13]

43 X and Y are elements of the third period.

X and Y are individually heated in excess chlorine. Each product is purified and then separately added to water, producing two solutions. Both solutions have a pH of less than 5.

What could be X and Y?

A Na and P **B** Mg and Al **C** Mg and Si **D** Si and P

[J'18 P13 Q13]

44 X and Y are elements in Period 3 of the Periodic Table.

- The oxide of X is a solid at room temperature. This oxide has a giant structure.
- The chloride of X does not react with water.
- Argon is the only element in Period 3 with a lower melting point than Y.

What could be the formula of a compound formed between elements X and Y?

A Al_2S_3 **B** MgS **C** NaCl **D** PCl_5

[N'18 P11 Q13]

45 The melting points of the Period 3 elements phosphorus to argon are shown in the table.

element	P	S	Cl	Ar
mp / K	317	392	172	84

Which factor explains the changes in melting points from phosphorus to argon?

A the changes in electronegativity from phosphorus to argon

B the changes in first ionisation energy from phosphorus to argon

C the increase in the number of electrons in each atom from phosphorus to argon

D the number of atoms in each molecule of the element from phosphorus to argon

[N’18 P12 Q12]

46 Which observations are made when a sample of silicon chloride, $SiCl_4$, is added to a beaker of water?

A No visible change is observed.

B Steamy fumes and a precipitate are both observed.

C The appearance of a precipitate is the only observation.

D The appearance of steamy fumes is the only observation.

[N’18 P12 Q13]

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 An element X and compound YZ react separately with acid as shown.

$$X(s) + 2H^+(aq) \rightarrow X^{2+}(aq) + H_2(g)$$

$$YZ(s) + 2H^+(aq) \rightarrow Y^{2+}(aq) + H_2Z(g)$$

When 1.0 g of either X or YZ is reacted with an excess of acid, the total volume of gas formed is the same.

Which statements are correct?

1 $A_r(X) = M_r(YZ)$

2 X and Y are metals.

3 X and Y must both be in the same Group of the Periodic Table.

2 Which chlorides of Period 3 elements will form a neutral solution when added to water?

1 $NaCl$

2 Al_2Cl_6

3 PCl_5

3 When added to water, which oxides will cause a change in the pH of the water?

1 SiO_2

2 CaO

3 SO_2

4 Which of the following influence the size of the ionisation energy of an atom?

1 the amount of shielding by the inner electrons

2 the charge on the nucleus

3 the distance between the outer electrons and the nucleus

5 Which chlorides, when added to water, can produce a solution with a pH of less than 5?

1 $SiCl_4$

2 $AlCl_3$

3 $MgCl_2$

6 The structure of metals is considered to be positive ions surrounded by delocalised electrons.

The melting points of the metals in Period 3 increase with increasing atomic number.

Which statements help to explain this trend from sodium to aluminium?

1 The charge on the metal ion increases.

2 There are more delocalised electrons per metal ion.

3 The radius of the metal ion decreases.

[S'18 3 Q35]

7 The structure of metals is considered to be positive ions surrounded by delocalised electrons.

The melting points of the metals in Period 3 increase with increasing atomic number.

Which statements help to explain this trend from sodium to aluminium?

1 The charge on the metal ion increases.

2 There are more delocalised electrons per metal ion.

3 The radius of the metal ion decreases.

[J'18 P13 Q35]

8 A sample containing *x* mol of Al_2Cl_6 is dissolved in water to give solution W.

In order to precipitate all of the aluminium as its hydroxide, *y* mol of sodium hydroxide are required.

More of the alkali is added to re-dissolve the precipitate, giving solution Z.

Which statements are correct?

1 the initial pH of solution W is below 7

2 $y = 3x$

3 Z contains *x* mol of aluminium

[N'18 P12 Q35]

PERIOD 3 WS 2

1 The acid/base behaviour of the oxides in the third period varies across the period.

(i) Describe this behaviour and explain it with reference to the structure and bonding of sodium oxide, Na_2O, aluminium oxide, Al_2O_3, and sulfur trioxide, SO_3.

....

....

.... [2]

(ii) Write equations for reactions of these three oxides with hydrochloric acid and/or sodium hydroxide as appropriate.

....

....

....

.... [4]

2 Aluminium is a metal in Period 3 and Group III of the Periodic Table.

(a) Describe the structure of solid aluminium.

....

....

.... [2]

(b) A common use of aluminium is to make the conducting cables in long distance overhead power lines.

(i) Suggest two properties of aluminium that make it suitable for this use.

....

....

.... [2]

The cables are attached to pylons by ceramic supports.

(ii) Describe the structure of a ceramic material.

....

.... [1]

(iii) State the property of a ceramic material that makes it suitable for this use.

....

.... [1]

(c) Aluminium reacts with chlorine to form a white, solid chloride that contains 79.7% chlorine and sublimes (changes straight from a solid to a gas) at 180 °C.

(i) Describe the structure and bonding in this compound. Suggest how it explains the low sublimation temperature.

....

....

....

....

.... [2]

(ii) Calculate the empirical formula of the chloride. You must show your working.

empirical formula = ... [2]

At 200 °C and 100 kPa, a 1.36 g sample of this chloride occupied a volume of 200 cm^3.

(iii) Calculate the relative molecular mass, M_r, of the chloride. Give your answer to **three** significant figures.

M_r = ... [2]

(iv) Deduce the molecular formula of this chloride at 200 °C.

.... [1]

3 The elements in Period 3, Na, Mg, A*l*, P and S, all react with oxygen when heated in air.

(a) **(i)** Give the formula of the oxide formed when each element is heated in air. One has been completed for you.

Na = ... Mg = ... A*l* = Al_2O_3

P = ... S = ...

[2]

(ii) Describe what you would **see** when sodium and sulfur are each heated separately in air and give an equation for each reaction.

Na ....

equation ....

S ....

equation ....

[4]

(b) The oxides show variations in their behaviour when added to water, acids and alkalis.

(i) Place the symbols of the elements in **(a)(i)** in the appropriate row of the table to indicate this behaviour.

acidic	
amphoteric	
basic	

[2]

(ii) State the bonding present in acidic and basic oxides.

acidic ....

basic ....

[2]

(iii) Write equations for the reaction of aluminium oxide with each of hydrochloric acid, HC*l*, and sodium hydroxide, NaOH.

with HC*l* ....

with NaOH ....

[2]

(c) Explain how the presence of an impurity in carbonaceous fuels can give rise to acid rain.

name of impurity ....

....

.... [2]

4 This question is about Period 3 elements and their compounds.

(a) Give an explanation for each of the following statements.

(i) The atomic radius decreases across Period 3 (Na to Ar).

....

....

....

.... [2]

(ii) The first ionisation energy of sulfur is lower than that of phosphorus.

....

....

....

.... [2]

(iii) Sodium is a better electrical conductor than phosphorus.

....

....

....

.... [2]

(iv) Magnesium is a better electrical conductor than sodium.

....

.... [1]

5 **D**, **E**, **F**, and **G** are four consecutive elements in the **fourth** period of the Periodic Table. (The letters are **not** the actual symbols of the elements.)

D is a soft, silvery metal with a melting point just above room temperature. Its amphoteric oxide, $\mathbf{D}_2O_3$, has a melting point of 1900 °C and can be formed by heating **D** in oxygen.

G is a solid that can exist as several different allotropes, most of which contain $\mathbf{G}_8$ molecules. **G** burns in air to form $\mathbf{G}O_2$ which dissolves in water to form an acidic solution. This solution reacts with sodium hydroxide to form the salt $Na_2\mathbf{G}O_3$.

(a) Suggest the identities of **D** and **G**.

D .... **G** ....
[1]

(b) Write equations for the reactions of $\mathbf{D}_2O_3$ with

(i) hydrochloric acid,

.... [2]

(ii) sodium hydroxide.

.... [2]

(c) Suggest the type of bonding and structure in $\mathbf{D}_2O_3$.

.... [1]

(d) Write an equation for the formation of an acidic solution when $\mathbf{G}O_2$ dissolves in water.

.... [1]

6 The fifth to eighth ionisation energies of three elements in the third period of the Periodic Table are given. The symbols used for reference are **not** the actual symbols of the elements.

	ionisation energies, kJ mol^{-1}			
	fifth	sixth	seventh	eighth
X	7012	8496	27 107	31 671
Y	6542	9362	11 018	33 606
Z	7238	8781	11 996	13 842

(i) State and explain the group number of element **Y**.

group number ....

explanation ....

.... [1]

(ii) State and explain the general trend in **first** ionisation energies across the third period.

....

....

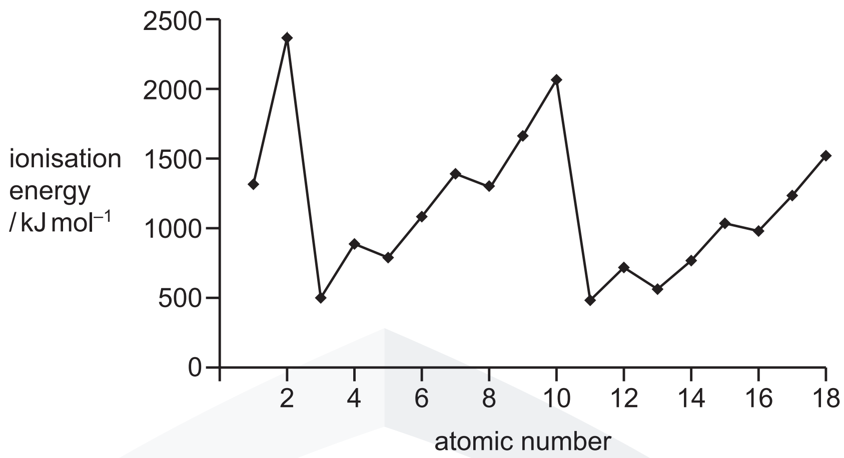
.... [2]

(iii) Complete the electronic configuration of element **X**.

$1s^2$ .... [1]

7 The Periodic Table is arranged such that the properties of the elements show a number of trends.

(a) A plot of the first ionisation energies for the first 18 elements is shown.



(i) Explain why the values show a general increase from atomic number 11 to 18.

....

....

.... [2]

(ii) Explain the decreases in first ionisation energies between

- atomic numbers 12 and 13,

....

....

....

- atomic numbers 15 and 16.

....

....

....

[4]

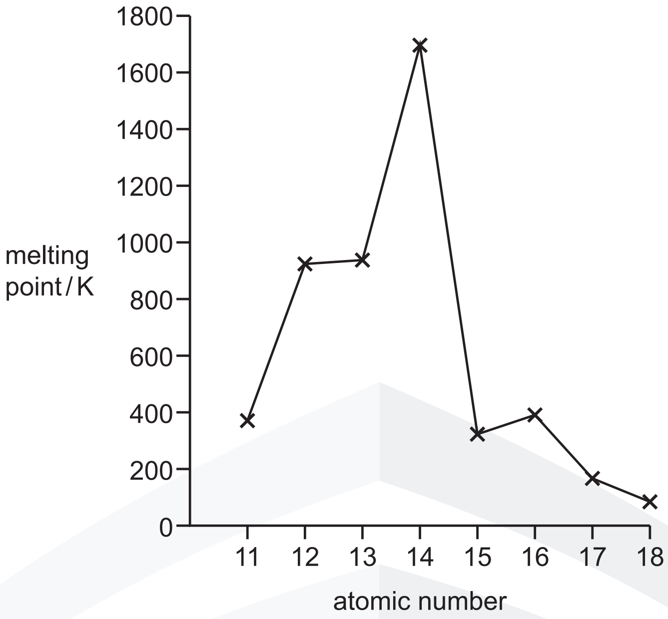
(iii) Suggest an explanation for the trend in the first ionisation energies of the elements with atomic numbers 2, 10 and 18.

....

....

.... [2]

(b) A plot of the melting points of the elements across the third period is shown.



(i) Explain the increase in melting point from atomic number 11 to 12.

....

....

.... [2]

(ii) Suggest a reason why the increase from atomic number 12 to 13 is much smaller than the increase from atomic number 11 to 12.

....

.... [1]

(iii) State and explain the pattern of the melting points from atomic number 15 to 18.

....

....

....

.... [3]

(iv) Explain why the element with atomic number 14 has a melting point so much higher than the rest of the elements in the third period.

....

.... [1]

8 **(a)** The table shows information about some of the elements in the third period.

element	Na	Mg	A*l*	P	S	C*l*
atomic radius / nm	0.186	0.160	0.143	0.110	0.104	0.099
radius of most common ion / nm	0.095	0.065	0.050	0.212	0.184	0.181
maximum oxidation number of the element in its compounds	+1					+7

(i) Complete the table to show the maximum oxidation number of each element in its compounds. [1]

(ii) Explain why the atomic radius of elements in the third period decreases from Na to C*l*.

....

....

....

....

.... [3]

(iii) The radius of the most common ion of Mg is much smaller than the radius of the most common ion of S.

Identify both ions and explain the difference in their radii.

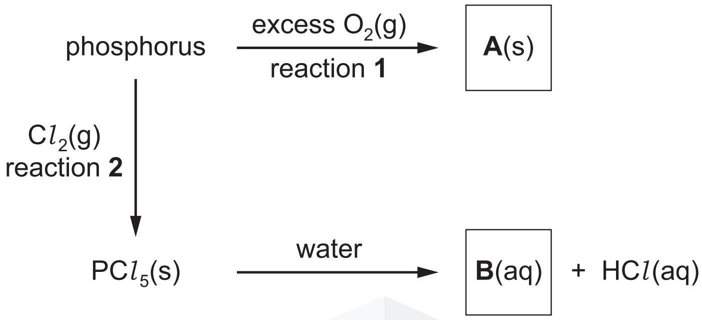
....

....

.... [2]

(b) Phosphorus is a non-metal in the third period. It reacts vigorously with excess oxygen but slowly with chlorine.

Some reactions of phosphorus are shown.



(i) Write an equation to represent reaction **1**, the formation of compound **A**.

.... [1]

(ii) Give **two** observations you could make in reaction **2**.

1. ....

2. ....
[2]

(iii) Name compound **B**.

.... [1]

(c) Cerium is a lanthanoid metal that shows similar chemical reactions to some elements in the third period. Most of cerium's compounds contain Ce^{3+} or Ce^{4+} ions.

(i) Cerium shows the same structure and bonding as a typical metal.

Draw a labelled diagram to show the structure and bonding in cerium.

[2]

(ii) Cerium(IV) oxide, CeO_2, is a ceramic.

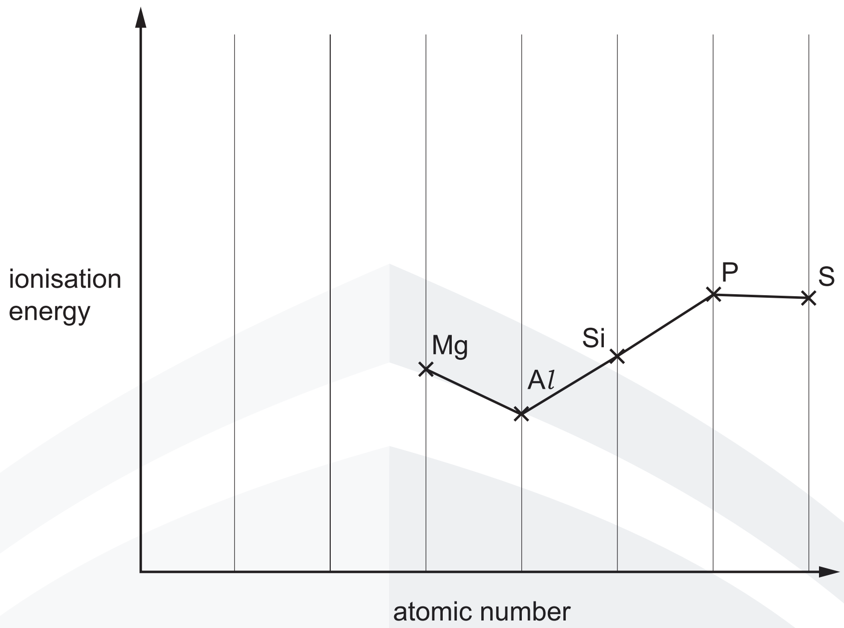
Suggest **two** physical properties of cerium(IV) oxide.

1. ....

2. ....
[2]

9 The elements in the third period, and their compounds, show trends in their physical and chemical properties.

(a) A sketch graph of the first ionisation energies of five successive elements in the third period is shown.



(i) Explain why there is a general increase in the first ionisation energy across the third period.

....

....

.... [2]

(ii) Sketch, on the graph, the position of the ionisation energies of the two elements that come before Mg in this sequence. [2]

(iii) Explain, with reference to electron arrangements, the decreases in first ionisation energy between Mg and A*l* and between P and S.

Mg and A*l* ....

....

....

P and S ....

....

....

[4]

(b) The chlorides of the elements in the third period behave in different ways when added to water, depending on their structure and bonding.

L and **M** are each a chloride of an element in Period 3. A student investigated **L** and **M** and their results are given.

L is a white crystalline solid with a melting point of 987 K. **L** dissolves in water to form an approximately neutral solution. Addition of NaOH(aq) to an aqueous solution of **L** produces a white precipitate.

M is a liquid with a boiling point of 331 K. **M** is hydrolysed rapidly by cold water to form a strongly acidic solution, a white solid and white fumes.

Identify **L** and **M**.
Explain any properties and observations described.
Give equations where appropriate.

(i) **L** is ....

....

....

....

.... [3]

(ii) **M** is ....

....

....

....

.... [3]

10 The elements sodium to sulfur react with chlorine. The melting points of some of the chlorides formed are shown.

chloride	$NaCl$	$MgCl_2$	$AlCl_3$	$SiCl_4$	PCl_3	SCl_2
melting point / K	1074	987	463	203	161	195

(a) Predict the shapes of $AlCl_3$ and PCl_3.

Draw diagrams to show the shapes, name the shapes and state the bond angles.

$AlCl_3$	PCl_3
shape	shape ....
angle	angle ....

[4]

(b) (i) Explain, in terms of structure and bonding, why the melting point of $SiCl_4$ is much lower than that of $NaCl$.

....

....

....

....

.... [3]

(ii) Explain why the melting point of $SiCl_4$ is higher than that of PCl_3.

....

....

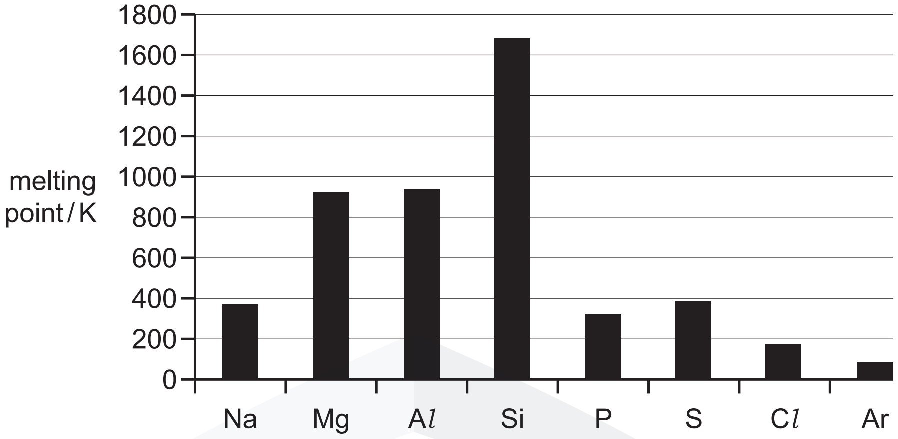
.... [2]

(iii) Draw the 'dot-and-cross' diagram of a molecule of $SiCl_4$.
Show outer electrons only.

[1]

11 The elements in Period 3 of the Periodic Table show variations in their behaviour across the period.

(a) The bar chart below shows the variation of melting points of the elements across Period 3.



In each of the following parts of this question you should clearly identify the interactions involved and, where appropriate, explain their relative magnitudes.

(i) Explain the general increase in melting point from Na to Al.

....

....

....

.... [3]

(ii) Explain the variation of melting points from P to Ar.

....

....

....

....

.... [3]

(iii) Explain why Si has a much higher melting point than any of the other elements in the period.

....

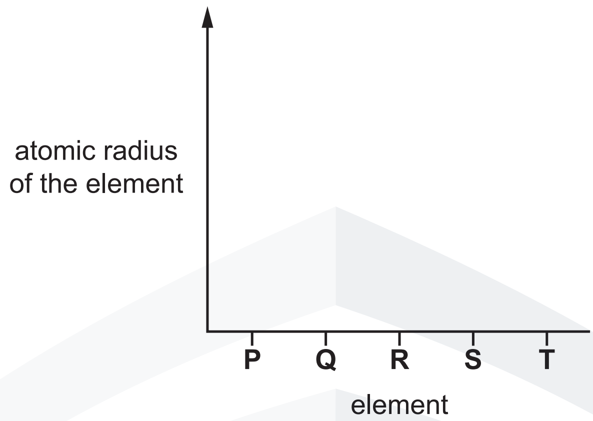
.... [1]

12 (b) **P**–**T** are successive elements in Period 3 of the Periodic Table.

The letters are **not** the symbols of the elements.

On the axes, sketch a graph to show the trend in the atomic radius of the elements **P**–**T**.

Explain your answer.



explanation ....

....

....

....

....

[3]

[M'18 P22 Q1]

13 **(d)** Silicon shows the same kind of bonding and structure as diamond.

(i) State the type of bonding and structure shown by silicon.

....

....

.... [2]

(ii) When silicon reacts with magnesium, Mg_2Si forms. Mg_2Si is thought to contain the Si^{4-} ion.

State the full electronic configuration of the Si^{4-} ion.

$1s^2$.. [1]

(iii) Solid Mg_2Si reacts with dilute hydrochloric acid to form gaseous SiH_4 and a solution of magnesium chloride.

Write an equation to show the reaction of solid Mg_2Si with dilute hydrochloric acid.

Include state symbols.

.... [2]

(iv) Predict the shape of the SiH_4 molecule.

.... [1]

(v) SiH_4 reacts spontaneously with oxygen to produce a white solid and a colourless liquid that turns anhydrous copper(II) sulfate blue. No other products are formed.

Write an equation for the reaction of SiH_4 with oxygen.

