1. NO(g), H_2(g), N_2(g) and H_2O(g) exist in equilibrium:

$$2NO(g) + 2H_2(g) \rightleftharpoons N_2(g) + 2H_2O(g)$$

At room temperature and pressure, the equilibrium lies well to the right-hand side.

Which of the following could be the equilibrium constant for this equilibrium?

A 1.54×10^{-3} mol dm^{-3}

B 6.50×10^{2} mol dm^{-3}

C 1.54×10^{-3} dm^{3} mol^{-1}

D 6.50×10^{2} dm^{3} mol^{-1}

Your answer ☐

[1]

2. Two students set up the equilibrium system below.

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

The students titrated samples of the equilibrium mixture with sodium hydroxide, NaOH(aq), to determine the concentration of CH_3COOH.

The students used their results to calculate a value for K_c.

The students' values for K_c were different.

Which of the reason(s) below could explain why the calculated values for K_c were different?

1: Each student carried out their experiment at a different temperature.

2: Each student used a different concentration of NaOH(aq) in their titration.

3: Each student titrated a different volume of the equilibrium mixture.

A 1, 2 and 3

B Only 1 and 2

C Only 2 and 3

D Only 1

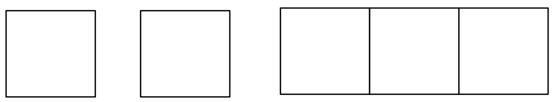
Your answer ☐

[1]

3. Ammonia is a gas with covalently-bonded molecules consisting of nitrogen and hydrogen atoms.

(a) Show the electron configuration of a nitrogen atom using '*electron-in-box*' diagrams.

Label each sub-shell.



1s ……… ………

[2]

(b) Ammonia can be made from the reaction of nitrogen and hydrogen in the Haber process.

$$N_2(g) + 3H_2(g) \underset{450\ ^\circ C\ \text{and}\ 200\ kPa}{\overset{\text{Fe catalyst}}{\rightleftharpoons}} 2NH_3(g) \qquad \Delta H = -92\ kJ\ mol^{-1}$$ **Equation 1**

What effect will increasing the temperature have on the composition of the equilibrium mixture **and** on the value of the equilibrium constant?

Explain your answer.

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…………………………………………………………………………………………… **[2]**

(c) A chemist mixes together 0.450 mol N_2 with 0.450 mol H_2 in a sealed container.

The mixture is heated and allowed to reach equilibrium.

At equilibrium, the mixture contains 0.400 mol N_2 and the total pressure is 500 kPa.

Calculate K_p.

Show **all** your working.

Include units in your answer.

K_p = ... units .... **[5]**

(d) A chemical company receives an order to supply 1.96×10^{10} dm^3 of ammonia at room temperature and pressure. The Haber process produces a 95.0% yield.

Calculate the mass of hydrogen, in tonnes, required to produce the ammonia.

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

required mass of hydrogen = ... tonnes **[3]**

(e) **(i)** Hydrazine, N_2H_4, is used as a rocket fuel. Hydrazine can be prepared from the reaction of ammonia with sodium chlorate(I). There are two other products in the reaction.

Write an equation for this reaction.

[1]

(ii) Using the electron pair repulsion theory, draw a 3-D diagram of a molecule of hydrazine.

Predict the H–N–H bond angle around each nitrogen atom.

H