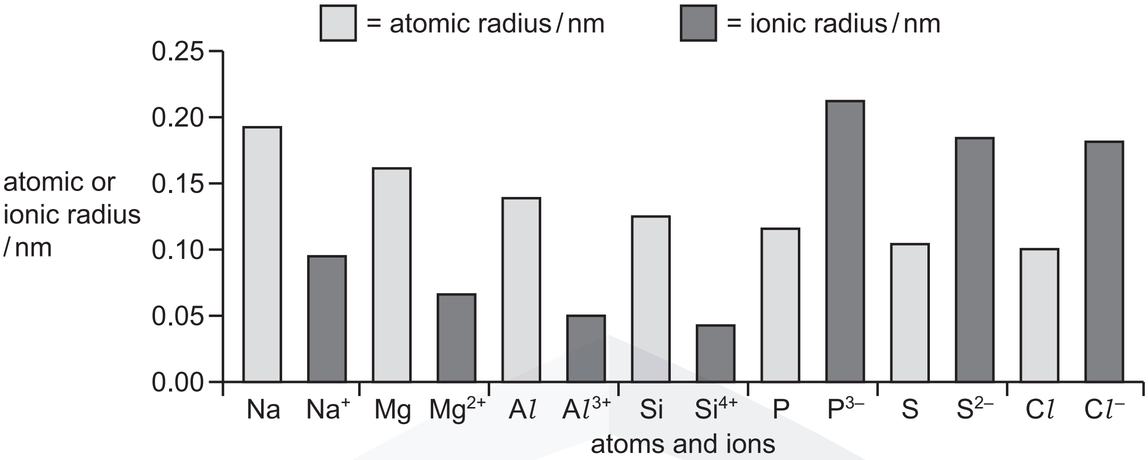
State symbols are **not** required.

.... [1]

[M'18 P22 Q2]

14 The elements in the third period exhibit periodicity in both their chemical and physical properties.

(a) A graph of the atomic and ionic radii across the third period is shown.



(i) Explain the decrease in atomic radius across the third period.

....

....

....

.... [2]

(ii) Explain why, for sodium to silicon, the ionic radii are less than the atomic radii.

....

.... [1]

(iii) Explain why, for phosphorus to chlorine, the ionic radii are greater than the atomic radii.

....

....

.... [2]

(b) The first ionisation energies of the elements across the third period show a general increase.

Aluminium and sulfur do **not** follow this general trend.

(i) Explain why aluminium has a lower first ionisation energy than magnesium.

....

....

.... [2]

(ii) Explain why sulfur has a lower first ionisation energy than phosphorus.

....

....

.... [2]

(c) The elements in the third period, from sodium to silicon, can react with chlorine to form chlorides.

(i) State and explain the pattern of change of oxidation number which occurs to both chlorine and the different Period 3 elements when they react together.

....

....

....

.... [3]

(ii) Give the equations to show the reactions of sodium chloride and silicon(IV) chloride when separately added to water.

sodium chloride ....

silicon(IV) chloride ....
[2]

(iii) Complete the table to describe the structure and bonding in sodium chloride and silicon(IV) chloride.

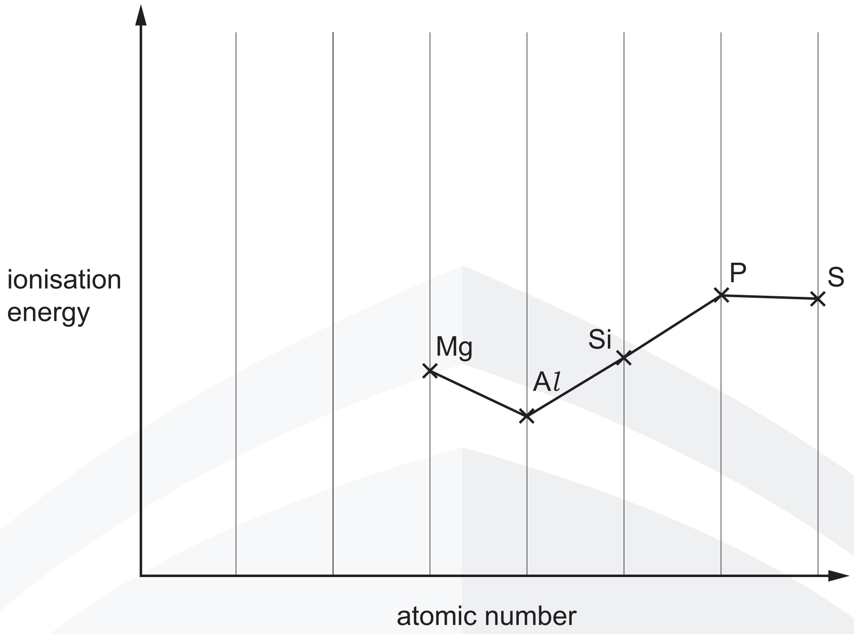
	structure	bonding
sodium chloride		
silicon(IV) chloride		

[2]

[J'18 P21 Q3]

15 The elements in the third period, and their compounds, show trends in their physical and chemical properties.

(a) A sketch graph of the first ionisation energies of five successive elements in the third period is shown.



(i) Explain why there is a general increase in the first ionisation energy across the third period.

....

....

.... [2]

(ii) Sketch, on the graph, the position of the ionisation energies of the two elements that come before Mg in this sequence. [2]

(iii) Explain, with reference to electron arrangements, the decreases in first ionisation energy between Mg and Al and between P and S.

Mg and Al ....

....

....

P and S ....

....

....

[4]

(b) The chlorides of the elements in the third period behave in different ways when added to water, depending on their structure and bonding.

L and **M** are each a chloride of an element in Period 3. A student investigated **L** and **M** and their results are given.

L is a white crystalline solid with a melting point of 987 K. **L** dissolves in water to form an approximately neutral solution. Addition of NaOH(aq) to an aqueous solution of **L** produces a white precipitate.

M is a liquid with a boiling point of 331 K. **M** is hydrolysed rapidly by cold water to form a strongly acidic solution, a white solid and white fumes.

Identify **L** and **M**.
Explain any properties and observations described.
Give equations where appropriate.

(i) **L** is ....

....

....

....

.... [3]

(ii) **M** is ....

....

....

....

.... [3]

The elements sodium to sulfur react with chlorine. The melting points of some of the chlorides formed are shown.

chloride	$NaCl$	$MgCl_2$	$AlCl_3$	$SiCl_4$	PCl_3	SCl_2
melting point / K	1074	987	463	203	161	195

(a) Predict the shapes of $AlCl_3$ and PCl_3.

Draw diagrams to show the shapes, name the shapes and state the bond angles.

$AlCl_3$	PCl_3
shape	shape ....
angle	angle ....

[4]

(b) **(i)** Explain, in terms of structure and bonding, why the melting point of $SiCl_4$ is much lower than that of $NaCl$.

....

....

....

....

.... [3]

(ii) Explain why the melting point of $SiCl_4$ is higher than that of PCl_3.

....

....

.... [2]

(iii) Draw the 'dot-and-cross' diagram of a molecule of $SiCl_4$.
Show outer electrons only.

[1]

[N'17 P22 Q1]

16 The table gives some data for elements in the third period and some of their compounds.

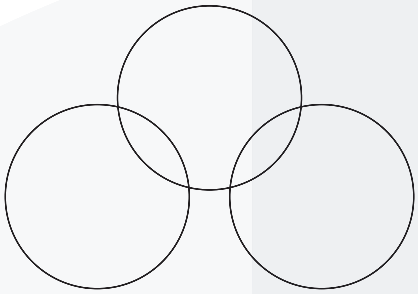
element	Na	Mg	Al	Si	P	S
type of bonding	metallic				covalent	covalent
formula of oxide					P_4O_{10}	SO_2
formula of chloride	NaCl	$MgCl_2$				SCl_2

(a) Complete the table to show the bonding in the elements, and the formulae of their oxides and chlorides. [3]

(b) SCl_2 is formed in the following reaction.

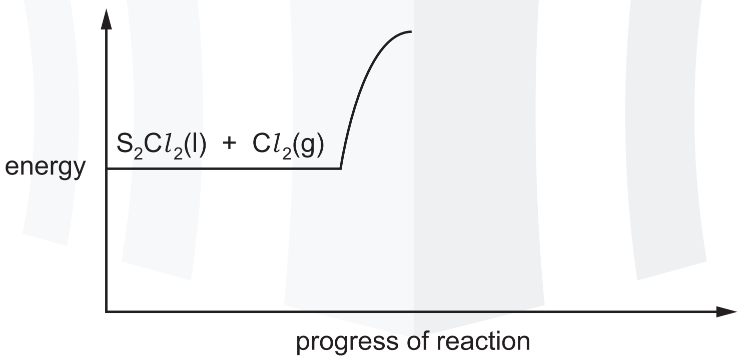
$$S_2Cl_2(l) + Cl_2(g) \rightleftharpoons 2SCl_2(l) \qquad \Delta H = -40.6\,\text{kJ mol}^{-1}$$

(i) Complete the 'dot-and-cross' diagram to show the bonding in a molecule of SCl_2. Show outer electrons only.



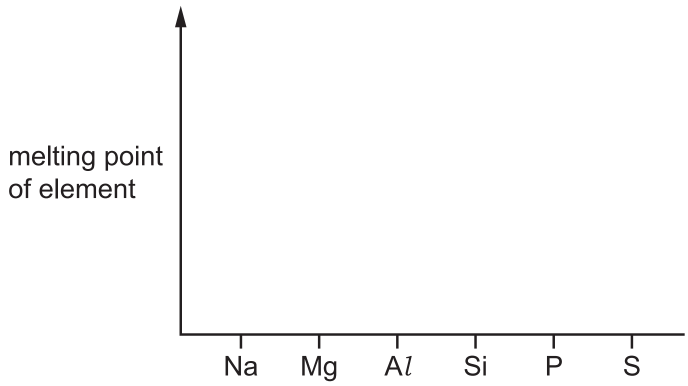
[1]

(ii) Complete and fully label the reaction pathway diagram for the reaction between S_2Cl_2 and Cl_2. Include labels for activation energy, E_a, and enthalpy change of the forward reaction, ΔH.



[2]

(c) **(i)** On the axes, sketch the trend in melting point of the elements Na to S.



[1]

(ii) Give three statements to explain your sketch.

1 ....

....

2 ....

....

3 ....

....

[3]

(d) Write an equation for the reaction of P_4O_{10} with water.

.... [1]

(e) SO_2 can be released into the atmosphere when fossil fuels containing sulfur are burnt.

State and explain one environmental consequence of the release of SO_2 into the atmosphere.

....

....

....

.... [2]

(f) The elements in the third period show a general increase in their first ionisation energies from left to right.

Identify **two** pairs of successive elements in the third period that do **not** agree with this statement.
For each pair, explain why the change in ionisation energy does **not** agree with this statement.

Use of the Data Booklet may help you to answer this question.

pair 1 ....

explanation ....

....

....

....

....

pair 2 ....

explanation ....

....

....

....

....

[4]

[N'18 P22 Q2]

PERIOD 3 WS 3

SECTION A

1 Which of the following oxides is **unlikely** to dissolve in aqueous sodium hydroxide?

A Al_2O_3 **B** MgO **C** SO_2 **D** SiO_2

2 An element of the third period (Na to S) is heated in chlorine. The product is purified and then added to water. The resulting solution is found to be neutral.

What is the element?

A sodium

B aluminium

C silicon

D phosphorus

3 Which statement explains the observation that magnesium hydroxide dissolves in aqueous ammonium chloride, but not in aqueous sodium chloride?

A The ionic radius of the NH_4^+ ion is similar to that of Mg^{2+} but not that of Na^+.

B NH_4Cl dissociates less fully than $NaCl$.

C The ions Na^+ and Mg^{2+} are isoelectronic (have the same number of electrons).

D The ion NH_4^+ acts as an acid.

4 Sulphur dioxide is an important food preservative.

What property makes sulphur dioxide useful in this role?

A It is a gas.

B It is a reducing agent.

C It reacts with oxygen to form sulphur trioxide.

D It reacts with water to form an acidic solution.

5 The chloride of element **Q** is hydrolysed by water to form an acidic solution and its oxide reacts with acid to form a salt.

What could be the element **Q**?

A magnesium

B aluminium

C silicon

D phosphorus

6 The propellant used in the solid rocket booster of a space shuttle is a mixture of aluminium and compound **X**. Compound **X** contains chlorine in an oxidation state of +7.

Which of the following could be compound **X**?

A NH_4Cl **B** NH_4ClO_3 **C** NH_4ClO_4 **D** N_2H_5Cl

7 When dangerous chemicals are transported by road, vehicles must carry signs that indicate what measures should be taken in the event of a spillage of the chemical carried.

Which material must be used if there were a spillage of metallic sodium?

A ethanol

B jets of water

C sand

D water spray

8 In an experiment, 0.1 g samples of Na_2O, MgO, P_4O_{10} and SO_2 are added to separate 100 cm^3 volumes of water.

For which oxide is the resulting mixture most alkaline?

A Na_2O **B** MgO **C** P_4O_{10} **D** SO_2

9 Consecutive elements X, Y, Z are in the third period of the Periodic Table. Element Y has the highest first ionisation energy and the lowest melting point.

What could be the identities of X, Y and Z?

A aluminium, silicon, phosphorus

B magnesium, aluminium, silicon

C silicon, phosphorus, sulfur

D sodium, magnesium, aluminium

10 The oxide and chloride of an element **X** are separately mixed with water. The two resulting solutions have the same effect on litmus.

What is element **X**?

A sodium

B magnesium

C aluminium

D phosphorus

11 When copper is extracted from its ores, the metal is not pure enough for electrical uses. The impure copper, which contains small amounts of silver and gold, is purified by electrolysis. During this process a ‘sludge’ forms beneath the anode which is found to contain silver and traces of gold.

Why is silver found in this sludge?

A Silver is less electropositive than copper.

B Silver is more dense than copper and falls off the cathode.

C Silver reacts with the electrolyte to form an insoluble chloride salt.

D Silver reacts with the electrolyte to form an insoluble sulfate salt.

12 Which oxide, when mixed with water, will produce the most acidic solution?

A CO **B** CO_2 **C** SiO_2 **D** P_2O_5

13 Which element of the third period requires the least number of moles of oxygen for the complete combustion of 1 mol of the element?

A aluminium

B magnesium

C phosphorus

D sodium

14 In the extraction of aluminium by the electrolysis of molten aluminium oxide, why is cryolite added to the aluminium oxide?

A to ensure the aluminium is not oxidised

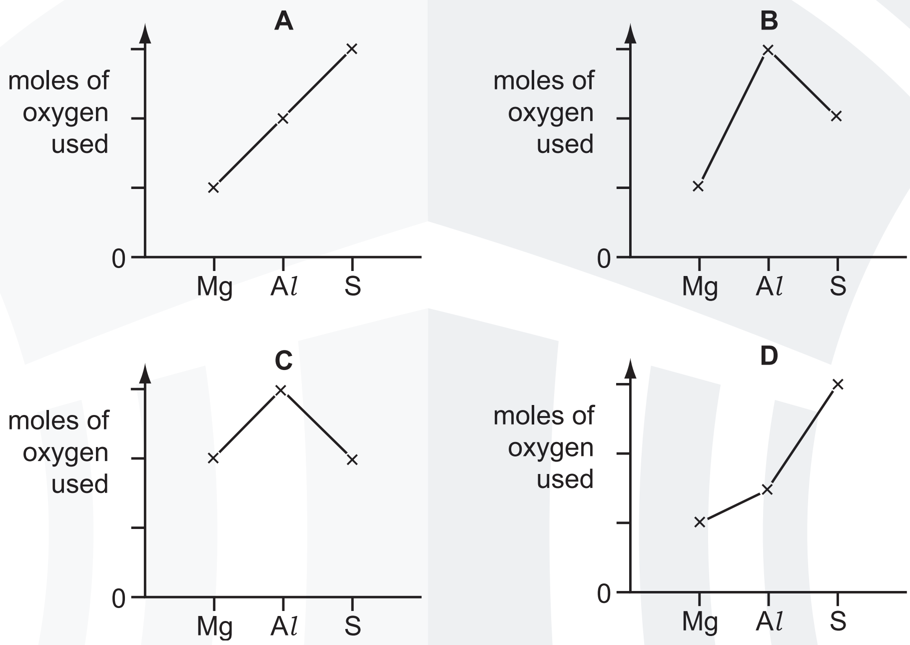
B to ensure the anode is not oxidised

C to lower the melting point of the aluminium oxide

D to prevent corrosion of the cathode

15 One mole of magnesium, aluminium and sulphur are each completely burned in an excess of oxygen gas.

Which graph shows the moles of oxygen used in each case?



16 The oxide and chloride of an element **X** are separately mixed with water. The two resulting solutions have the same effect on litmus.

What is element **X**?

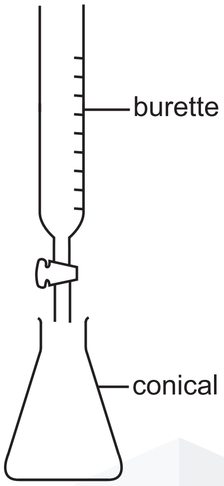
A sodium

B magnesium

C aluminium

D phosphorus

17



Which of these acid-base (neutralisation) reactions could be titrated using the apparatus shown above to give a sharp end-point?

A sulphuric acid and aluminium oxide

B sulphuric acid and magnesium hydroxide

C sulphuric acid and magnesium oxide

D sulphuric acid and sodium hydroxide

18 In the extraction of aluminium by electrolysis, why is it necessary to dissolve aluminium oxide in molten cryolite?

A to reduce the very high melting point of the electrolyte

B cryolite provides the ions needed to carry the current

C cryolite reacts with the aluminium oxide to form ions

D molten aluminium oxide alone would not conduct electricity

19 A cheap carbon monoxide detector for a gas heater consists of a patch containing palladium chloride crystals. When carbon monoxide is present, the crystals turn from orange to black as the following reaction takes place.

$$\underset{\text{orange}}{CO(g) + PdCl_2(s)} + H_2O(l) \rightarrow CO_2(g) + \underset{\text{black}}{Pd(s)} + 2HCl(aq)$$

Which is the element whose oxidation number **decreases** in this reaction?

A carbon

B chlorine

C hydrogen

D palladium

20 Which element has the same oxidation number in all of its known compounds?

A beryllium

B chlorine

C nitrogen

D sulphur

21 Which ion is most polarising?

A Al^{3+}

B Ba^{2+}

C Mg^{2+}

D Na^{+}

22 At the age of 17, in a woodshed in Ohio, Charles Martin Hall discovered the commercial process for the production of aluminium metal by the electrolysis of a mixture of bauxite, Al_2O_3, and cryolite, Na_3AlF_6.

What is the main purpose of the cryolite?

A Al_2O_3 is covalent, and AlF_6^{3-} ions interact with it to produce Al^{3+} ions which can be discharged at the cathode.

B Cryolite is a base, forming $NaAlO_2$ with bauxite, enabling aluminium to be discharged at the anode.

C Cryolite reduces the melting point of the bauxite.

D Cryolite minimises the release of O^{2-} ions at the graphite anodes, which are otherwise burnt away to CO.

23 A mixture of the oxides of two elements of the third period is dissolved in water. The solution is approximately neutral.

What could be the constituents of the mixture?

A Al_2O_3 and MgO

B Na_2O and MgO

C Na_2O and P_4O_{10}

D SO_3 and P_4O_{10}

24 Sulphur dioxide is an important food preservative.

Which property makes sulphur dioxide useful in this role?

A It is a gas.

B It is a reducing agent.

C It reacts with oxygen to form sulphur trioxide.

D It reacts with water to form an acidic solution.

25 Which chlorine compound has bonding that can be described as ionic with some covalent character?

A NaCl **B** $MgCl_2$ **C** $AlCl_3$ **D** $SiCl_4$

26 Which of these equations represents the reaction of sulphur dioxide with an excess of aqueous sodium hydroxide?

A $SO_2 + NaOH \rightarrow NaHSO_3$

B $SO_2 + 2NaOH \rightarrow Na_2SO_3 + H_2O$

C $SO_2 + 2NaOH \rightarrow Na_2SO_4 + H_2O$

D $SO_2 + 2NaOH \rightarrow Na_2SO_4 + H_2$

27 0.02 mol of aluminium is burned in oxygen and the product is reacted with 2.00 mol dm^{-3} hydrochloric acid.

What minimum volume of acid will be required for complete reaction?

A 15 cm^3 **B** 20 cm^3 **C** 30 cm^3 **D** 60 cm^3

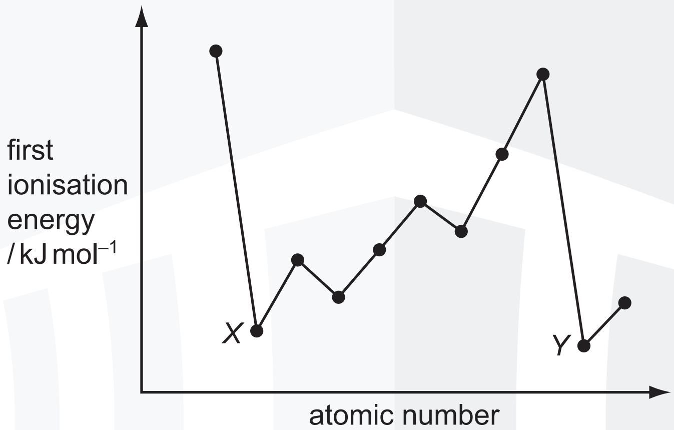
28 In 1999, researchers working in the USA believed that they had made a new element and that it had the following electronic configuration.

$$[Rn]\ 5f^{14}6d^{10}7s^{2}7p^{6}$$

In which Group of the Periodic Table would you expect to find this element?

A II **B** IV **C** VI **D** 0

29 The diagram shows the first ionisation energies of 11 consecutive elements.



Which type of elements are labelled *X* and *Y*?

A Group I metals

B Group II metals

C halogens

D noble gases

30 Why does aluminium oxide dissolve in sodium hydroxide solution?

A Aluminium oxide can behave as a base.

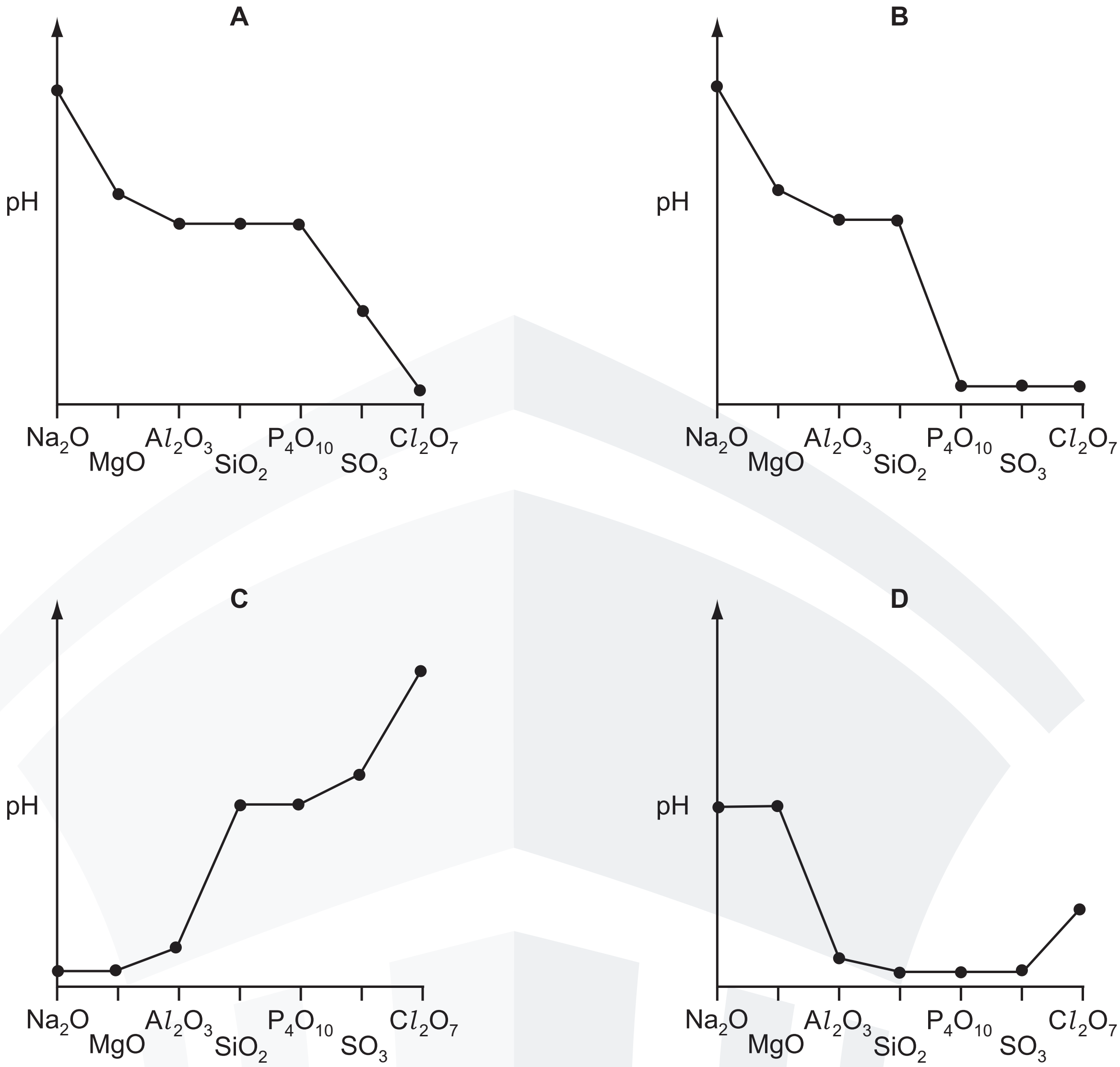
B Aluminium oxide can behave as an acid.

C Aluminium oxide has a giant structure.

D The bonding in aluminium oxide is ionic.

31 The highest oxides of the elements sodium to chlorine are separately added to water.

Which diagram best represents the pH of the resulting mixtures?



32 Which element shows the greatest tendency to form some covalent compounds?

A aluminium

B magnesium

C neon

D potassium

33 Total removal of the pollutant sulfur dioxide, SO_2, is difficult, both for economic and technical reasons. The quantities emitted from furnace chimneys can be lowered by using desulfurisation plants. The gases are scrubbed (washed) with calcium hydroxide to remove the SO_2.

What is the main product formed **initially**?

A $Ca(HSO_4)_2$ **B** CaS **C** $CaSO_3$ **D** $CaSO_4$

34 Which element shows the greatest tendency to form some covalent compounds?

A aluminium

B magnesium

C neon

D potassium

35 Why is the ionic radius of a chloride ion larger than the ionic radius of a sodium ion?

A A chloride ion has one more occupied electron shell than a sodium ion.

B Chlorine has a higher proton number than sodium.

C Ionic radius increases regularly across the third period.

D Sodium is a metal, chlorine is a non-metal.

36 Elements **X** and **Y** are both in period three.

When the chloride of **X** is added to water, it reacts and a solution of pH 2 is produced.

When the chloride of **Y** is added to water, it dissolves and a solution of pH 7 is produced.

Which statement explains these observations?

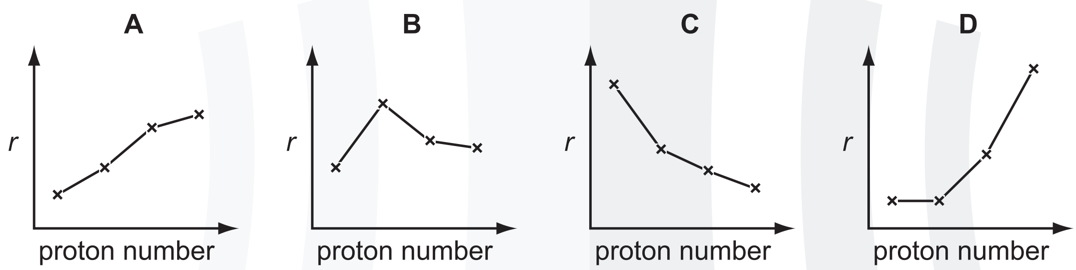
A Both chlorides hydrolyse in water.

B **X** is phosphorus and **Y** is aluminium.

C **X** is silicon and **Y** is sodium.

D **X** is sodium and **Y** is phosphorus.

37 Which diagram shows the variation of the metallic radius *r* of the Group I elements, Li, Na, K and Rb, with increasing proton (atomic) number?



38 Why is the ionic radius of a sulfide ion larger than the ionic radius of a potassium ion?

A Ionic radius always decreases with increasing atomic number.

B Positive ions have smaller radii than negative ions.

C The potassium ion has more protons in its nucleus than the sulfide ion.

D The sulfide ion is doubly charged; the potassium ion is singly charged.

39 Which oxide, when mixed with water, will produce the solution with the lowest pH?

A CO_2 **B** Na_2O **C** P_4O_{10} **D** SiO_2

40 Deposits of ammonium sulfate have been discovered in areas of high atmospheric pollution.

They are believed to arise from the following reaction.

$$SO_3 + H_2O + 2NH_3 \rightarrow (NH_4)_2SO_4$$

What does **not** occur in this reaction?

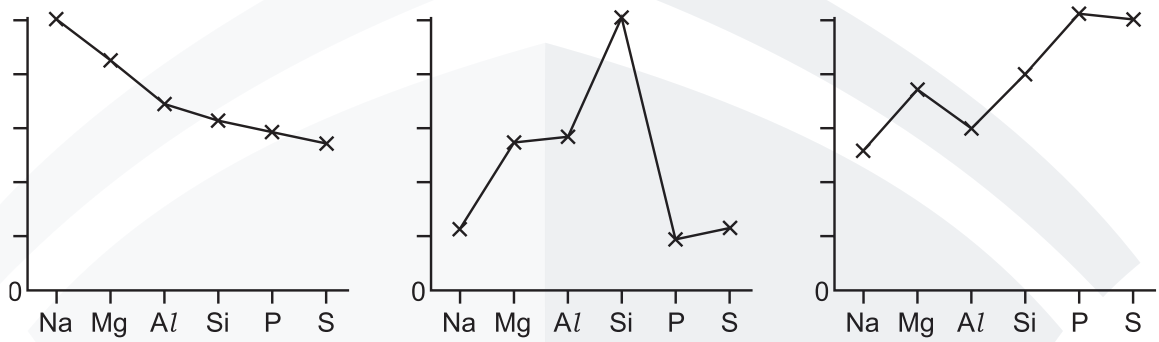
A acid / base neutralisation

B dative bond formation

C ionic bond formation

D oxidation / reduction

41 The trends in three physical properties of the elements Na, Mg, A*l*, Si, P and S are shown in the graphs.



Which physical property is **not** illustrated?

A atomic radius

B electrical conductivity

C first ionisation energy

D melting point

42 In the redox reaction shown, how do the oxidation states of vanadium and sulfur change?

$$VO_2^{+} + SO_2 \rightarrow V^{3+} + SO_4^{2-}$$

	vanadium		sulfur	
	from	to	from	to
A	+1	+3	0	–2
B	+1	+3	+4	+6
C	+5	+3	0	–2
D	+5	+3	+4	+6

43 The following half reactions occur when potassium iodate(V), KIO_3, in hydrochloric acid solution oxidises iodine to ICl_2^-.

$$IO_3^- + 2Cl^- + 6H^+ + 4e^- \rightarrow ICl_2^- + 3H_2O$$

$$I_2 + 4Cl^- \rightarrow 2ICl_2^- + 2e^-$$

What is the ratio of IO_3^- to I_2 in the balanced chemical equation for the overall reaction?

A 1 : 1 **B** 1 : 2 **C** 1 : 4 **D** 2 : 1

44 Consecutive elements **X**, **Y** and **Z** are in the third period of the Periodic Table. Element **Y** has the highest first ionisation energy and the lowest melting point of these three elements.

What could be the identities of **X**, **Y** and **Z**?

A sodium, magnesium, aluminium

B magnesium, aluminium, silicon

C aluminium, silicon, phosphorus

D silicon, phosphorus, sulfur

45 A $10\,cm^3$ sample of $0.30\,mol\,dm^{-3}$ $Tl^+NO_3^-$ required $20\,cm^3$ of $0.10\,mol\,dm^{-3}$ acidified NH_4VO_3 to oxidise it to Tl^{3+} in solution. Vanadium is the only element reduced in this reaction.

What is the oxidation number of the vanadium in the reduced form?

A +1 **B** +2 **C** +3 **D** +4

46 The reaction between aluminium powder and anhydrous barium nitrate is used as the propellant in some fireworks. The reaction produces the metal oxides and nitrogen.

$$10Al + 3Ba(NO_3)_2 \rightarrow 5Al_2O_3 + 3BaO + 3N_2$$

Which mass of barium oxide is produced when 5.40 g of aluminium powder reacts with an excess of anhydrous barium nitrate?

A 1.62 g **B** 3.06 g **C** 9.18 g **D** 10.2 g

47 Which oxide is insoluble in aqueous sodium hydroxide?

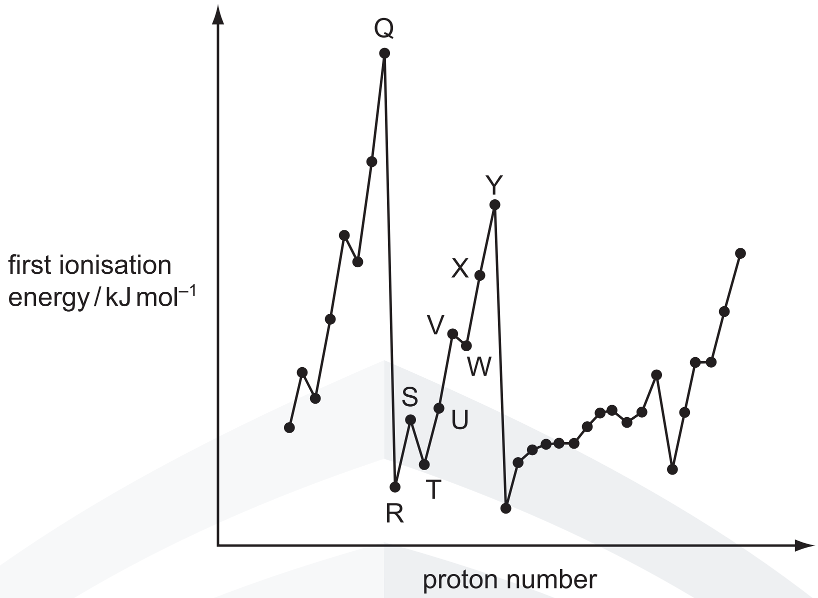
A MgO **B** Al_2O_3 **C** P_4O_{10} **D** SO_2

48 Elements **J** and **K** react together to form compound **L**. Elements **J** and **K** are both in Period 3. Element **J** has the smallest atomic radius in Period 3. There are only two elements in Period 3 which have a lower melting point than element **K**.

Which compound could be **L**?

A $MgCl_2$ **B** MgS **C** Na_2S **D** PCl_3

49 The graph below shows the variation of the first ionisation energy with the number of protons for some elements.



Which statement is correct?

A Elements Q and Y are in the same period in the Periodic Table.

B The general increase from elements R to Y is due to increasing atomic radius.

C The small decrease between elements S and T is due to decreased shielding.

D The small decrease between elements V and W is due to repulsion between paired electrons.

50 $AlCl_3$ vapour forms molecules with formula Al_2Cl_6 as it is cooled.

What happens to the bond angles during the change from $AlCl_3$ to Al_2Cl_6?

A Some decrease, some remain the same.

B Some increase, some remain the same.

C They all decrease.

D They all increase.

51 When making sparkler fireworks, a mixture of barium nitrate powder with aluminium powder, water and glue is coated onto wires and allowed to dry. At this stage, the following exothermic reaction may occur.

$$16Al + 3Ba(NO_3)_2 + 36H_2O \rightarrow 3Ba(OH)_2 + 16Al(OH)_3 + 6NH_3$$

Which conditions would be best to reduce the rate of this reaction during the drying process, and would also keep the aluminium and barium nitrate unchanged?

	temperature / K	pH
A	298	7
B	298	14
C	398	7
D	398	14

52 Which description of the bonding and acid / base nature of aluminium oxide is correct?

	bonding	acid / base nature
A	covalent	amphoteric
B	covalent	basic
C	ionic	amphoteric
D	ionic	basic

53 In which reaction is the species in **bold** acting as an oxidising agent?

A $\mathbf{2Ca} + O_2 \rightarrow 2CaO$

B $Cr_2O_7^{2-} + 8H^+ + \mathbf{3SO_3^{2-}} \rightarrow 2Cr^{3+} + 4H_2O + 3SO_4^{2-}$

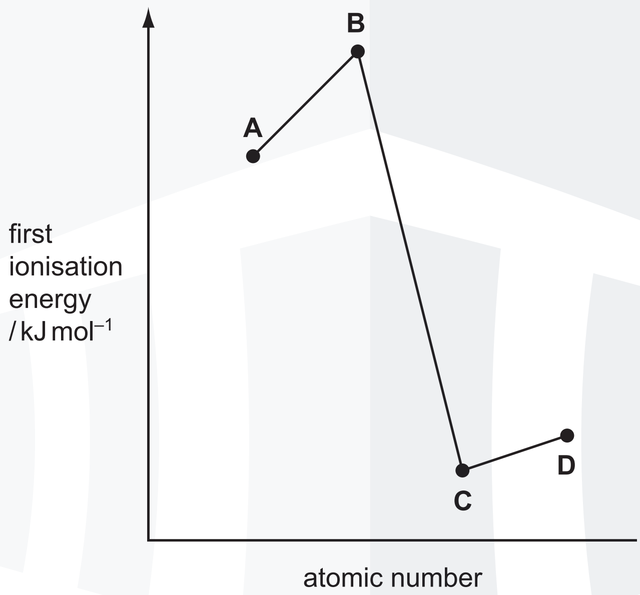
C $Mg + \mathbf{Fe^{2+}} \rightarrow Mg^{2+} + Fe$

D $\mathbf{SO_2} + 2H_2O + 2Cu^{2+} + 2Cl^- \rightarrow H_2SO_4 + 2H^+ + 2CuCl$

54 Shown on the graph are the relative values of the first ionisation energies of four elements that have consecutive atomic numbers.

One of the elements reacts with hydrogen to form a covalent compound with formula HX.

Which element could be X?



55 X and Y are oxides of different Period 3 elements.

If one mole of Y is added to water, the solution formed is neutralised by exactly one mole of X.

What could be the identities of X and Y?

	X	Y
A	Al_2O_3	P_4O_{10}
B	Al_2O_3	SO_3
C	Na_2O	P_4O_{10}
D	Na_2O	SO_3

56 A student investigated the chloride of a Period 3 element. This is what he wrote down as his record of what he did and what he saw.

> The compound was a white crystalline solid. It dissolved easily in water to give a solution of pH 12. When placed in a test-tube and heated in a roaring Bunsen flame, the compound melted after several minutes heating.

What can be deduced from this record?

A At least one of the recorded observations is incorrect.

B The compound was magnesium chloride, $MgCl_2$.

C The compound was phosphorus pentachloride, PCl_5.

D The compound was sodium chloride, $NaCl$.

57 Which properties do compounds of aluminium and silicon have in common?

A Aqueous solutions of their chlorides contain aluminium or silicon cations.

B Their chlorides have co-ordinate bonding.

C Their oxides are amphoteric.

D Their oxides are insoluble in water.

58 In which reaction does hydrogen behave as an oxidising agent?

A $H_2 + Cl_2 \rightarrow 2HCl$

B $C_2H_4 + H_2 \rightarrow C_2H_6$

C $N_2 + 3H_2 \rightarrow 2NH_3$

D $2Na + H_2 \rightarrow 2NaH$

59 Element **X**, in Period 3, has the following properties.

- Its oxide has a giant structure.
- It forms covalent bonds with chlorine.
- Its oxide will neutralise $HCl(aq)$.

What is element **X**?

A Mg **B** Al **C** Si **D** P

60 Which property is **not** associated with the element sodium?

A It can react with cold water to form hydrogen.

B It forms a basic oxide.

C It forms a neutral chloride.

D It is an oxidising agent.

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 Which statements about the commercial extraction of aluminium are correct?

1 The cathode reaction is $Al^{3+} + 3e^- \rightarrow Al$.

2 The lining of the electrolytic cell acts as the cathode.

3 The electrolyte is purified Al_2O_3 in Na_3AlF_6.

2 Which statements concerning the third period elements (sodium to argon) and their compounds are correct?

1 The elements become more electronegative from sodium to chlorine.

2 Aluminium oxide is the only oxide which is insoluble in water.

3 The maximum oxidation state is shown by silicon.

3 Which of the following statements are correct for the sequence of compounds below considered from left to right?

NaF MgO AlN SiC

1 The electronegativity difference between the elements in each compound increases.

2 The formula-units of these compounds are isoelectronic (have the same number of electrons).

3 The bonding becomes increasingly covalent.

4 It is suggested that the solid deposits of ammonium compounds on the leaves of trees found in areas of high pollution are caused by the following reaction.

$$2NH_3 + SO_3 + H_2O \rightarrow (NH_4)_2SO_4$$

Which of these take place in this reaction?

1 an acid-base reaction

2 ionic bond formation

3 oxidation and reduction

5 When ammonia, NH_3, is produced in a school or college laboratory, it is usually dried before being collected.

Which drying agents may be used to dry ammonia?

1 calcium oxide, CaO

2 phosphorus(V) oxide, P_4O_{10}

3 concentrated sulfuric acid, H_2SO_4

6 Which mixtures, on heating, produce the gas ND_3?
[D = $^{2}_{1}H$, an isotope of hydrogen]

1 $CaO(s)$ and $ND_4Cl(s)$

2 CH_3CN and NaOD in D_2O

3 NDH_3Cl and NaOD in D_2O

7 Water is added to anhydrous aluminium chloride to make a 0.1 mol dm^{-3} solution.

Which observations are correct?

1 The reaction is endothermic.

2 The solution is acidic.

3 The solution contains the ion $[Al(H_2O)_6]^{3+}$.

8 Compound **X**

- does not conduct electricity when in a liquid state,
- when added to water produces a solution that readily conducts electricity.

What could **X** be?

1 $MgCl_2$

2 $SiCl_4$

3 PCl_3

9 Which pairs of compounds contain one that is giant ionic and one that is simple molecular?

1 Al_2O_3 and Al_2Cl_6

2 SiO_2 and $SiCl_4$

3 P_4O_{10} and PCl_3

10 Which statements are correct?

1 Aluminium chloride dissolves in water to give an acidic solution.

2 Magnesium chloride dissolves in water to give a slightly acidic solution.

3 Sodium chloride dissolves in water to give an alkaline solution.

11 Zirconium, Zr, proton number 40, is a metal which is used in corrosion-resistant alloys.

Zirconium metal is extracted from the oxide ZrO_2 by the following sequence of reactions.

reaction 1 $ZrO_2 + 2Cl_2 + 2C \rightarrow ZrCl_4 + 2CO$

reaction 2 $ZrCl_4 + 2Mg \rightarrow Zr + 2MgCl_2$

Which statements about this extraction process are correct?

1 Carbon in reaction 1 behaves as a reducing agent.

2 Magnesium in reaction 2 behaves as a reducing agent.

3 Chlorine in reaction 1 behaves as a reducing agent.

12 Which statements concerning the third period elements (sodium to argon) and their compounds are correct?

1 The elements become more electronegative from sodium to chlorine.

2 Aluminium oxide is the only oxide which is insoluble in water.

3 The maximum oxidation state is shown by silicon.

13 Which oxides react with water to give a solution of pH 10 or higher?

1 CaO

2 Na_2O

3 SrO

14 Why does aluminium chloride, Al_2Cl_6, sublime at the relatively low temperature of 180 °C?

1 The intermolecular forces between the Al_2Cl_6 molecules are weak.

2 The co-ordinate bonds between aluminium and chlorine are weak.

3 The covalent bonds between aluminium and chlorine are weak.

15 When added to water, which oxides will **not** cause a change in pH?

1 Al_2O_3

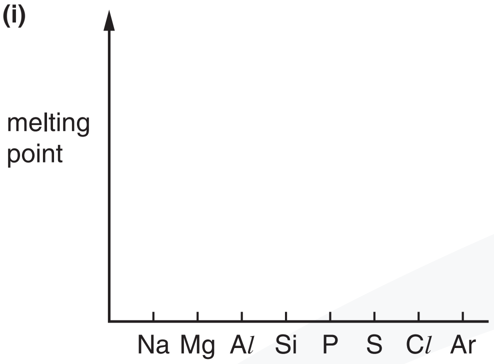
2 SiO_2

3 P_4O_{10}

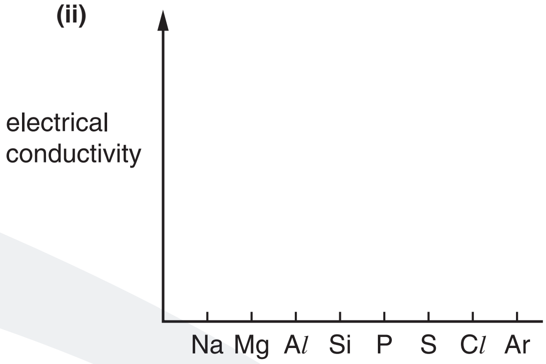
PERIOD 3 WS 4

1 **(a)** The use of the *Data Booklet* is relevant to this question. Complete these sketches for elements of the third period (sodium to argon) to show how each property changes along the period.

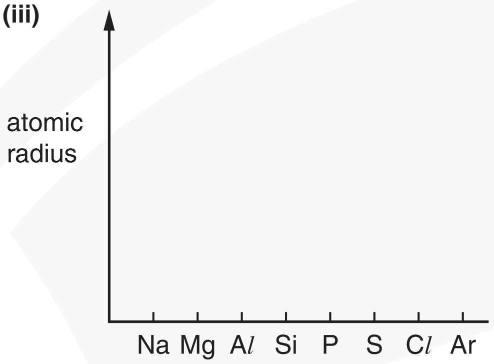
(i)



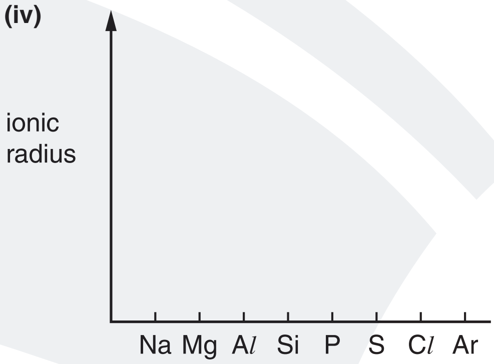
(ii)



(iii)



(iv)



[6]

(b) **(i)** In the boxes below, write the formulae of **one** of the oxides of each of these five elements.

sodium	magnesium	aluminium	phosphorus	sulphur

(ii) Write an equation for sodium oxide reacting with water.

....

(iii) Write an equation for your chosen oxide of sulphur reacting with an alkali.

....[3]

2 The oxides of the third period include the following:

Na_2O; MgO; Al_2O_3; SO_2; SO_3.

(a) Showing outer electrons only, draw a dot-and-cross electron diagram for magnesium oxide, MgO.

[1]

(b) From the list above, identify one oxide (in each case) which fits the description given.

(i) An oxide that reacts with water forming a strongly alkaline solution.

....

(ii) An oxide that is insoluble in water.

....

(iii) An oxide that reacts vigorously with water forming a strongly acidic solution.

....

(iv) An oxide that has a simple molecular structure.

....

(v) An oxide that acts as a food preservative.

....

[5]

(c) Write equations for the reaction of

(i) aluminium oxide and dilute hydrochloric acid,

....

(ii) sulphur dioxide and aqueous sodium hydroxide.

....

[2]

3 This question refers to the elements shown in the Periodic Table below.

							H										He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr

(a) From the elements shown, identify in **each** case **one** element that has the property described. Give the name or formula of the element.

(i) An element that has a molecule which contains only one atom.

....

(ii) An element that has a molecule which contains only four atoms.

....

(iii) The element that has the largest atomic radius.

....

(iv) The element that is a liquid at room temperature and pressure.

....

(v) The element in Period 3 (Na to Ar) that has the highest melting point.

....

(vi) The element in Period 3 (Na to Ar) that forms the largest anion.

....

[6]

(b) Use the elements shown opposite to answer the following questions.

(i) Give the formulae of **two** acidic oxides formed by the same element.

.... and ....

(ii) Give the name or formula of an oxide that is amphoteric.

....

(iii) Identify an element whose oxide dissolves readily in water to give a strongly alkaline solution.

....

(iv) Identify an element in Period 3 (Na to Ar) whose chloride dissolves in water to give a neutral solution.

....

(v) Identify an element that reacts with water to give a solution that can behave as an oxidising agent.

....

[6]

4 The table below gives data on some oxides of elements in Period 3 of the Periodic Table.

oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_{10}	SO_3
melting point / K	1193	3125	2345	1883	853	290
boiling point / K	1548	3873	3253	2503	–	318

(a) Write an equation for the reaction of aluminium with oxygen to form aluminium oxide.

....[1]

(c) Water was added to each of the oxides in the table.

Choosing a suitable oxide in each case, write an equation for the formation of

(i) an alkaline solution, ...

(ii) an acidic solution. ....[2]

5 Magnesium will react on heating with chlorine, or oxygen, or nitrogen to give the chloride, or oxide, or nitride respectively. Each of these compounds is ionic and in them magnesium has the same +2 oxidation state.

(a) **(i)** Write an equation, with state symbols, for the **second** ionisation energy of magnesium.

....

(ii) Use the *Data Booklet* to calculate the enthalpy change that occurs when one mole of gaseous magnesium ions, Mg^{2+}, is formed from one mole of gaseous magnesium atoms.

Include a sign in your answer.

enthalpy change = ... kJ mol^{-1}
[3]

(b) Separate samples of magnesium chloride and magnesium oxide are shaken with water. In **each** case, describe what you would see when this is done, and state the approximate pH of the water after the solid has been shaken with it.

(i) magnesium chloride

observation ....

approximate pH of the water ....

(ii) magnesium oxide

observation ....

approximate pH of the water ....

[4]

(c) Magnesium burns in nitrogen to give magnesium nitride, a yellow solid which has the formula Mg_3N_2.

Magnesium nitride reacts with water to give ammonia and magnesium hydroxide.

(i) Construct an equation for the reaction of magnesium nitride with water.

....

(ii) Does a redox reaction occur when magnesium nitride reacts with water?

Use the oxidation numbers of nitrogen to explain your answer.

....

....

....

.... [4]

6 Phosphorus is a very reactive non-metallic element which readily forms ionic compounds with metals such as calcium and covalent compounds with non-metals such as chlorine and oxygen.

(a) (i) Write an equation, with state symbols, for the **second** ionisation energy of calcium.

....

(ii) Use the *Data Booklet* to calculate the enthalpy change that occurs when one mole of gaseous calcium ions, Ca^{2+}, is formed from one mole of gaseous calcium atoms.
Include a sign in your answer.

enthalpy change = ... $kJ\ mol^{-1}$ [3]

(b) Separate small samples of phosphorus(V) chloride and phosphorus(V) oxide are shaken with water. In **each** case, describe what you would see when this is done, and state the approximate pH of the water after the solid has been shaken with it.

(i) phosphorus(V) chloride

observation ....

approximate pH of the water ....

(ii) phosphorus(V) oxide

observation ....

approximate pH of the water .... [4]

(c) When phosphorus is heated with an excess of sulfur in an inert atmosphere, a pale yellow solid, with formula P_4S_{10} is formed.
P_4S_{10} reacts with water to give phosphoric acid, H_3PO_4, and hydrogen sulfide, H_2S.

(i) Complete the equation for the reaction of P_4S_{10} with water.

P_4S_{10} + $16H_2O$ $\rightarrow$

(ii) Does a redox reaction occur when P_4S_{10} reacts with water?
Use the oxidation numbers of phosphorus to explain your answer.

....

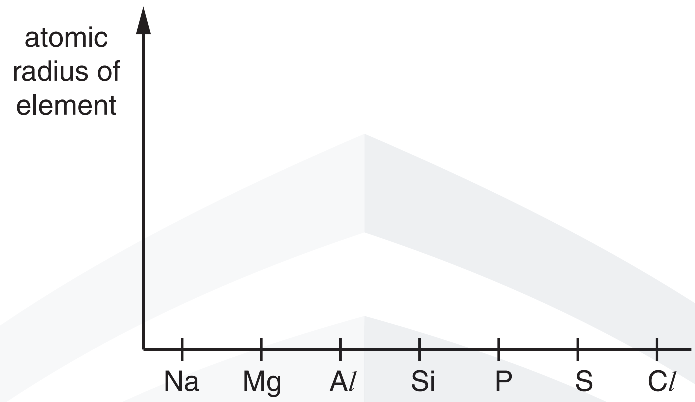
....

....

.... [4]

7 Elements in the same period of the Periodic Table show trends in physical and chemical properties. The grids on this page and on the opposite page refer to the elements of the third period, Na to C*l*.
On **each** of these grids, draw a clear sketch to show the variation of the stated property.
Below **each** grid, briefly explain the variation you have described in your sketch.
For each explanation you should refer to the important factors that cause the differences in the property you are describing.

(a)



explanation ....

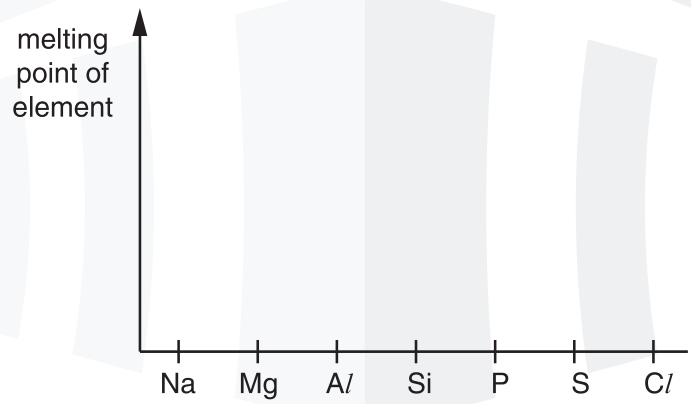
....

....

....

[3]

(b)



explanation ....

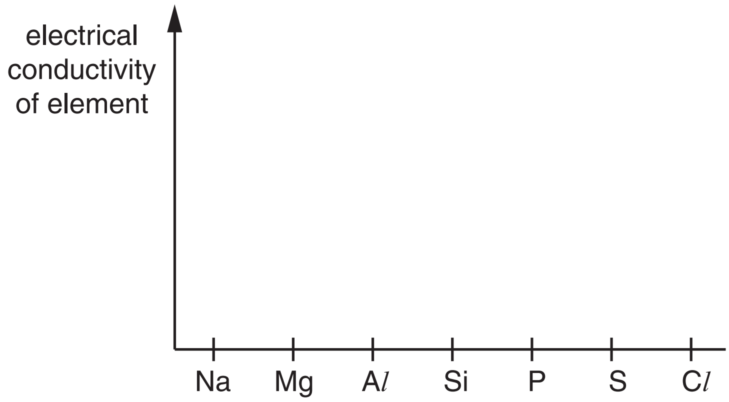
....

....

....

[4]

(c)



explanation ....

....

....

....

[4]

(d) The melting points of some of the oxides of the elements sodium to sulfur are given in the table below.

compound	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_6	SO_2
mp/K	1193	3173	2313	1883	297	198

(i) What type of bond is broken when **each** of the following compounds is melted?

Na_2O ....

SiO_2 ....

P_4O_6 ....

(ii) Identify **one** of these six oxides that has no reaction at all with water.

....

[4]

8 The table below gives data for some of the oxides of Period 3 elements.

oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_6	SO_2
melting point/°C	1275	2827	2017	1607	24	–75
bonding						
structure						

(a) Complete the table by filling in

(i) the 'bonding' row by using **only** the words 'ionic' **or** 'covalent',

(ii) the 'structure' row by using **only** the words 'simple' **or** 'giant'.

[2]

(b) From the table of oxides above, suggest the formula of **one** oxide that is **completely** insoluble in water.

.... [1]

(c) Separate samples of Na_2O and SO_2 were added to water.

(i) For **each** oxide, write a balanced equation for its reaction with water and suggest a numerical value for the pH of the resulting solution.

Na_2O

equation ....

pH ....

SO_2

equation ....

pH ....

(ii) Construct a balanced equation for the reaction that occurs when a solution of Na_2O in water reacts with a solution of SO_2 in water.

....

[5]

(d) Separate samples of the oxides MgO and SiO_2 are melted.
Each molten sample is then tested to see whether or not it conducts electricity.

Suggest what would be the results in **each** case. Explain your answers.

MgO ....

....

....

SiO_2 ....

....

....

[4]

9 This question refers to the elements shown in the portion of the Periodic Table given below.

							H										He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr

(a) From this table, identify in **each** case **one** element that has the property described. Give the **symbol** of the element in each case.

(i) The element that has a molecule which contains exactly eight atoms.

....

(ii) The element that forms the largest cation.

....

(iii) An element that floats on water and reacts with it.

....

(iv) An element that reacts with water to give a solution that can behave as an oxidising agent.

....

(v) An element whose nitrate gives a brown gas on thermal decomposition.

....

[5]

(b) **(i)** Give the formula of the oxide of the most electronegative element.

....

(ii) Several of these elements form more than one acidic oxide.
Give the formulae of **two** such oxides formed by the **same** element.

.... and ....

[3]

The formulae and melting points of the fluorides of the elements in Period 3, Na to C*l*, are given in the table.

formula of fluoride	NaF	MgF_2	AlF_3	SiF_4	PF_5	SF_6	ClF_5
m.p./K	1268	990	1017	183	189	223	170

(c) **(i)** Suggest the formulae of **two** fluorides that could possibly be ionic.

....

(ii) What is the shape of the SF_6 molecule?

....

(iii) In the sequence of fluorides above, the oxidation number of the elements increases from NaF to SF_6 and then falls at ClF_5.
Attempts to make ClF_7 have failed but IF_7 has been prepared.
Suggest an explanation for the existence of IF_7 and for the non-existence of ClF_7.

....

....

....

[4]

10 **(c)** Write an equation for the reaction of silicon tetrachloride with water.

....[1]

(d) What is the pH of the solution formed when **each** of the following compounds is dissolved in water?

$NaCl$ ....

PCl_5 .... [2]

(e) When solid aluminium chloride is heated above 451 K, a vapour is formed which has M_r = 267.
When this vapour is heated above 1100 K, the vapour has M_r = 133.5.

(i) What are the molecular formulae of these two forms of aluminium chloride?

at 460 K .... at 1150 K ....

(ii) Draw a 'dot-and-cross' diagram of the form of aluminium chloride that exists at the **higher** temperature.

(iii) Draw a displayed formula of the form of aluminium chloride that exists at the **lower** temperature. Indicate clearly the different types of bonds present.

[5]

11 This question refers to the elements shown in the section of the Periodic Table below.

							H										He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr

(a) From this list of elements, identify in **each** case **one** element that has the property described. Give the symbol of the element.

(i) an element that sinks in cold water and reacts readily with it

....

(ii) an element that forms an oxide that is a reducing agent

....

(iii) the element that has the largest first ionisation energy

....

(iv) the metal in Period 3 (Na to Ar) that has the smallest cation

....

(v) the element which has a giant molecular structure **and** forms an oxide which also has a giant molecular structure

....

(vi) the element in Period 3 (Na to Ar) with the greatest electrical conductivity

....

[6]

(b) From the section of the Periodic Table above, identify **two** elements whose hydrides form hydrogen bonds between their molecules.

.... and .... [1]

(c) Use the elements in Period 3 (Na to Ar) in the section of the Periodic Table opposite to identify the oxide(s) referred to below.
In **each** case, give the formula of the oxide(s).

(i) an oxide which has no reaction with water

....

(ii) **two** acidic oxides formed by the same element

.... and ....

(iii) an oxide which dissolves readily in water to give a strongly alkaline solution

....

(iv) an oxide which is amphoteric

....

[5]

(d) Chlorine is very reactive and will form compounds by direct combination with many elements.

Describe what you would see when chlorine is passed over separate heated samples of sodium and phosphorus. In **each** case write an equation for the reaction.

sodium ....

....

....

phosphorus ....

....

.... [4]

(e) Magnesium chloride, $MgCl_2$, and silicon tetrachloride, $SiCl_4$, each dissolve in or react with water.

Suggest the approximate pH of the solution formed in **each** case.

$MgCl_2$ .... $SiCl_4$ ....

Explain, with the aid of an equation, the difference between the two values.

....

....

....

.... [5]

12 The elements of the third period of the Periodic Table form chlorides of general formula ECl_x where E represents the element. These chlorides show a variation in oxidation number from sodium to sulfur.

(a) (i) Use the information given to complete the table below.

formula of chloride	$NaCl$	$MgCl_2$	$AlCl_3$	$SiCl_4$	PCl_3	SCl_2
oxidation number of element in the chloride						

(ii) By considering the electron configurations of the elements, explain the variation in oxidation number in the chlorides from Na to Al and from Si to S.

Na to Al ....

....

Si to S ....

....

[5]

Sodium hydride, NaH, is a colourless crystalline solid which melts at 800 °C and has the same crystal structure as sodium chloride which has a melting point of 808 °C. When molten sodium chloride is electrolysed using graphite electrodes, a shiny deposit, **D**, forms on the cathode and a greenish-yellow gas is evolved from the anode. When molten sodium hydride is electrolysed, under suitable conditions using graphite electrodes, the same shiny deposit **D** is formed on the cathode and a colourless gas, **G**, is evolved from the anode.

(b) (i) Describe with the aid of a diagram the bonding in a sodium chloride crystal.

(ii) Suggest the type of bonding that is present in sodium hydride.

....

(iii) What is the oxidation number of hydrogen in sodium hydride?

....

(iv) Draw a 'dot-and-cross' diagram for sodium hydride. Show outer electrons only.

(v) The metals magnesium and aluminium form hydrides with formulae MgH_2 and AlH_3. The non-metals phosphorus and sulfur form hydrides with formulae PH_3 and H_2S.
By considering their positions in the Periodic Table, suggest oxidation numbers for these four elements in their hydrides.

compound	MgH_2	AlH_3	PH_3	H_2S
oxidation number of element in the hydride				

[8]

At room temperature, the chlorides of sodium, magnesium and aluminium are all solids which dissolve in water.
The hydrides of sodium, magnesium and aluminium are also solids which react with water with the rapid evolution of the **same** colourless gas **G** in each case.

(c) (i) What is the pH of the solutions formed when separate samples of sodium chloride, magnesium chloride, and aluminium chloride are dissolved in water?

chloride	sodium	magnesium	aluminium
pH			

(ii) Suggest an equation for the reaction between sodium hydride and water.

....

(iii) Suggest a value for the pH of the solution formed in **(ii)**.

....

[4]

At room temperature, the chlorides of silicon, phosphorus and sulfur are all low melting point solids or low boiling point liquids that can be seen to react with water.

(d) (i) Suggest what type of bonding is present in sulfur dichloride, SCl_2.

....

(ii) Write a balanced equation for the reaction between the chloride of silicon, $SiCl_4$, and water.

.... [2]

13 The oxides of the elements of the third Period behave differently with NaOH(aq) and HC*l* (aq). In some cases, no reaction occurs.

Complete the table below by writing a balanced equation for any reaction that occurs, with heating if necessary. If you think no reaction takes place write 'no reaction'.

You do not need to include state symbols in your answers.

.....MgO(s) + ... NaOH (aq) $\rightarrow$
.....MgO(s) + ... HC*l* (aq) $\rightarrow$
.....Al_2O_3(s) + ... NaOH (aq) + ...H_2O (l) $\rightarrow$
.....Al_2O_3(s) + ... HC*l* (aq) $\rightarrow$
.....SO_2(g) + ... NaOH (aq) $\rightarrow$
.....SO_2(g) + ... HC*l* (aq) $\rightarrow$

[6]

14 Oxides are compounds which usually contain oxygen combined with one other element.

Oxides are classified as follows.

acidic alkaline amphoteric basic

(a) **Using these terms only**, complete the table to describe the oxides of the elements of the third period of the Periodic Table sodium to sulfur.

Na_2O	MgO	Al_2O_3	SiO_2	P_4O_{10}	SO_2	Cl_2O_7
						acidic

[4]

(b) Give the names of **two** elements from sodium to chlorine which form more than one oxide.

.... and .... [1]

(c) Sodium reacts with water.

(i) Describe, as fully as you can, what you would see when a piece of sodium is reacted with water.

....

....

....

(ii) Write an equation for the reaction of sodium with water.

....

[4]

(d) Sulfur dioxide is present in small, but significant, amounts in the Earth's atmosphere.

(i) State **one** way by which sulfur dioxide enters the atmosphere.

....

(ii) Give the formula of another sulfur compound which is formed in the atmosphere from sulfur dioxide.

....

(iii) What are the environmental consequences of the compound you have identified in **(ii)**?

....
[3]

(e) Sulfur dioxide is used as a food preservative.
What property of sulfur dioxide enables it to act in this way?

.... [1]

(f) Another sulfur compound which is present in the Earth's atmosphere is carbonyl sulfide, OCS. The sequence of atoms in the molecule is oxygen-carbon-sulfur and the molecule is **not** cyclic.

(i) Draw a 'dot-and-cross' diagram of the OCS molecule.
Show outer electrons only.

(ii) Suggest a value for the O – C – S bond angle.

....

[2]

15 The elements of the third period of the Periodic Table, sodium to sulfur, all form chlorides by direct combination.

(a) **(i)** Sulfur forms a number of chlorides which are liquid at room temperature.
Which other element of the third period forms a chloride which is liquid at room temperature?

....

(ii) Name **one** element of the third period which burns in chlorine with a coloured flame.

....

(iii) Aluminium chloride may be produced by passing a stream of chlorine over heated aluminium powder in a long hard-glass tube.
State **two** observations you could make during this reaction.

.... and ....

(iv) Write a balanced equation, with state symbols, for this reaction of aluminium with chlorine.

....

(v) No chloride of argon has ever been produced.
Suggest a reason for this.

....

....

[7]

(b) When chlorides of the elements of the third period are added to water, some simply dissolve while others can be seen to react with the water.

(i) Complete the table below, stating how the chlorides of Na, A*l*, and Si behave when mixed with water. In the first column use only the terms 'dissolve' or 'react'.

element	Does the chloride dissolve or react?	approximate pH of the resulting solution
Na		
A*l*		
Si		

(ii) What *type of reaction* takes place between a chloride and water?

....

[7]

16 Each of the elements Na to C*l* forms at least one oxide. Na_2O is an ionic oxide, SO_2 is a covalent oxide. Both oxides react with water.

(i) Write an equation for the reaction of **each** of these oxides with water.

Na_2O ....

SO_2 ....

(ii) What is the pH of the resulting solution in **each** case?

Na_2O .... SO_2 ....

(iii) Write an equation for the reaction that occurs between the products of your reactions in **(i)**.

....

[5]

17 This question refers to the elements in the section of the Periodic Table shown below.

		H						He
Li	Be		B	C	N	O	F	Ne
Na	Mg		Al	Si	P	S	Cl	Ar
K	Ca	.... transition elements	Ga	Ge	As	Se	Br	Kr

(a) From this list of elements, identify in **each** case **one** element that has the property described. Give the **symbol** of the element.

(i) An element that floats on cold water and reacts readily with it.

....

(ii) An element that forms an oxide that is a reducing agent.

....

(iii) The element that has the smallest first ionisation energy.

....

(iv) The element which has a giant molecular structure **and** forms an oxide which has a simple molecular structure.

....

(v) The element in Period 3 (Na to Ar) that has the smallest anion.

....

(vi) The element in Period 3 (Na to Ar) which forms a chloride with a low melting point and an oxide with a very high melting point.

....

[6]

(b) Use the elements in Period 3 (Na to Ar) in the section of the Periodic Table opposite to identify the oxide(s) referred to below.
In **each** case, give the **formula** of the oxide(s).

(i) An oxide which when placed in water for a long time has no reaction with it.

....

(ii) An oxide which dissolves readily in water to give a strongly alkaline solution.

....

(iii) Two acidic oxides formed by the same element.

.... and ....

(iv) An oxide which is amphoteric.

....

[5]

(c) Fluorine reacts with other elements in Group VII to form a number of different compounds. Two such compounds and their boiling points are given in the table.

compound	ClF_3	BrF_3
boiling point / °C	12	127

(i) The two molecules have similar electronic configurations.
Showing outer electrons only, draw a 'dot-and-cross' diagram of the bonding in ClF_3.

(ii) The two molecules have the same shape.
Suggest why the boiling points are significantly different.

....

....

....

....

[4]

18 This question refers to the elements in the section of the Periodic Table shown below.

		H						He
Li	Be		B	C	N	O	F	Ne
Na	Mg		Al	Si	P	S	Cl	Ar
K	Ca	.... transition elements	Ga	Ge	As	Se	Br	Kr

(a) From this list of elements, identify in **each** case **one** element that has the property described. Give the **symbol** of the element.

(i) An element that when placed in cold water sinks and reacts readily.

....

(ii) An element whose molecules contain π bonding.

....

(iii) An element that forms a gaseous toxic oxide.

....

(iv) The element which has a giant molecular structure **and** forms an oxide which also has a giant molecular structure.

....

(v) An element that forms a covalent chloride which dissolves in water to give a conducting solution.

....

(vi) The element in Period 3 (Na to Ar) with the greatest electrical conductivity.

....

[6]

(b) Some of the elements in Period 3 (Na to Ar) burn with a coloured flame when heated in oxygen or chlorine.

(i) Give the symbol of **one** such element, the formula of the **oxide** formed, and state the flame colour that would be seen.

symbol of element ....

formula of oxide ....

flame colour ....

(ii) For the element you have used in **(i)**, give the formula of the chloride formed, and state the pH of the solution produced when this chloride is shaken with water.

formula of chloride ....

pH of solution ....

[4]

(c) Chlorine reacts with both bromine and iodine to form $BrCl$ and ICl respectively.
The melting points of chlorine and the two chlorides are shown in the table.

substance	Cl_2	$BrCl$	ICl
m.p. / °C	–101	–66	24

(i) Showing outer electrons only draw a 'dot-and-cross' diagram of the bonding in ICl.

(ii) Suggest why the melting points increase from Cl_2 to ICl.

....

....

....

(iii) Suggest which of these three molecules has the largest permanent dipole.
Explain your answer.

....

....

....

[5]

19 This question refers to the elements in the section of the Periodic Table shown below.

		H						He
Li	Be		B	C	N	O	F	Ne
Na	Mg		Al	Si	P	S	Cl	Ar
K	Ca	.... transition elements	Ga	Ge	As	Se	Br	Kr

(a) From this list of elements, identify in **each** case **one** element that has the property described. Give the **symbol** of the element.

(i) An element that has molecules which consist of single atoms.

....

(ii) An element that has a molecule which contains exactly four atoms.

....

(iii) The element that is a liquid at room temperature and pressure.

....

(iv) The element in Period 3 (Na to Ar) that has the largest atomic radius.

....

(v) The element in Period 3 (Na to Ar) that has the highest melting point.

....

(vi) The element in Period 3 (Na to Ar) that forms the largest anion.

....

(vii) An element that reacts with water to give a solution that can behave as an oxidising agent.

....

[7]

(b) The formulae and melting points of some of the oxides of the elements in Period 3, Na to C*l*, are given in the table.

formula of oxide	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_6	SO_2	Cl_2O_7
m.p. / °C	1132	2830	2054	1710	24	–73	–92

(i) Give the formulae of **two** of these oxides that have simple molecular structures.

.... and ....

(ii) Give the formula of one of these oxides that will give no reaction with water when placed in it for a long time.

....

(iii) Give the formula of the product formed when MgO is reacted with SO_2.

....

[4]

(c) The melting points of the elements Si to C*l* are given in the table.

element	Si	P	S	C*l*
m.p. / °C	1414	44	115	–102

(i) Explain why the melting point of Si is very much greater than those of the other three elements.

....

....

(ii) Suggest why the melting points of the other three elements are in the order S > P > C*l*.

....

....

....

....

[4]

20 Chlorine gas is manufactured by the electrolysis of brine using a diaphragm cell.

(a) **(i)** Write half-equations, including state symbols, for the reactions occurring at **each** of the electrodes of a diaphragm cell.

anode ....

cathode ....

(ii) In the diaphragm cell, the anode is made of titanium and the cathode is made of steel.

Suggest why steel is never used for the anode.

....

....

[3]

(b) Chlorine is very reactive and will form compounds by direct combination with many elements.

Describe what you would see when chlorine is passed over separate heated samples of sodium and phosphorus.
In **each** case write an equation for the reaction.

sodium

....

....

....

phosphorus

....

....

.... [4]

(c) Chlorine reacts with aqueous sodium hydroxide in two different ways, depending on the conditions used. In each case, water, sodium chloride and one other chlorine-containing compound are formed.

For **each** condition below, give the formula of the **other** chlorine-containing compound and state the oxidation number of chlorine in it.

condition	formula of **other** chlorine-containing compound	oxidation number of chlorine in this compound
cold dilute NaOH(aq)		
hot concentrated NaOH(aq)		

[4]

(d) Magnesium chloride, $MgCl_2$, and silicon tetrachloride, $SiCl_4$, each dissolve in or react with water.

Suggest the approximate pH of the solution formed in **each** case.

$MgCl_2$ .... $SiCl_4$ ....

Explain, with the aid of an equation, the difference between the two values.

....

....

....

.... [5]

21 The commonest form of iron(II) sulfate is the heptahydrate, $FeSO_4.7H_2O$. On heating at 90 °C this loses **some** of its water of crystallisation to form a different hydrated form of iron(II) sulfate, $FeSO_4.xH_2O$.

3.40 g of $FeSO_4.xH_2O$ was dissolved in water to form 250 cm^3 of solution.

A 25.0 cm^3 sample of this solution was acidified and titrated with 0.0200 mol dm^{-3} potassium manganate(VII).

In this titration 20.0 cm^3 of this potassium manganate(VII) solution was required to react fully with the Fe^{2+} ions present in the sample.

(a) The MnO_4^- ions in the potassium manganate(VII) *oxidise* the Fe^{2+} ions in the acidified solution.

(i) Explain, in terms of electron transfer, the meaning of the term *oxidise* in the sentence above.

....

.... [1]

(ii) Complete and balance the ionic equation for the reaction between the manganate(VII) ions and the iron(II) ions.

$MnO_4^-(aq)$ + $5Fe^{2+}(aq)$ + ...$H^+(aq)$ → ....(aq) + $5Fe^{3+}(aq)$ + ...$H_2O(l)$

[3]

(b) **(i)** Calculate the number of moles of manganate(VII) used in the titration.

[1]

(ii) Use the equation in **(a)(ii)** and your answer to **(b)(i)** to calculate the number of moles of Fe^{2+} present in the 25.0 cm^3 sample of solution used.

[1]

(iii) Calculate the number of moles of $FeSO_4.xH_2O$ in 3.40 g of the compound.

[1]

(iv) Calculate the relative formula mass of $FeSO_4.xH_2O$.

[1]

(v) The relative formula mass of anhydrous iron(II) sulfate, $FeSO_4$, is 151.8.

Calculate the value of x in $FeSO_4.xH_2O$.

[1]

22 **(d)** The chlorides of elements in Period 3 of the Periodic Table show different behaviours on addition to water, depending on their structure and bonding.

(i) Write equations to show the behaviour of sodium chloride, $NaCl$, and silicon chloride, $SiCl_4$, when separately added to an excess of water.

$NaCl$ ....

$SiCl_4$ ....

[2]

(ii) State and explain the differences in behaviour of these two chlorides when added to water, in terms of their structure and the bonding found in the compounds.

....

....

....

....

....

.... [4]

(e) Sulfur reacts with fluorine to form SF_6. State the shape and bond angle of SF_6.

shape of SF_6 ....

bond angle of SF_6 ....

[2]

23 **(d)** The elements in Period 3 of the Periodic Table show different behaviours in their reactions with oxygen.

(i) Describe what you would **see** when separate samples of magnesium and sulfur are reacted with oxygen.

Write an equation for each reaction.

magnesium

....

....

sulfur

....

....
[4]

(ii) Write equations for the reactions of aluminium oxide, Al_2O_3, with

sodium hydroxide,

....

hydrochloric acid.

....
[2]

(e) Phosphorus reacts with chlorine to form PCl_5.

State the shape of and two different bond angles in a molecule of PCl_5.

shape of PCl_5 ....

bond angles in PCl_5 ....
[2]

24 A 6.30 g sample of hydrated ethanedioic acid, $H_2C_2O_4.xH_2O$, was dissolved in water and the solution made up to 250 cm^3.

A 25.0 cm^3 sample of this solution was acidified and titrated with 0.100 mol dm^{-3} potassium manganate(VII) solution. 20.0 cm^3 of this potassium manganate(VII) solution was required to react fully with the ethanedioate ions, $C_2O_4^{2-}$, present in the sample.

(a) The MnO_4^- ions in the potassium manganate(VII) *oxidise* the ethanedioate ions.

(i) Explain, in terms of electron transfer, the meaning of the term *oxidise* in the sentence above.

....

.... [1]

(ii) Complete and balance the ionic equation for the reaction between the manganate(VII) ions and the ethanedioate ions.

$2MnO_4^-(aq) + 5C_2O_4^{2-}(aq) + ...H^+(aq) \rightarrow ....(aq) + 10CO_2(aq) + ...H_2O(l)$

[3]

(b) **(i)** Calculate the number of moles of manganate(VII) used in the titration.

[1]

(ii) Use the equation in **(a)(ii)** and your answer to **(b)(i)** to calculate the number of moles of $C_2O_4^{2-}$ present in the 25.0 cm^3 sample of solution used.

[1]

(iii) Calculate the number of moles of $H_2C_2O_4.xH_2O$ in 6.30 g of the compound.

[1]

(iv) Calculate the relative formula mass of $H_2C_2O_4.xH_2O$.

[1]

(v) The relative formula mass of anhydrous ethanedioic acid, $H_2C_2O_4$, is 90.

Calculate the value of x in $H_2C_2O_4.xH_2O$.

[1]

25 Sodium and silicon also react directly with chlorine to produce the chlorides shown.

chloride	melting point / °C	difference between the electronegativities of the elements
$NaCl$	801	2.2
$SiCl_4$	–69	1.3

(i) Describe what you would **see** during the reaction between sodium and chlorine.

....

....

.... [2]

(ii) Explain the differences between the melting points of these two chlorides in terms of their structure **and** bonding. You should refer to the difference between the electronegativities of the elements in your answer.

$NaCl$ structure **and** bonding ....

....

$SiCl_4$ structure **and** bonding ....

....

explanation ....

....

....

....

....

.... [4]

Nitrogen & Sulphur

This topic introduces some of the chemistry associated with nitrogen and sulfur.

a explain the lack of reactivity of nitrogen ☐

b describe and explain:

(i) the basicity of ammonia ☐

(ii) he structure of the ammonium ion and its formation by an acid-base reaction ☐

(iii) the displacement of ammonia from its salts ☐

c state the industrial importance of ammonia and nitrogen compounds derived from ammonia ☐

d state and explain the environmental consequences of the uncontrolled use of nitrate fertilisers ☐

e state and explain the natural and man-made occurrences of oxides of nitrogen and their catalytic removal from the exhaust gases of internal combustion engines ☐

f explain why atmospheric oxides of nitrogen are pollutants, including their catalytic role in the oxidation of atmospheric sulfur dioxide ☐

g describe the formation of atmospheric sulfur dioxide from the combustion of sulfur-contaminated fossil fuels ☐

h state the role of sulfur dioxide in the formation of acid rain and describe the main environmental consequences of acid rain ☐

NITROGEN & SULFUR

13 Nitrogen and sulfur

This topic introduces some of the chemistry associated with nitrogen and sulfur.

	Learning outcomes Candidates should be able to:
13.1 Nitrogen	a) explain the lack of reactivity of nitrogen b) describe and explain: (i) the basicity of ammonia (see also Section 7.2) (ii) the structure of the ammonium ion and its formation by an acid-base reaction (iii) the displacement of ammonia from its salts c) state the industrial importance of ammonia and nitrogen compounds derived from ammonia d) state and explain the environmental consequences of the uncontrolled use of nitrate fertilisers e) state and explain the natural and man-made occurrences of oxides of nitrogen and their catalytic removal from the exhaust gases of internal combustion engines f) explain why atmospheric oxides of nitrogen are pollutants, including their catalytic role in the oxidation of atmospheric sulfur dioxide (see also Section 8.3(e)(iii))
13.2 Sulfur: the formation of atmospheric sulfur dioxide, its role in acid rain	a) describe the formation of atmospheric sulfur dioxide from the combustion of sulfur-contaminated fossil fuels b) state the role of sulfur dioxide in the formation of acid rain and describe the main environmental consequences of acid rain

NITROGEN AND SULFUR

NITROGEN

Although 78% of air is Nitrogen, only a small portion is involved in the nitrogen cycle.

Biological fixation and lightening remove nitrogen from the atmosphere.

Nitrogen is then returned to the atmosphere by bacterial action.

Commercially, it is obtained by fractional distillation of liquified air.

Nitrogen exists as a diatomic gas, with a triple bonding between nitrogen atoms giving a bond energy of 994 kJ/mol.

NITROGEN

This results in Nitrogen being inert as a lot of heat is required for the bond to break.

Hence, most reactions involving Nitrogen are endothermic, owing to the high bond energy.

Nitrogen is used to provide an inert atmosphere for food storage.

Nitrogen is also used to manufacture Ammonia.

This is done by reacting it with Hydrogen at 500°C and 100 atm.

Iron catalyst is used to speed up the reaction.

3

AMMONIA

Ammonia is a colourless gas with a pungent odour.

Trigonal pyramidal, ammonia is a polar molecule, facilitating hydrogen bonds.

Ammonia is highly soluble in water, and produces ammonium ions, releasing hydroxide ions in the process.

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

A weak base, ammonia precipitates all insoluble metallic hydroxides from aqueous solutions of their salts.

4

AMMONIA

Ammonia, due to the presence of a lone pair is able to accept protons.

This is done by forming dative bonds.

The ammonium ion formed is tetrahedral in shape, with a positive charge.

Ammonium salts are all soluble in water, as they can form hydrogen bonds with water.

Ammonia forms the basis of nitrogen industry. This industry covers a large array of products.

Such as to manufacture nitric acid, as well as nitrate and sulfate based fertilizers.

Also, Ammonia is used in window cleaning as well as in the manufacture of nylon.

5

EUTROPHICATION

To be absorbed by plants, fertilizers have to be soluble in water. Excess fertilizers often get leached into the soil.

This leads to high concentrations of nitrates in reservoirs, facilitating a rapid growth of algae.

The algae soon block off sunlight from reaching the submerged aquatic plants, which soon die due to lack of photosynthesis.

Bacteria feed on the dead organisms, and further lowers oxygen concentrations, resulting in death of almost all aquatic life.

6

SULFUR

Sulfur is a yellow, non metal solid.

Found as S_8 molecules, Sulfur has a melting point of 119°C with a boiling point of 444°C.

Sulfur burns in air with a blue flame to form sulfur dioxide and trace amounts of sulfur trioxide.

7

SULFUR DIOXIDE

Sulfur dioxide is an acidic oxide, that forms sulfurous acid when dissolved in water.

It is obtained by burning sulfur compounds in air.

Sulfur dioxide is released into the atmosphere by combustion of sulfur contaminated fuels and smelting of sulfide ores.

Dissolving in water to give sulfurous acid, it rapidly gets oxidised to sulfuric acid.

Nitrogen oxides from exhaust fumes catalyse this oxidation.

This causes acid rain, which is harmful to marine life, humans, plants and buildings alike.

8

NITROGEN AND SULFUR WS 1

SECTION A

1 Ammonium sulfate in the soil is slowly oxidised by air, producing sulfuric acid, nitric acid and water as the only products.

How many moles of oxygen gas are needed for the complete oxidation of one mole of ammonium sulfate?

A 1 **B** 2 **C** 3 **D** 4

2 Total removal of the pollutant sulfur dioxide, SO_2, is difficult. The quantities emitted from furnace chimneys can be lowered by using desulfurisation plants. The gases are reacted with calcium hydroxide to remove the SO_2.

What is the main product formed **initially**?

A $Ca(HSO_4)_2$ **B** CaS **C** $CaSO_3$ **D** $CaSO_4$

3 Carbon monoxide, CO, nitrogen dioxide, NO_2, and sulfur dioxide, SO_2, are all atmospheric pollutants.

Which reaction concerning these compounds occurs in the atmosphere?

A CO is spontaneously oxidised to CO_2

B NO_2 is reduced to NO by CO

C NO_2 is reduced to NO by SO_2

D SO_2 is oxidised to SO_3 by CO_2

4 The compound S_2O_7 is hydrolysed by water to produce sulfuric acid and oxygen only.

Which volume of oxygen, measured at room temperature and pressure, is evolved when 0.352 g of S_2O_7 is hydrolysed?

A $12\,cm^3$ **B** $24\,cm^3$ **C** $48\,cm^3$ **D** $96\,cm^3$

5 Element X forms a pollutant oxide Y. Y can be further oxidised to Z. Two students made the following statements.

Student P 'The molecule of Y contains lone pairs of electrons.'

Student Q 'The oxidation number of X increases by 1 from Y to Z.'

X could be carbon or nitrogen or sulfur.

Which student(s) made a correct statement?

A P only

B Q only

C both P and Q

D neither P nor Q

6 4.70 g of an ammonium salt is heated with excess aqueous sodium hydroxide. The volume of ammonia gas given off, measured at room temperature and pressure, is 1.41 dm^3.

Which ammonium salt was used?

A ammonium bromide (M_r = 97.9)

B ammonium carbonate (M_r = 96)

C ammonium nitrate (M_r = 80)

D ammonium sulfate (M_r = 132.1)

7 Ammonium sulfate, $(NH_4)_2SO_4$, and ammonium nitrate, NH_4NO_3, are used as fertilisers.

These salts have different percentages by mass of nitrogen. They have the same effect as each other on the pH of neutral soil.

Which row is correct?

	higher percentage of nitrogen by mass	effect on pH of soil
A	ammonium nitrate	decrease
B	ammonium nitrate	increase
C	ammonium sulfate	decrease
D	ammonium sulfate	increase

8 Which statement about the ammonia molecule and/or the ammonium ion is correct?

A Ammonia molecules are basic because they can donate H^+ ions.

B Ammonium ions are basic because they can accept H^+ ions.

C If ammonium ions are heated with NaOH(aq), ammonia molecules are formed.

D The bond angle in NH_4^+ is 2.5° less than the bond angle in NH_3.

9 Which reaction **does not** contribute to the problem of acid rain?

A the combustion of fossil fuels

B the oxidation of sulfur dioxide to sulfur trioxide catalysed by nitrogen dioxide

C the reaction between nitrogen monoxide and carbon monoxide in a catalytic converter

D the reaction of sulfur trioxide with water

10 Ammonia gas, NH_3, and hydrogen sulfide gas, H_2S, react together to form the salt ammonium sulfide, $(NH_4)_2S$. Ammonium sulfide dissolves in water to produce an orange alkaline solution.

$$(NH_4)_2S(aq) \rightleftharpoons NH_3(aq) + NH_4SH(aq)$$

The addition of NaOH(aq) to this solution produces a gas, **X**.
The addition of HC*l*(aq) to a separate portion of this solution produces a gas, **Y**.

What are the identities of **X** and **Y**?

	X	Y
A	H_2S	H_2S
B	H_2S	NH_3
C	NH_3	H_2S
D	NH_3	NH_3

11 Nitrogen(II) oxide, NO, nitrogen(IV) oxide, NO_2, carbon monoxide, CO, and unburnt hydrocarbons are present in the exhaust gases of internal combustion engines. When catalytic converters are used to remove these compounds from the exhaust gases, redox reactions occur.

What happens to each compound in the catalytic converter?

	NO	NO_2	CO	hydrocarbons
A	oxidised	oxidised	reduced	oxidised
B	oxidised	oxidised	oxidised	oxidised
C	reduced	reduced	oxidised	oxidised
D	reduced	reduced	reduced	reduced

12 Sulfur dioxide is used as a preservative in wine making.

The following equations describe the reactions that occur when sulfur dioxide dissolves in water.

$$H_2O + SO_2 \rightleftharpoons HSO_3^- + H^+$$

$$HSO_3^- + H^+ \rightleftharpoons SO_3^{2-} + 2H^+$$

Which statement about **these two reactions** is correct?

A HSO_3^- acts as a base.

B SO_2 acts as an oxidising agent.

C SO_3^{2-} acts as an acid.

D SO_3^{2-} acts as a reducing agent.

13 Which statement does **not** describe an effect of acid rain on the environment?

A Acid rain causes erosion of stone buildings.

B Acid rain causes ozone depletion.

C Acid rain increases the corrosion of some metals.

D Acid rain increases the leaching away of essential nutrients and minerals from soils.

14 Water and ammonia take part in a reaction that produces the ammonium ion.

Which statement about this reaction is correct?

A Neither the ammonia molecule nor the ammonium ion has a dipole moment.

B The bond angle changes from 109.5° in the ammonia molecule to 107° in the ammonium ion.

C The reaction is a redox reaction.

D The water is acting as an acid.

15 The reaction of nitrogen and oxygen to produce oxides of nitrogen happens at high temperatures in car engines or lightning strikes during thunderstorms.

What is the main reason for these reactions requiring such high temperatures?

A the lack of reactivity of nitrogen, due to the half-filled 2p subshell in the nitrogen atom

B the lack of reactivity of nitrogen, due to the strength of the bond in N_2

C the lack of reactivity of oxygen, due to electron-electron repulsion in one of its 2p orbitals

D the lack of reactivity of oxygen, due to the strength of the bond in O_2

16 Nitrogen dioxide, NO_2, is a brown gas.

Dinitrogen tetroxide, N_2O_4, is a colourless gas.

An equilibrium is established between NO_2 and N_2O_4 in a closed vessel.

$$\underset{\text{brown}}{2NO_2(g)} \rightleftharpoons \underset{\text{colourless}}{N_2O_4(g)} \qquad \Delta H = -57\,\text{kJ mol}^{-1}$$

Which row describes the effects of changing conditions on the colour of an equilibrium mixture of NO_2 and N_2O_4?

	increasing the pressure	increasing the temperature
A	colour becomes darker	colour becomes darker
B	colour becomes darker	colour becomes lighter
C	colour becomes lighter	colour becomes darker
D	colour becomes lighter	colour becomes lighter

17 Which statement about nitrogen or its compounds is correct?

A In the Haber process the temperature is kept high to give a good equilibrium yield of ammonia.

B Nitrogen gas is unreactive because of the strong nitrogen-nitrogen double bond.

C Nitrogen monoxide will react with carbon monoxide under suitable conditions.

D The formula of ammonium sulfate is NH_4SO_4.

18 The reaction of nitrogen and oxygen to produce oxides of nitrogen happens at high temperatures in car engines or lightning strikes during thunderstorms.

What is the main reason for these reactions requiring such high temperatures?

A the lack of reactivity of nitrogen, due to the half-filled 2p subshell in the nitrogen atom

B the lack of reactivity of nitrogen, due to the strength of the bond in N_2

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D the lack of reactivity of oxygen, due to the strength of the bond in O_2

[W'17 P12 Q18]

19 Oxides of nitrogen are present in the environment due to natural and man-made sources.

Which row is correct?

	natural source of nitrogen oxides	man-made source of nitrogen oxides
A	electrical discharges in the atmosphere	internal combustion engines
B	electrical discharges in the atmosphere	as a by-product of the Haber process
C	decomposition of dead plants in rivers	internal combustion engines
D	decomposition of dead plants in rivers	as a by-product of the Haber process

[J'18 P11 Q17]

20 Sulfur dioxide can be catalytically oxidised by an oxide of nitrogen in the atmosphere.

Which reaction shows the regeneration of the catalyst?

A $N_2 + 2O_2 \rightleftharpoons 2NO_2$

B $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

C $N_2 + O_2 \rightarrow 2NO$

D $NO + \frac{1}{2}O_2 \rightarrow NO_2$

[J'18 P12 Q19]

21 Sodium and sulfur are burned separately in oxygen.

Each reaction has a distinctive coloured flame.

Which row is correct?

	$Na + O_2$	$S + O_2$
A	white	blue
B	white	yellow
C	yellow	blue
D	yellow	yellow

[N'18 P11 Q12]

22 If ammonium cyanate is heated in the absence of air, the only product of the reaction is urea, $CO(NH_2)_2$. No other products are formed in the reaction.

What is the formula of the cyanate ion present in ammonium cyanate?

A CON_2^- **B** CON_2^{2-} **C** OCN^- **D** OCN^{2-}

[N'18 P12 Q19]

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 Nitrogen exists in air as covalently bonded diatomic molecules, N_2.

Which features are present in one N_2 molecule?

1 three π bonds

2 three shared pairs of electrons

3 two lone pairs of electrons

2 When dilute acid is added to an aqueous solution containing nitrite ions, NO_2^-, a mixture of gases is produced.

$$2H^+(aq) + 2NO_2^-(aq) \rightarrow H_2O(l) + NO(g) + NO_2(g)$$

Which statements correctly describe the process?

1 Some nitrogen atoms are oxidised and some nitrogen atoms are reduced.

2 The $H^+(aq)$ ion is oxidised by $NO_2^-(aq)$.

3 The $H^+(aq)$ ion acts as a catalyst.

3 Under atmospheric conditions, in which transformations is sulfur dioxide involved as either a reagent or a catalyst?

1 NO_2 to NO

2 NO to NO_2

3 CO to CO_2

4 Ammonia and chlorine react in the gas phase.

$$8NH_3 + 3Cl_2 \rightarrow N_2 + 6NH_4Cl$$

Which statements are correct?

1 Each nitrogen atom is oxidised.

2 Each chlorine atom is reduced.

3 Ammonia behaves as a base.

5 Which descriptions of the ammonium ion are correct?

1 It contains ten electrons.

2 It has a bond angle of 109.5°.

3 It has only three bonding pairs of electrons.

6 Ammonia is a colourless gas that is produced by the Haber process.

Which statements about ammonia are correct?

1 An ammonia molecule has three bond pairs and one lone pair of electrons.

2 If ammonia is bubbled into water the pH of the solution will increase.

3 Ammonia gas can be made by warming ammonium sulfate with aqueous hydrochloric acid.

7 Which statements explain why nitrogen gas is unreactive?

1 Nitrogen atoms are highly electronegative.

2 Nitrogen molecules are non-polar.

3 The triple bond between nitrogen atoms is very strong.

8 Sulfur dioxide is an atmospheric pollutant.

What might result from the release of sulfur dioxide gas into the atmosphere?

1 reduction of NO_2 to NO

2 depletion of aquatic life

3 corrosion of limestone statues

9 Nitrogen and phosphorus are both in Group 15 of the Periodic Table. Phosphorus forms a chloride with the formula PCl_5 but nitrogen does not form NCl_5.

Which statements help to explain this?

1 Nitrogen's outer shell cannot contain more than eight electrons.

2 Nitrogen cannot have an oxidation state of +5.

3 Nitrogen is less electronegative than phosphorus.

10 Acid rain continues to be a problem.

Which statements about acid rain are correct?

1 Acid rain is formed when oxides of nitrogen or oxides of sulfur react with water in the atmosphere.

2 Acid rain causes an increase in the concentration of heavy metal ions in water courses.

3 Nitrogen dioxide will catalyse the formation of SO_3 from SO_2 in the atmosphere.

11 Modern cars are fitted with catalytic converters to reduce atmospheric pollution caused by unwanted reactions during the combustion of the fuel.

Which statements are correct?

1 Carbon monoxide is oxidised to carbon dioxide in a catalytic converter.

2 Catalytic converters have a very large surface area.

3 Nitrogen dioxide is reduced to nitrogen monoxide in a catalytic converter.

[W'17 2 Q36]

12 Which statements correctly describe an oxide of nitrogen acting as an atmospheric pollutant?

1 Nitrogen monoxide, NO, reacts with oxygen to form nitrogen dioxide which contributes to acid rain.

2 Nitrogen dioxide reacts with sulfur dioxide to form sulfur trioxide which reacts with water to form sulfuric acid.

3 Nitrogen oxides react with unburnt hydrocarbons in sunlight to form other pollutants.

[J'18 P11 Q36]

NITROGEN AND SULFUR WS 2

1 The Contact process for the manufacture of sulfuric acid was originally patented in the 19th century and is still in use today.

The key step in the overall process is the reversible conversion of sulfur dioxide to sulfur trioxide in the presence of a vanadium(V) oxide catalyst.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H = -196\,kJ\,mol^{-1}$$

(a) One way in which the sulfur dioxide for this reaction is produced is by heating the sulfide ore iron pyrites, FeS_2, in air. Iron(III) oxide is also produced. Write an equation for this reaction.

.... [2]

(b) The sulfur trioxide produced in the Contact process is reacted with 98% sulfuric acid. The resulting compound is **then** reacted with water to produce sulfuric acid.

(i) Explain why the sulfur trioxide is not first mixed directly with water.

....

.... [1]

(ii) Write equations for the two steps involved in the conversion of sulfur trioxide into sulfuric acid.

....

.... [2]

(c) **(i)** Sulfur dioxide and sulfur trioxide both contain only S=O double bonds.

Draw labelled diagrams to show the shapes of these two molecules.

SO_2 SO_3

[2]

(ii) For your diagrams in **(i)**, name the shapes and suggest the bond angles.

SO_2 shape .... SO_3 shape ....

SO_2 bond angle .... SO_3 bond angle ....

[2]

2 Sulfuric acid is an important chemical with a variety of uses.

It is manufactured by the Contact process, the first stage of which involves the conversion of sulfur or a sulfide ore, such as galena, PbS, into sulfur dioxide, SO_2.

(a) (i) Write an equation for the reaction between galena and oxygen to form sulfur dioxide and lead(II) oxide.

.... [2]

(ii) Identify the oxidation number changes that take place during this reaction.

....

.... [2]

(e) The sulfur dioxide content of wine is most commonly measured by the Ripper Method which involves titration with iodine in the presence of starch as an indicator.

$$SO_2(aq) + I_2(aq) + 2H_2O(l) \rightarrow 2I^-(aq) + SO_4^{2-}(aq) + 4H^+(aq)$$

A $50.0\,cm^3$ sample of wine required $12.35\,cm^3$ of $0.010\,mol\,dm^{-3}$ $I_2(aq)$ for complete reaction with the SO_2.

(i) How many moles of SO_2 are present in $50.0\,cm^3$ of wine?

moles of SO_2 in $50.0\,cm^3$ = ... [1]

(ii) How many moles of SO_2 are present in $1\,dm^3$ of wine?

moles of SO_2 in $1\,dm^3$ = ... [1]

(iii) How many milligrams, mg, of SO_2 are present in $1\,dm^3$ of wine? Give your answer to **three** significant figures. (1 g = 1000 mg)

mass of SO_2 in $1\,dm^3$ = ... mg [1]

3 **(c)** One of the major uses of ammonia is in the manufacture of fertilisers such as diammonium hydrogen phosphate, $(NH_4)_2HPO_4$.

(i) Write an equation for the formation of diammonium hydrogen phosphate by the reaction between ammonia and phosphoric acid, H_3PO_4.

.... [1]

(ii) Explain this reaction in terms of the Brønsted-Lowry theory.

....

....

....

.... [2]

(d) The use of nitrate fertilisers can give rise to environmental consequences in terms of effects on both rivers and the atmosphere.

(i) Explain how the uncontrolled use of nitrate fertilisers can result in a severe reduction in water quality in rivers.

....

....

....

.... [3]

(ii) Oxides of nitrogen are produced by the action of bacteria on nitrate fertilisers.

Explain the problems associated with the release of oxides of nitrogen into the atmosphere. Include an equation in your answer.

....

....

.... [2]

4 Ammonium nitrate is an important fertiliser made by the acid-base reaction between ammonia and nitric acid.

(a) Write an equation for the production of ammonium nitrate from ammonia and nitric acid.

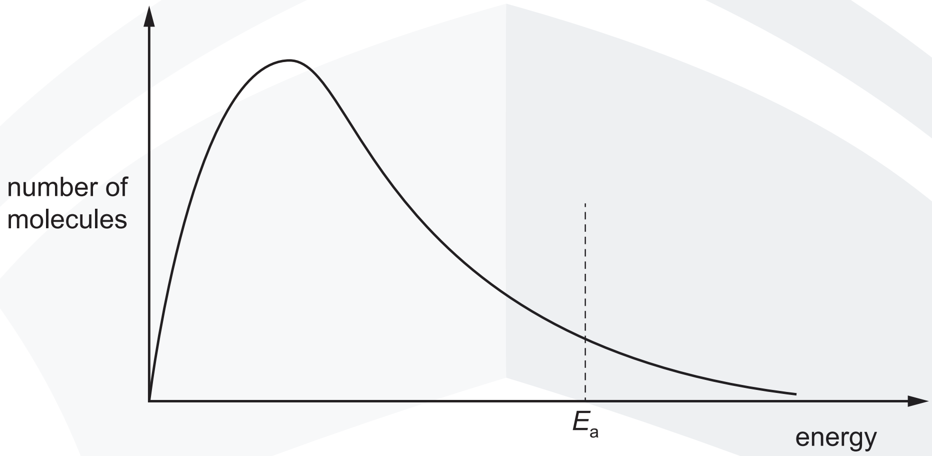
.... [1]

The ammonia for this reaction is produced by the Haber process and the nitric acid is produced by oxidation of ammonia.

(b) The Haber process involves a reaction between nitrogen and hydrogen at a temperature of 450 °C and a pressure of 20 000 kPa. At a higher reaction temperature, the rate of production of ammonia would be greater.

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

The Boltzmann distribution curve shows the distribution of energies in a mixture of nitrogen and hydrogen at 450 °C.



(i) Sketch a second line onto the axes above to show the distribution of energies in the same mixture of gases at a higher temperature. [2]

(ii) With reference to the two curves, explain why the rate of production of ammonia would be greater at a higher temperature.

....

....

.... [2]

(iii) Add a suitable label to the horizontal axis above and use it to explain why a catalyst is used in the Haber process.

....

....

.... [2]

(iv) Explain why a higher temperature is **not** used despite the fact that it would increase the rate of production of ammonia.

....

....

.... [2]

(c) The first stage in the production of nitric acid involves the reaction of ammonia with oxygen to form nitrogen monoxide, NO, and water.

Suggest an equation for this reaction and use oxidation numbers to show that it is a redox reaction.

....

....

....

.... [3]

(d) **(i)** Draw a dot-and-cross diagram of the ammonium ion. Show the outer electrons only.
Use the following code for your electrons.
- • electrons from nitrogen
- × electrons from hydrogen

[2]

(ii) State the shape of an ammonium ion and give the H–N–H bond angle.

shape ....

bond angle ....
[2]

(e) State and explain the problems that arise from the overuse of ammonium nitrate fertiliser when the excess is washed into rivers.

....

....

....

.... [3]

5 Nitrogen gas, N_2, is very unreactive.

(a) Explain why nitrogen gas is so unreactive.

....

....

.... [2]

(b) Despite the low reactivity of N_2, oxides of nitrogen occur in the atmosphere through both natural and man-made processes.

(i) Explain why oxides of nitrogen can be produced by internal combustion engines.

....

....

.... [2]

(ii) State and explain, using a suitable equation, how oxides of nitrogen produced by internal combustion engines can be prevented from reaching the atmosphere.

....

.... [2]

(iii) State the role of nitrogen dioxide, NO_2, in the formation of acid rain by oxides of sulfur. Write suitable equations to explain this role.

role ....

equation 1 ....

equation 2 ....

[3]

(iv) Suggest an equation to show how NO_2 can contribute **directly** to acid rain.

.... [1]

(c) Explain how the uncontrolled use of nitrate fertilisers on land can lead to a severe reduction in water quality in rivers.

....

....

....

.... [3]

6 Nitrogen gas, N_2, is very unreactive.

(a) Explain why nitrogen gas is so unreactive.

....

....

.... [2]

(b) Despite the low reactivity of N_2, oxides of nitrogen occur in the atmosphere through both natural and man-made processes.

(i) Explain why oxides of nitrogen can be produced by internal combustion engines.

....

....

.... [2]

(ii) State and explain, using a suitable equation, how oxides of nitrogen produced by internal combustion engines can be prevented from reaching the atmosphere.

....

.... [2]

(iii) State the role of nitrogen dioxide, NO_2, in the formation of acid rain by oxides of sulfur. Write suitable equations to explain this role.

role ....

equation 1 ....

equation 2 ....

[3]

(iv) Suggest an equation to show how NO_2 can contribute **directly** to acid rain.

.... [1]

(c) Explain how the uncontrolled use of nitrate fertilisers on land can lead to a severe reduction in water quality in rivers.

....

....

....

.... [3]

[S'17 2 Q2]

NITROGEN AND SULFUR WS 3

SECTION A

1 When ammonia is converted into nitric acid on a commercial scale, the following reactions can occur.

In which reaction does the greatest change in oxidation number of the nitrogen occur?

reaction	
A	$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$
B	$3NO_2 + H_2O \rightarrow 2HNO_3 + NO$
C	$2NO + O_2 \rightarrow 2NO_2$
D	$4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O$

2 Nitrogen is frequently used as an inert atmosphere because it is an unreactive gas.

Which is the best explanation of this unreactivity?

A Its molecule contains a triple bond.

B The bond energy of the molecule is high ($994\,kJ\,mol^{-1}$).

C The bond in its molecule is very short (0.110 nm).

D The three p orbitals of nitrogen are half-filled.

3 In a solution of ammonia in water, what combination of ionic and molecular forms of ammonia are present?

A ions only

B ions and simple molecules only

C simple molecules and hydrogen-bonded molecules only

D simple molecules, hydrogen–bonded molecules and ions

4 A solid nitrate fertiliser reacts with an alkali to produce a gas which turns damp pH paper blue.

What is the empirical formula of this fertiliser?

A NO_3 **B** NHO_3 **C** NH_2O **D** $N_2H_4O_3$

5 Which reagent, when mixed and heated with ammonium sulphate, liberates ammonia?

A aqueous bromine

B dilute hydrochloric acid

C limewater

D acidified potassium dichromate(VI)

6 Ammonium sulphate in nitrogenous fertilisers in the soil can be slowly oxidised by air producing sulphuric acid, nitric acid and water.

How many moles of oxygen are needed to oxidise completely one mole of ammonium sulphate?

A 1 **B** 2 **C** 3 **D** 4

7 The emissions from a power station contain about 14 tonnes of SO_2 per hour from the oxidation of FeS_2 contained in the coal.

What is the most practical way of preventing the SO_2 from being released into the atmosphere?

A Cool the gases and the SO_2 will liquefy and can be removed.

B Dissolve the ionic FeS_2 in hexane.

C Pass the emissions through a bed of calcium oxide.

D Pass the gases through concentrated sulphuric acid to dissolve the SO_2.

8 Which salt is produced by adding aqueous ammonia to aqueous sulphur dioxide until just alkaline?

A NH_4SO_3 **B** NH_4SO_4 **C** $(NH_4)_2SO_3$ **D** $(NH_4)_2SO_4$

9 In flooded soils, like those used for rice cultivation, the oxygen content is low. In such soils, anaerobic bacteria cause the loss of nitrogen from the soil as shown in the following sequence.

In which step is the change in oxidation number (oxidation state) of nitrogen different to the changes in the other steps?

$$NO_3^-(aq) \xrightarrow{\textbf{A}} NO_2^-(aq) \xrightarrow{\textbf{B}} NO(g) \xrightarrow{\textbf{C}} N_2O(g) \xrightarrow{\textbf{D}} N_2(g)$$

10 Deposits of ammonium compounds have been discovered in areas of high atmospheric pollution.

They are believed to arise from the following reaction.

$$SO_3 + H_2O + 2NH_3 \rightarrow (NH_4)_2SO_4$$

What does **not** occur in this reaction?

A acid / base neutralisation

B dative bond formation

C ionic bond formation

D oxidation / reduction

11 In an experiment, 50.0 cm^3 of a 0.10 mol dm^{-3} solution of a metallic salt reacted exactly with 25.0 cm^3 of 0.10 mol dm^{-3} aqueous sodium sulphite.

The half-equation for oxidation of sulphite ion is shown below.

$$SO_3^{2-}(aq) + H_2O(l) \rightarrow SO_4^{2-}(aq) + 2H^+(aq) + 2e^-$$

If the original oxidation number of the metal in the salt was +3, what would be the new oxidation number of the metal?

A +1 **B** +2 **C** +4 **D** +5

12 Sulfur dioxide, SO_2, is added to wines to prevent oxidation of ethanol by air. To determine the amount of SO_2, a sample of wine is titrated with iodine, I_2. In this reaction, **one** mole of SO_2 is oxidised by **one** mole of I_2.

What is the change in oxidation number of sulfur in this reaction?

A +2 to +4 **B** +2 to +6 **C** +4 to +5 **D** +4 to +6

13 Hydrazine, N_2H_4, is widely used as a rocket fuel because it reacts with oxygen as shown, producing 'environmentally friendly' gases.

$$N_2H_4(l) + O_2(g) \rightarrow N_2(g) + 2H_2O(g) \qquad \Delta H = -534\,\text{kJ mol}^{-1}$$

Despite its use as a rocket fuel, hydrazine does not burn spontaneously in oxygen.

Which statement explains why hydrazine does **not** burn spontaneously?

A Hydrazine is a liquid.

B The activation energy is too high.

C The N$\equiv$N bond is very strong.

D The reaction is exothermic.

14 Ammonium nitrate, NH_4NO_3, is manufactured in large quantities for use in fertiliser.

Which statement about ammonium nitrate fertiliser is **not** correct?

A It can cause environmental problems.

B It consists of 35% nitrogen by mass.

C It is insoluble in water.

D Nitric acid is used in its manufacture.

15 Sulfur dioxide is used as a preservative in wine making.

The following equations describe how sulfur dioxide dissolves.

$$H_2O + SO_2 \rightleftharpoons HSO_3^- + H^+$$

$$HSO_3^- + H^+ \rightleftharpoons SO_3^{2-} + 2H^+$$

Which statement about these two reactions is correct?

A HSO_3^- acts as a base.

B SO_2 acts as an oxidising agent.

C SO_3^{2-} acts as an acid.

D SO_3^{2-} acts as a reducing agent.

16 Nitrogenous fertilisers are used extensively in modern farming. If rainwater washes excess fertiliser into a nearby lake, a process called eutrophication may occur.

Three of the stages of eutrophication are described below.

P Water plants growing on the lake bed die due to lack of sunlight.

Q An excessive growth of algae occurs.

R Excessive bacterial activity causes a reduction in oxygen levels.

In which order do these three stages occur?

A $P \rightarrow Q \rightarrow R$

B $P \rightarrow R \rightarrow Q$

C $Q \rightarrow P \rightarrow R$

D $Q \rightarrow R \rightarrow P$

17 Which pollutant, present in the exhaust fumes of an internal combustion engine, has an element in the +2 oxidation state and an odd number of electrons in one molecule of the pollutant?

A CO **B** H_2S **C** NO **D** NO_2

18 In which substance does nitrogen exhibit the highest oxidation state?

A NO **B** N_2O **C** N_2O_4 **D** $NaNO_2$

19 Carbon monoxide, CO, nitrogen monoxide, NO, and sulfur dioxide, SO_2, may all be present in the exhaust fumes from a car engine.

Which reaction concerning these compounds occurs in the atmosphere?

A CO is spontaneously oxidised to CO_2

B NO_2 is reduced to NO by CO

C NO_2 is reduced to NO by SO_2

D SO_2 is oxidised to SO_3 by CO_2

20 Which gas is present in the exhaust fumes of a car engine in a much greater amount than any other gas?

A carbon dioxide

B carbon monoxide

C nitrogen

D water vapour

21 In a car engine, non-metallic element *X* forms a pollutant oxide *Y*. *Y* can be further oxidised to *Z*. Two students made the following statements.

Student P	The molecule of *Y* contains lone pairs of electrons.
Student Q	The oxidation number of *X* increases by 1 from *Y* to *Z*.

X could be carbon or nitrogen or sulfur.

Which student could be correct if *X* were any of these elements?

A P only

B Q only

C both P and Q

D neither P nor Q

22 Deposits of ammonium sulfate have been discovered in areas of high atmospheric pollution.

They are believed to arise from the following reaction.

$$SO_3 + H_2O + 2NH_3 \rightarrow (NH_4)_2SO_4$$

What does **not** occur in this reaction?

A acid / base neutralisation

B dative bond formation

C ionic bond formation

D oxidation / reduction

23 Sulfur trioxide is manufactured from sulfur dioxide and oxygen, using the Contact process.

Which condition affects the value of the equilibrium constant, K_c?

A adjusting the temperature

B increasing the pressure

C removing SO_3 from the equilibrium mixture

D using a catalyst

24 Which reagent, when mixed and heated with ammonium sulfate, liberates ammonia?

A aqueous bromine

B dilute hydrochloric acid

C limewater

D potassium dichromate(VI) in acidic solution

25 In which reaction does a single nitrogen atom have the greatest change in oxidation number?

A $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

B $3NO_2 + H_2O \rightarrow 2HNO_3 + NO$

C $2NO + O_2 \rightarrow 2NO_2$

D $4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O$

26 Solid potassium halides react with concentrated sulfuric acid, according to the following equations.

reaction 1 $2KCl + H_2SO_4 \rightarrow K_2SO_4 + 2HCl$

reaction 2 $2KBr + 2H_2SO_4 \rightarrow K_2SO_4 + SO_2 + Br_2 + 2H_2O$

reaction 3 $8KI + 5H_2SO_4 \rightarrow 4K_2SO_4 + H_2S + 4I_2 + 4H_2O$

What is the largest **change** in the oxidation number of sulfur in each of these reactions?

	reaction 1	reaction 2	reaction 3
A	0	0	4
B	0	2	4
C	0	2	8
D	0	4	8

27 Ammonium nitrate, NH_4NO_3, can decompose explosively when heated.

$$NH_4NO_3 \rightarrow N_2O + 2H_2O$$

What are the changes in the oxidation numbers of the two nitrogen atoms in NH_4NO_3 when this reaction proceeds?

A –2, –4 **B** +2, +6 **C** +4, –6 **D** +4, –4

28 Ammonia exists as simple covalent molecules, NH_3. Ammonia can react with suitable reagents to form products containing ammonium ions, NH_4^+. Ammonia can also react with suitable reagents to form products containing amide ions, NH_2^-.

Which of these nitrogen-containing species are present in an aqueous solution of ammonia?

A ammonia molecules, ammonium ions and amide ions

B ammonia molecules and ammonium ions only

C ammonia molecules only

D ammonium ions only

29 Carbon, nitrogen and sulfur are non-metals.

Which statement about their oxides, XO_2, is correct? (Where X represents carbon, nitrogen or sulfur.)

A All of the XO_2 molecules are linear.

B In XO_2, each element has its highest oxidation number.

C All XO_2 molecules dissolve in water to form dibasic acids.

D All XO_2 molecules are formed as a result of burning petrol in a car engine.

30 A chemist took 2.00 dm^3 of nitrogen gas, measured under room conditions, and reacted it with a large volume of hydrogen gas, in order to produce ammonia. Only 15.0% of the nitrogen gas reacted to produce ammonia.

What mass of ammonia was formed?

A 0.213 g **B** 0.425 g **C** 1.42 g **D** 2.83 g

SECTION B

The responses **A** to **D** should be selected on the basis of

A	B	C	D
1, **2** and **3** are correct	**1** and **2** only are correct	**2** and **3** only are correct	**1** only is correct

1 Ammonia and chlorine react in the gas phase.

$$8NH_3 + 3Cl_2 \rightarrow N_2 + 6NH_4Cl$$

Which statements are correct?

1 Ammonia behaves as a reducing agent.

2 Ammonia behaves as a base.

3 The oxidation number of the hydrogen changes.

2 A farmer added lime to damp soil, followed by the nitrogenous fertiliser ammonium sulfate. A chemical reaction occurred in the soil.

Which substances were formed in this reaction?

1 sulfuric acid

2 calcium sulfate

3 ammonia

3 Many crude oils contain sulphur as H_2S. During refining, by the Claus process, the H_2S is converted into solid sulphur, which is then removed.

reaction **I** $\quad 2H_2S(g) + 3O_2(g) \rightarrow 2H_2O(l) + 2SO_2(g)$

reaction **II** $\quad 2H_2S(g) + SO_2(g) \rightarrow 2H_2O(l) + 3S(s)$

Which statements about the Claus process are correct?

1 H_2S is oxidised in reaction **I**.

2 SO_2 oxidises H_2S in reaction **II**.

3 SO_2 behaves as a catalyst.

4 Element X is a solid. It occurs as a contaminant of carbonaceous fuels.

Its oxide Y is formed in car engines.

Further oxidation of Y to Z can occur in the atmosphere.

Which statements about Y and Z are correct?

1 Molecule Y has lone pairs of electrons.

2 The atmospheric oxidation of Y to Z is a catalysed reaction.

3 Y is a colourless gas.

5 Which fertilisers, when washed out of soil by rain, cause excessive growth of river plants and algae with the result that fish in the river die?

1 K_2SO_4

2 NH_4NO_3

3 $NaNO_3$

6 How may nitrogen exist in compounds?

1 bonded by a triple covalent bond

2 as part of a cation

3 having lost 3 electrons to form an anion

7 When the yellow liquid NCl_3 is stirred into aqueous sodium hydroxide, the reaction that occurs can be represented by the following equation.

$$2NCl_3(l) + 6NaOH(aq) \rightarrow N_2(g) + 3NaCl(aq) + 3NaOCl(aq) + 3H_2O(l)$$

What will be the result of this reaction?

1 The nitrogen undergoes a redox reaction.

2 A bleaching solution remains after the reaction.

3 The final solution gives a precipitate with acidified silver nitrate.

8 In a car engine pollutant oxide **Y**, which contains non-metallic element **X**, is formed.

Further oxidation of **Y** to **Z** occurs in the atmosphere. In this further oxidation, 1 mol of **Y** reacts with 0.5 mol of gaseous oxygen.

X could be either nitrogen or sulfur.

Which statements about **X**, **Y** and **Z** can be correct?

1 The oxidation number of **X** increases by two from **Y** to **Z**.

2 **Y** may have an unpaired electron in its molecule.

3 **Y** is a polar molecule.

9 In a car engine, non-metallic element X forms a pollutant oxide Y.

Further oxidation of Y to Z occurs spontaneously in the atmosphere. In this further oxidation, 1 mol of Y reacts with 0.5 mol of gaseous oxygen.

Which statements about X, Y and Z are correct?

1 X forms a basic hydride.

2 Y is a diatomic molecule.

3 Z is a polar molecule.

10 In a car engine, non-metallic element ***X*** forms a pollutant oxide ***Y***.

Further oxidation of ***Y*** to ***Z*** occurs spontaneously in the atmosphere. In this further oxidation, 1 mol of ***Y*** reacts with 0.5 mol of gaseous oxygen.

Which statements about ***X***, ***Y*** and ***Z*** are correct?

1 The oxidation number of ***X*** increases by 2 from ***Y*** to ***Z***.

2 The molecule of ***Y*** has no unpaired electrons.

3 The molecule of ***Z*** contains three oxygen atoms.

11 Nitrogen and phosphorus are both in Group V of the Periodic Table. Phosphorus forms a chloride with the formula PCl_5.

Why is it **not** possible for nitrogen to form NCl_5?

1 Nitrogen's outer shell can only contain eight electrons.

2 Nitrogen cannot have oxidation state +5.

3 Nitrogen is almost inert.

12 Ammonia and chlorine react in the gas phase.

$$8NH_3 + 3Cl_2 \rightarrow N_2 + 6NH_4Cl$$

Which statements are correct?

1 Ammonia behaves as a reducing agent.

2 Ammonia behaves as a base.

3 The oxidation number of the hydrogen changes

13 Sulfur dioxide is an atmospheric pollutant that causes acid rain. One of the reactions in this process is the oxidation of sulfur dioxide to sulfur trioxide.

This oxidation takes place by a two stage reaction involving oxygen and nitrogen monoxide, NO.

$$NO + \tfrac{1}{2}O_2 \rightarrow NO_2$$

$$NO_2 + SO_2 \rightarrow SO_3 + NO$$

Which statements are correct?

1 Nitrogen monoxide is acting as a catalyst for the oxidation.

2 Nitrogen atoms are oxidised in the second stage.

3 Oxygen atoms are first reduced and are then oxidised.

14 Element **J** is a solid. It occurs as a contaminant of fossil fuels.

Its oxide **K** is formed in car engines.

In the atmosphere, **K** can be further oxidised to **L**.

Which statements about **J**, **K** and **L** are correct?

1 Atoms of **J** have paired p electrons.

2 The atmospheric oxidation of **K** to **L** is a catalysed reaction.

3 With water, **L** forms a strong acid.

15 Which types of bonding are present in ammonium carbonate, $(NH_4)_2CO_3$?

1 ionic

2 covalent

3 co-ordinate (dative covalent)

16 When the liquid N_2F_4 is heated, it decomposes into a single product, X.

Which statements are correct?

1 N – F bonds are broken during this decomposition.

2 The enthalpy change when N_2F_4 decomposes into X is approximately $+160\,kJ\,mol^{-1}$.

3 Molecules of X are non-linear.

17 Pollutant oxide **Y**, which contains non-metallic element **X**, is formed in a car engine.

Further oxidation of **Y** to **Z** occurs in the atmosphere. In this further oxidation, 1 mol of **Y** reacts with 0.5 mol of gaseous oxygen molecules.

X could be either nitrogen or sulfur.

Which statements about **X**, **Y** and **Z** can be correct?

1 The oxidation number of **X** increases by two from **Y** to **Z**.

2 **Y** has an unpaired electron in its molecule.

3 **Y** is a polar molecule.

18 Sulfuric acid is a Brønsted-Lowry acid.

In which reactions is sulfuric acid behaving as an acid?

1 $H_2SO_4 + HNO_3 \rightarrow H_2NO_3^+ + HSO_4^-$

2 $H_2SO_4 + CO_3^{2-} \rightarrow CO_2 + H_2O + SO_4^{2-}$

3 $H_2SO_4 + MgO \rightarrow MgSO_4 + H_2O$

19 Many crude oils contain H_2S. During refining, by the Claus process, the H_2S is converted into solid sulfur, which is then removed.

reaction I $2H_2S(g) + 3O_2(g) \rightarrow 2H_2O(l) + 2SO_2(g)$

reaction II $2H_2S(g) + SO_2(g) \rightarrow 2H_2O(l) + 3S(s)$

Which statements about the Claus process are correct?

1 H_2S is oxidised in reaction I.

2 SO_2 oxidises H_2S in reaction II.

3 Hydrogen is oxidised in reaction II.

20 Which of these reactions are redox reactions?

1 $6NO(g) + 4NH_3(g) \rightarrow 5N_2(g) + 6H_2O(g)$

2 $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$

3 $SO_3(g) + H_2O(g) \rightarrow H_2SO_4(g)$

NITROGEN AND SULFUR WS 4

1 Nitrogen, which makes up about 80% of the Earth's atmosphere, is very unreactive.

(a) **(i)** Explain the lack of reactivity of nitrogen.

....

....

....

(ii) Nitrogen does, however, undergo some reactions. Write an equation for **one** reaction of nitrogen, stating the conditions under which it occurs.

equation ....

conditions ....

....

....

(iii) Suggest why nitrogen does react in the example you have chosen.

....

....

[6]

Ammonium nitrate, NH_4NO_3, is a commercially important compound of nitrogen.

(b) **(i)** State **one** large-scale use of ammonium nitrate.

....

(ii) What are the environmental consequences of the uncontrolled use of ammonium nitrate?

....

....

....

....

[4]

When solid ammonium nitrate is heated with solid sodium hydroxide in a test-tube, three products are formed. A colourless alkaline gas, **Y**, is given off, and a colourless liquid can be seen on the cooler parts of the test-tube. A white solid remains in the tube.

(c) **(i)** Identify gas **Y**.

....

(ii) Write an equation, with state symbols, for the reaction of ammonium nitrate with sodium hydroxide.

....

[3]

(d) In order to produce gas **Y** in a pure state in the laboratory, it must be passed through a drying agent.

Why is concentrated sulphuric acid not suitable for drying gas **Y**?

....

.... [1]

2 In many countries, new cars have to comply with regulations which are intended to reduce the pollutants coming from their internal combustion engines.

Two pollutants that may be formed in an internal combustion engine are carbon monoxide, CO, and nitrogen monoxide, NO.

(e) **(i)** Outline how **each** of these pollutants may be formed in an internal combustion engine.

CO ....

....

NO ....

....

(ii) State the main hazard associated with **each** of these pollutants.

CO ....

NO .... [4]

Pollutants such as CO and NO are removed from the exhaust gases of internal combustion engines by catalytic converters which are placed in the exhaust system of a car.

(f) **(i)** What metal is most commonly used as the catalyst in a catalytic converter?

....

(ii) Construct **one** balanced equation for the reaction in which **both** CO **and** NO are removed from the exhaust gases by a catalytic converter.

....[2]

(iii) Calculate the volume of 0.50 mol dm^{-3} sulphuric acid that is required to neutralise the 200 cm^3 of aqueous ammonia.

[3]

(d) In the boxes below, draw diagrams to show the shapes of an ammonia molecule and an ammonium ion. Clearly show the bond angles on your diagrams.

ammonia	ammonium ion

[4]

(e) Ammonia does not burn in air but will burn in pure oxygen.

(i) Balance the equation for this reaction:

$$\ldots\ldots\ NH_3(g) + \ldots\ldots\ O_2(g) \longrightarrow \ldots\ldots\ N_2(g) + \ldots\ldots\ H_2O(g)$$

(ii) Use oxidation numbers to explain why this is a redox reaction.

....

....

....[3]

3 A sample of a fertiliser was known to contain ammonium sulfate, $(NH_4)_2SO_4$, and sand only.

A 2.96 g sample of the solid fertiliser was heated with 40.0 cm^3 of NaOH(aq), an excess, and all of the ammonia produced was boiled away.

After cooling, the remaining NaOH(aq) was exactly neutralised by 29.5 cm^3 of 2.00 mol dm^{-3} HC*l*.

In a separate experiment, 40.0 cm^3 of the original NaOH(aq) was exactly neutralised by 39.2 cm^3 of the 2.00 mol dm^{-3} HC*l*.

(a) **(i)** Write balanced equations for the following reactions.

NaOH with HC*l*

....

$(NH_4)_2SO_4$ with NaOH

....

(ii) Calculate the amount, in moles, of NaOH present in the 40.0 cm^3 of the original NaOH(aq) that was neutralised by 39.2 cm^3 of 2.00 mol dm^{-3} HC*l*.

(iii) Calculate the amount, in moles, of NaOH present in the 40.0 cm^3 of NaOH(aq) that remained after boiling the $(NH_4)_2SO_4$.

(iv) Use your answers to **(ii)** and **(iii)** to calculate the amount, in moles, of NaOH that reacted with the $(NH_4)_2SO_4$.

(v) Use your answers to **(i)** and **(iv)** to calculate the amount, in moles, of $(NH_4)_2SO_4$ that reacted with the NaOH.

(vi) Hence calculate the mass of $(NH_4)_2SO_4$ that reacted.

(vii) Use your answer to **(vi)** to calculate the percentage, by mass, of $(NH_4)_2SO_4$ present in the fertiliser.
Write your answer to a suitable number of significant figures.

[9]

(b) The uncontrolled use of nitrogenous fertilisers can cause environmental damage to lakes and streams. This is known as *eutrophication*.

What are the processes that occur when excessive amounts of nitrogenous fertilisers get into lakes and streams?

....

....

.... [2]

(c) Large quantities of ammonia are manufactured by the Haber process.
Not all of this ammonia is used to make fertilisers.
State **one** large-scale use for ammonia, **other than** in the production of nitrogenous fertilisers.

.... [1]

4 Hydrogen sulphide, H_2S, is a foul-smelling compound found in the gases from volcanoes. Hydrogen sulphide is covalent, melting at –85 °C and boiling at –60 °C.

(c) **(i)** Draw a 'dot-and-cross' diagram to show the structure of the H_2S molecule.

(ii) Predict the shape of the H_2S molecule.

....

(iii) Oxygen and sulphur are both in Group VI of the Periodic Table.

Suggest why the melting and boiling points of water, H_2O, are much higher than those of H_2S.

....

....

.... [4]

Hydrogen sulphide burns with a blue flame in an excess of oxygen to form sulphur dioxide and water.

(d) **(i)** Write a balanced equation for the complete combustion of H_2S.

....

(ii) What is the change in the oxidation number of sulphur in this reaction?

from .... to ....

(iii) What volume of oxygen, measured at room temperature and pressure, is required for the complete combustion of 8.65 g of H_2S? Give your answer to two decimal places.

[5]

Hydrogen sulphide is a weak diprotic (dibasic) acid. Its solution in water contains HS^- and a few S^{2-} ions.

(e) **(i)** What is meant by the term *weak acid*?

....

....

(ii) Write an equation, with state symbols, for the **first** ionisation of H_2S when it dissolves in water.

.... [3]

5 **(d)** Most of the sulfur that is used in the Contact process is recovered from sulfur compounds present in crude oil and natural gas by using the Claus process.

(i) In this process, about one third of the hydrogen sulfide, H_2S, present in the oil or gas, is converted into sulfur dioxide, SO_2.

Balance the equation for this reaction.

$$.....H_2S \quad + ...O_2 \rightarrow .....SO_2 \quad + ...H_2O$$

(ii) The SO_2 formed is then reacted catalytically with the remaining H_2S, producing sulfur and water.

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O$$

What are the oxidation numbers of each of the sulfur-containing substances in this reaction?

H_2S......... SO_2 ....   S ....

Which substance is reduced? Explain your answer.

substance ....

explanation ....[3]

The sulfur present in crude oil is removed in order to prevent the formation of sulfur dioxide when fuels such as petrol (gasoline) or diesel fuel are burned in internal combustion engines.
Other substances that may be present in the exhaust gases of motor vehicles include CO, CO_2, NO/NO_2, and unburnt hydrocarbons.

The emission of sulfur dioxide can produce ‘acid rain’.

(e) **(i)** Outline, with the aid of equations, how acid rain is formed from the exhaust gases of motor vehicles.

....

....

....

....

(ii) State **one** environmental effect of acid rain.

....[4]

(f) Sulfur dioxide is used to preserve dried fruits and vegetables.

What chemical property of SO_2 enables it to be used as a food preservative?

....[1]

6 **(d)** In modern plants, nearly all the SO_2/SO_3 mixture is absorbed but up to 0.05% by volume of SO_2 may be allowed to pass into the atmosphere through a chimney stack.

Give **two** reasons why SO_2 should not be discharged into the atmosphere.

....

....

....[2]

(e) **(i)** When concentrated sulphuric acid is warmed with solid sodium chloride, misty fumes are produced.

Identify the fumes. ....

Write an equation for the reaction.

....

(ii) When concentrated sulphuric acid is warmed with solid sodium iodide, purple fumes are produced.

Identify the fumes. ....

[3]

DATA BOOKLET

1 Important values, constants and standards

molar gas constant	$R = 8.31\ \text{J K}^{-1}\ \text{mol}^{-1}$
the Faraday constant	$F = 9.65 \times 10^{4}\ \text{C mol}^{-1}$
the Avogadro constant	$L = 6.02 \times 10^{23}\ \text{mol}^{-1}$
the Planck constant	$h = 6.63 \times 10^{-34}\ \text{J s}$
speed of light in a vacuum	$c = 3.00 \times 10^{8}\ \text{m s}^{-1}$
rest mass of proton, ${}^{1}_{1}\text{H}$	$m_p = 1.67 \times 10^{-27}\ \text{kg}$
rest mass of neutron, ${}^{1}_{0}\text{n}$	$m_n = 1.67 \times 10^{-27}\ \text{kg}$
rest mass of electron, ${}^{0}_{-1}\text{e}$	$m_e = 9.11 \times 10^{-31}\ \text{kg}$
electronic charge	$e = -1.60 \times 10^{-19}\ \text{C}$
molar volume of gas	$V_m = 22.4\ \text{dm}^3\ \text{mol}^{-1}$ at s.t.p $V_m = 24.0\ \text{dm}^3\ \text{mol}^{-1}$ under room conditions (where s.t.p. is expressed as 101 kPa, approximately, and 273 K (0 °C))
ionic product of water	$K_w = 1.00 \times 10^{-14}\ \text{mol}^2\ \text{dm}^{-6}$ (at 298 K (25 °C))
specific heat capacity of water	$= 4.18\ \text{kJ kg}^{-1}\ \text{K}^{-1}$ $(= 4.18\ \text{J g}^{-1}\ \text{K}^{-1})$

2 Ionisation energies (1st, 2nd, 3rd and 4th) of selected elements, in kJ mol^{-1}

	Proton number	First	Second	Third	Fourth
H	1	1310	–	–	–
He	2	2370	5250	–	–
Li	3	519	7300	11800	–
Be	4	900	1760	14800	21000
B	5	799	2420	3660	25000
C	6	1090	2350	4610	6220
N	7	1400	2860	4590	7480
O	8	1310	3390	5320	7450
F	9	1680	3370	6040	8410
Ne	10	2080	3950	6150	9290
Na	11	494	4560	6940	9540
Mg	12	736	1450	7740	10500
A*l*	13	577	1820	2740	11600
Si	14	786	1580	3230	4360
P	15	1060	1900	2920	4960
S	16	1000	2260	3390	4540
C*l*	17	1260	2300	3850	5150
Ar	18	1520	2660	3950	5770
K	19	418	3070	4600	5860
Ca	20	590	1150	4940	6480
Sc	21	632	1240	2390	7110
Ti	22	661	1310	2720	4170
V	23	648	1370	2870	4600
Cr	24	653	1590	2990	4770
Mn	25	716	1510	3250	5190
Fe	26	762	1560	2960	5400
Co	27	757	1640	3230	5100
Ni	28	736	1750	3390	5400
Cu	29	745	1960	3350	5690
Zn	30	908	1730	3828	5980
Ga	31	577	1980	2960	6190

	Proton number	First	Second	Third	Fourth
Br	35	1140	2080	3460	4850
Rb	37	403	2632	3900	5080
Sr	38	548	1060	4120	5440
Ag	47	731	2074	3361	–
I	53	1010	1840	2040	4030
Cs	55	376	2420	3300	–
Ba	56	502	966	3390	–

3 Bond energies

3(a) Bond energies in diatomic molecules (these are exact values)

Homonuclear

Bond	Energy/kJ mol^{-1}
H–H	436
D–D	442
N≡N	944
O=O	496
P≡P	485
S=S	425
F–F	158
Cl–Cl	242
Br–Br	193
I–I	151

Heteronuclear

Bond	Energy/kJ mol^{-1}
H–F	562
H–Cl	431
H–Br	366
H–I	299
C≡O	1077

3(b) Bond energies in polyatomic molecules (these are average values)

Homonuclear

Bond	Energy/kJ mol^{-1}
C–C	350
C=C	610
C≡C	840
C⋯C (benzene)	520
N–N	160
N=N	410
O–O	150
Si–Si	222
P–P	200
S–S	264

Heteronuclear

Bond	Energy/kJ mol^{-1}
C–H	410
C–C*l*	340
C–Br	280
C–I	240
C–N	305
C=N	610
C≡N	890
C–O	360
C=O	740
C=O in CO_2	805
N–H	390
N–C*l*	310
O–H	460
Si–C*l*	359
Si–H	320
Si–O (in SiO_2(s))	460
Si=O (in SiO_2(g))	640
P–H	320
P–C*l*	330
P–O	340
P=O	540
S–H	347
S–C*l*	250
S–O	360
S=O	500

4 Standard electrode potential and redox potentials, $E^\ominus$ at 298 K (25 °C)

For ease of reference, two tables are given:

(a) an extended list in alphabetical order

(b) a shorter list in decreasing order of magnitude, i.e. a redox series.

(a) $E^\ominus$ in alphabetical order

Electrode reaction			$E^\ominus$/V
$Ag^+ + e^-$	$\rightleftharpoons$	Ag	+0.80
$Al^{3+} + 3e^-$	$\rightleftharpoons$	Al	–1.66
$Ba^{2+} + 2e^-$	$\rightleftharpoons$	Ba	–2.90
$Br_2 + 2e^-$	$\rightleftharpoons$	$2Br^-$	+1.07
$Ca^{2+} + 2e^-$	$\rightleftharpoons$	Ca	–2.87
$Cl_2 + 2e^-$	$\rightleftharpoons$	$2Cl^-$	+1.36
$2HOCl + 2H^+ + 2e^-$	$\rightleftharpoons$	$Cl_2 + 2H_2O$	+1.64
$ClO^- + H_2O + 2e^-$	$\rightleftharpoons$	$Cl^- + 2OH^-$	+0.89
$Co^{2+} + 2e^-$	$\rightleftharpoons$	Co	–0.28
$Co^{3+} + e^-$	$\rightleftharpoons$	Co^{2+}	+1.82
$[Co(NH_3)_6]^{2+} + 2e^-$	$\rightleftharpoons$	$Co + 6NH_3$	–0.43
$Cr^{2+} + 2e^-$	$\rightleftharpoons$	Cr	–0.91
$Cr^{3+} + 3e^-$	$\rightleftharpoons$	Cr	–0.74
$Cr^{3+} + e^-$	$\rightleftharpoons$	Cr^{2+}	–0.41
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	$\rightleftharpoons$	$2Cr^{3+} + 7H_2O$	+1.33
$Cu^+ + e^-$	$\rightleftharpoons$	Cu	+0.52
$Cu^{2+} + 2e^-$	$\rightleftharpoons$	Cu	+0.34
$Cu^{2+} + e^-$	$\rightleftharpoons$	Cu^+	+0.15
$[Cu(NH_3)_4]^{2+} + 2e^-$	$\rightleftharpoons$	$Cu + 4NH_3$	–0.05
$F_2 + 2e^-$	$\rightleftharpoons$	$2F^-$	+2.87
$Fe^{2+} + 2e^-$	$\rightleftharpoons$	Fe	–0.44
$Fe^{3+} + 3e^-$	$\rightleftharpoons$	Fe	–0.04
$Fe^{3+} + e^-$	$\rightleftharpoons$	Fe^{2+}	+0.77
$[Fe(CN)_6]^{3-} + e^-$	$\rightleftharpoons$	$[Fe(CN)_6]^{4-}$	+0.36
$Fe(OH)_3 + e^-$	$\rightleftharpoons$	$Fe(OH)_2 + OH^-$	–0.56
$2H^+ + 2e^-$	$\rightleftharpoons$	H_2	0.00
$2H_2O + 2e^-$	$\rightleftharpoons$	$H_2 + 2OH^-$	–0.83
$I_2 + 2e^-$	$\rightleftharpoons$	$2I^-$	+0.54

Electrode reaction			$E^\ominus$ / V
$K^+ + e^-$	⇌	K	–2.92
$Li^+ + e^-$	⇌	Li	–3.04
$Mg^{2+} + 2e^-$	⇌	Mg	–2.38
$Mn^{2+} + 2e^-$	⇌	Mn	–1.18
$Mn^{3+} + e^-$	⇌	Mn^{2+}	+1.49
$MnO_2 + 4H^+ + 2e^-$	⇌	$Mn^{2+} + 2H_2O$	+1.23
$MnO_4^- + e^-$	⇌	MnO_4^{2-}	+0.56
$MnO_4^- + 4H^+ + 3e^-$	⇌	$MnO_2 + 2H_2O$	+1.67
$MnO_4^- + 8H^+ + 5e^-$	⇌	$Mn^{2+} + 4H_2O$	+1.52
$NO_3^- + 2H^+ + e^-$	⇌	$NO_2 + H_2O$	+0.81
$NO_3^- + 3H^+ + 2e^-$	⇌	$HNO_2 + H_2O$	+0.94
$NO_3^- + 10H^+ + 8e^-$	⇌	$NH_4^+ + 3H_2O$	+0.87
$Na^+ + e^-$	⇌	Na	–2.71
$Ni^{2+} + 2e^-$	⇌	Ni	–0.25
$[Ni(NH_3)_6]^{2+} + 2e^-$	⇌	$Ni + 6NH_3$	–0.51
$H_2O_2 + 2H^+ + 2e^-$	⇌	$2H_2O$	+1.77
$HO_2^- + H_2O + 2e^-$	⇌	$3OH^-$	+0.88
$O_2 + 4H^+ + 4e^-$	⇌	$2H_2O$	+1.23
$O_2 + 2H_2O + 4e^-$	⇌	$4OH^-$	+0.40
$O_2 + 2H^+ + 2e^-$	⇌	H_2O_2	+0.68
$O_2 + H_2O + 2e^-$	⇌	$HO_2^- + OH^-$	–0.08
$Pb^{2+} + 2e^-$	⇌	Pb	–0.13
$Pb^{4+} + 2e^-$	⇌	Pb^{2+}	+1.69
$PbO_2 + 4H^+ + 2e^-$	⇌	$Pb^{2+} + 2H_2O$	+1.47
$SO_4^{2-} + 4H^+ + 2e^-$	⇌	$SO_2 + 2H_2O$	+0.17
$S_2O_8^{2-} + 2e^-$	⇌	$2SO_4^{2-}$	+2.01
$S_4O_6^{2-} + 2e^-$	⇌	$2S_2O_3^{2-}$	+0.09
$Sn^{2+} + 2e^-$	⇌	Sn	–0.14
$Sn^{4+} + 2e^-$	⇌	Sn^{2+}	+0.15
$V^{2+} + 2e^-$	⇌	V	–1.20
$V^{3+} + e^-$	⇌	V^{2+}	–0.26
$VO^{2+} + 2H^+ + e^-$	⇌	$V^{3+} + H_2O$	+0.34
$VO_2^+ + 2H^+ + e^-$	⇌	$VO^{2+} + H_2O$	+1.00
$VO_3^- + 4H^+ + e^-$	⇌	$VO^{2+} + 2H_2O$	+1.00
$Zn^{2+} + 2e^-$	⇌	Zn	–0.76

(b) $E^\ominus$ in decreasing order of oxidising power

(a selection only – see also the extended alphabetical list on the previous pages)

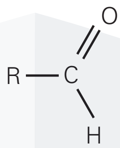
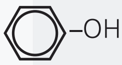
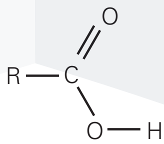
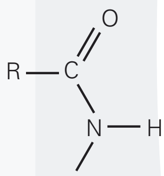
Electrode reaction			$E^\ominus / V$
$F_2 + 2e^-$	⇌	$2F^-$	+2.87
$S_2O_8^{2-} + 2e^-$	⇌	$2SO_4^{2-}$	+2.01
$H_2O_2 + 2H^+ + 2e^-$	⇌	$2H_2O$	+1.77
$MnO_4^- + 8H^+ + 5e^-$	⇌	$Mn^{2+} + 4H_2O$	+1.52
$PbO_2 + 4H^+ + 2e^-$	⇌	$Pb^{2+} + 2H_2O$	+1.47
$Cl_2 + 2e^-$	⇌	$2Cl^-$	+1.36
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	⇌	$2Cr^{3+} + 7H_2O$	+1.33
$O_2 + 4H^+ + 4e^-$	⇌	$2H_2O$	+1.23
$Br_2 + 2e^-$	⇌	$2Br^-$	+1.07
$ClO^- + H_2O + 2e^-$	⇌	$Cl^- + 2OH^-$	+0.89
$NO_3^- + 10H^+ + 8e^-$	⇌	$NH_4^+ + 3H_2O$	+0.87
$NO_3^- + 2H^+ + e^-$	⇌	$NO_2 + H_2O$	+0.81
$Ag^+ + e^-$	⇌	Ag	+0.80
$Fe^{3+} + e^-$	⇌	Fe^{2+}	+0.77
$I_2 + 2e^-$	⇌	$2I^-$	+0.54
$O_2 + 2H_2O + 4e^-$	⇌	$4OH^-$	+0.40
$Cu^{2+} + 2e^-$	⇌	Cu	+0.34
$SO_4^{2-} + 4H^+ + 2e^-$	⇌	$SO_2 + 2H_2O$	+0.17
$Sn^{4+} + 2e^-$	⇌	Sn^{2+}	+0.15
$S_4O_6^{2-} + 2e^-$	⇌	$2S_2O_3^{2-}$	+0.09
$2H^+ + 2e^-$	⇌	H_2	0.00
$Pb^{2+} + 2e^-$	⇌	Pb	–0.13
$Sn^{2+} + 2e^-$	⇌	Sn	–0.14
$Fe^{2+} + 2e^-$	⇌	Fe	–0.44
$Zn^{2+} + 2e^-$	⇌	Zn	–0.76
$2H_2O + 2e^-$	⇌	$H_2 + 2OH^-$	–0.83
$V^{2+} + 2e^-$	⇌	V	–1.20
$Mg^{2+} + 2e^-$	⇌	Mg	–2.38
$Ca^{2+} + 2e^-$	⇌	Ca	–2.87
$K^+ + e^-$	⇌	K	–2.92

5 Atomic and ionic radii

(a) Period 1	**atomic/nm**		**ionic/nm**			
single covalent	H	0.037	H^{+}	0.208		
van der Waals	He	0.140				
(b) Period 2						
metallic	Li	0.152	Li^{+}	0.060		
	Be	0.112	Be^{2+}	0.031		
single covalent	B	0.080	B^{3+}	0.020		
	C	0.077	C^{4+}	0.015	C^{4-}	0.260
	N	0.074			N^{3-}	0.171
	O	0.073			O^{2-}	0.140
	F	0.072			F^{-}	0.136
van der Waals	Ne	0.160				
(c) Period 3						
metallic	Na	0.186	Na^{+}	0.095		
	Mg	0.160	Mg^{2+}	0.065		
	Al	0.143	Al^{3+}	0.050		
single covalent	Si	0.117	Si^{4+}	0.041		
	P	0.110			P^{3-}	0.212
	S	0.104			S^{2-}	0.184
	Cl	0.099			Cl^{-}	0.181
van der Waals	Ar	0.190				
(d) Group 2						
metallic	Be	0.112	Be^{2+}	0.031		
	Mg	0.160	Mg^{2+}	0.065		
	Ca	0.197	Ca^{2+}	0.099		
	Sr	0.215	Sr^{2+}	0.113		
	Ba	0.217	Ba^{2+}	0.135		
	Ra	0.220	Ra^{2+}	0.140		

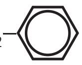
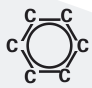
(e) Group 14	atomic/nm		ionic/nm			
single covalent	C	0.077				
	Si	0.117	Si^{4+}	0.041		
	Ge	0.122	Ge^{2+}	0.093		
metallic	Sn	0.162	Sn^{2+}	0.112		
	Pb	0.175	Pb^{2+}	0.120		
(f) Group 17						
single covalent	F	0.072	F^{-}	0.136		
	Cl	0.099	Cl^{-}	0.181		
	Br	0.114	Br^{-}	0.195		
	I	0.133	I^{-}	0.216		
	At	0.140				
(g) First row transition elements						
metallic	Sc	0.164			Sc^{3+}	0.081
	Ti	0.146	Ti^{2+}	0.090	Ti^{3+}	0.067
	V	0.135	V^{2+}	0.079	V^{3+}	0.064
	Cr	0.129	Cr^{2+}	0.073	Cr^{3+}	0.062
	Mn	0.132	Mn^{2+}	0.067	Mn^{3+}	0.062
	Fe	0.126	Fe^{2+}	0.061	Fe^{3+}	0.055
	Co	0.125	Co^{2+}	0.078	Co^{3+}	0.053
	Ni	0.124	Ni^{2+}	0.070	Ni^{3+}	0.056
	Cu	0.128	Cu^{2+}	0.073		
	Zn	0.135	Zn^{2+}	0.075		

6 Typical proton (^{1}H) chemical shift values (δ) relative to TMS = 0

Type of proton	Environment of proton	Example structures	Chemical shift range (δ)
C–H	alkane	$-CH_3$, $-CH_2-$, $>CH-$	0.9–1.7
	alkyl next to C=O	$CH_3-C=O$, $-CH_2-C=O$, $>CH-C=O$	2.2–3.0
	alkyl next to aromatic ring	CH_3-Ar, $-CH_2-Ar$, $>CH-Ar$	2.3–3.0
	alkyl next to electronegative atom	CH_3-O, $-CH_2-O$, $-CH_2-Cl$, $>CH-Br$	3.2–4.0
	attached to alkyne	$\equiv C-H$	1.8–3.1
	attached to alkene	$=CH_2$, $=CH-$	4.5–6.0
	attached to aromatic ring		6.0–9.0
	aldehyde		9.3–10.5
O–H (see note below)	alcohol	RO–H	0.5–6.0
	phenol		4.5–7.0
	carboxylic acid		9.0–13.0
N–H (see note below)	alkyl amine	R–NH–	1.0–5.0
	aryl amine		3.0–6.0
	amide		5.0–12.0

Note: δ values for –O–H and –N–H protons can vary depending on solvent and concentration.

7 Typical carbon (^{13}C) chemical shift values (δ) relative to TMS = 0

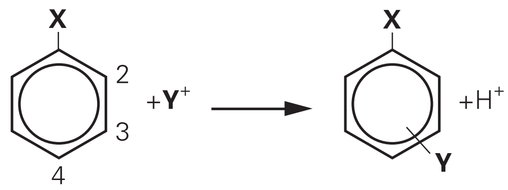
Hybridisation of the carbon atom	Environment of carbon atom	Example structures	Chemical shift range (δ)
sp^3	alkyl	$\mathbf{C}H_3$–, $\mathbf{C}H_2$–, –$\mathbf{C}$H<	0–50
sp^3	next to alkene/arene	–$\mathbf{C}H_2$–C=C, –$\mathbf{C}H_2$– 	10–40
sp^3	next to carbonyl/carboxyl	–$\mathbf{C}H_2$–COR, –$\mathbf{C}H_2$–CO_2R	25–50
sp^3	next to nitrogen	–$\mathbf{C}H_2$–NH_2, –$\mathbf{C}H_2$–NR_2, –$\mathbf{C}H_2$–NHCO	30–65
sp^3	next to chlorine (–CH_2–Br and –CH_2–I are in the same range as alkyl)	–$\mathbf{C}H_2$–C*l*	30–60
sp^3	next to oxygen	–$\mathbf{C}H_2$–OH, –$\mathbf{C}H_2$–O–CO–	50–70
sp^2	alkene or arene	>$\mathbf{C}$=$\mathbf{C}$<, 	110–160
sp^2	carboxyl	R–$\mathbf{C}O_2$H, R–$\mathbf{C}O_2$R	160–185
sp^2	carbonyl	R–$\mathbf{C}$HO, R–$\mathbf{C}$O–R	190–220
sp	alkyne	R–$\mathbf{C}$≡$\mathbf{C}$–	65–85
sp	nitrile	R–$\mathbf{C}$≡N	100–125

8 Characteristic infra-red absorption frequencies for some selected bonds

Bond	Functional groups containing the bond	Absorption range (in wavenumbers)/cm^{-1}	Appearance of peak (*s = strong, w = weak*)
C–O	alcohols, ethers, esters	1040–1300	***s***
C=C	aromatic compounds, alkenes	1500–1680	***w*** unless conjugated
C=O	amides ketones and aldehydes esters	1640–1690 1670–1740 1710–1750	***s*** ***s*** ***s***
C≡C	alkynes	2150–2250	***w*** unless conjugated
C≡N	nitriles	2200–2250	***w***
C–H	alkanes, CH_2–H alkenes/arenes, =C–H	2850–2950 3000–3100	***s*** ***w***
N–H	amines, amides	3300–3500	***w***
O–H	carboxylic acids, RCO_2–H H-bonded alcohol, RO–H free alcohol, RO–H	2500–3000 3200–3600 3580–3650	***s*** and very broad ***s*** ***s*** and sharp

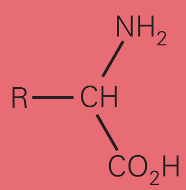
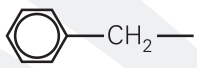
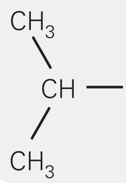
9 The orientating effect of groups in aromatic substitution reactions.

The position of the incoming group, **Y**, is determined by the nature of the group, **X**, already bonded to the ring, and not by the nature of the incoming group **Y**.



X– groups that direct the incoming Y group to the 2– or 4– positions	X– groups that direct the incoming Y group to the 3– position
$-NH_2$, $-NHR$ or $-NR_2$	$-NO_2$
$-OH$ or $-OR$	$-NH_3$
$-NHCOR$	$-CN$
$-CH_2$, –alkyl	$-CHO$, $-COR$
$-Cl$	$-CO_2H$, $-CO_2R$

10 Names, structures and abbreviations of some amino acids

Name	**3-letter abbreviation**	**1-letter symbol**	**structure of side chain R– in** 
alanine	Ala	A	CH_3–
aspartic acid	Asp	D	HO_2CCH_2–
cysteine	Cys	C	$HSCH_2$–
glutamic acid	Glu	E	$HO_2CCH_2CH_2$–
glycine	Gly	G	H–
lysine	Lys	K	$H_2NCH_2CH_2CH_2CH_2$–
phenylalanine	Phe	F	
serine	Ser	S	$HOCH_2$–
tyrosine	Tyr	Y	
valine	Val	V	

Key

atomic number
atomic symbol
name
relative atomic mass

Group																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
							1 H hydrogen 1.0										2 He helium 4.0
3 Li lithium 6.9	4 Be beryllium 9.0											5 B boron 10.8	6 C carbon 12.0	7 N nitrogen 14.0	8 O oxygen 16.0	9 F fluorine 19.0	10 Ne neon 20.2
11 Na sodium 23.0	12 Mg magnesium 24.3											13 Al aluminium 27.0	14 Si silicon 28.1	15 P phosphorus 31.0	16 S sulfur 32.1	17 Cl chlorine 35.5	18 Ar argon 39.9
19 K potassium 39.1	20 Ca calcium 40.1	21 Sc scandium 45.0	22 Ti titanium 47.9	23 V vanadium 50.9	24 Cr chromium 52.0	25 Mn manganese 54.9	26 Fe iron 55.8	27 Co cobalt 58.9	28 Ni nickel 58.7	29 Cu copper 63.5	30 Zn zinc 65.4	31 Ga gallium 69.7	32 Ge germanium 72.6	33 As arsenic 74.9	34 Se selenium 79.0	35 Br bromine 79.9	36 Kr krypton 83.8
37 Rb rubidium 85.5	38 Sr strontium 87.6	39 Y yttrium 88.9	40 Zr zirconium 91.2	41 Nb niobium 92.9	42 Mo molybdenum 95.9	43 Tc technetium –	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs caesium 132.9	56 Ba barium 137.3	57–71 lanthanoids	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.8	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.6	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 209.0	84 Po polonium –	85 At astatine –	86 Rn radon –
87 Fr francium –	88 Ra radium –	89–103 actinoids	104 Rf rutherfordium –	105 Db dubnium –	106 Sg seaborgium –	107 Bh bohrium –	108 Hs hassium –	109 Mt meitnerium –	110 Ds darmstadtium –	111 Rg roentgenium –	112 Cn copernicium –		114 Fl flerovium –		116 Lv livermorium –		

lanthanoids	57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.4	61 Pm promethium –	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.3	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.1	71 Lu lutetium 175.0
actinoids	89 Ac actinium –	90 Th thorium 232.0	91 Pa protactinium 231.0	92 U uranium 238.0	93 Np neptunium –	94 Pu plutonium –	95 Am americium –	96 Cm curium –	97 Bk berkelium –	98 Cf californium –	99 Es einsteinium –	100 Fm fermium –	101 Md mendelevium –	102 No nobelium –	103 Lr lawrencium –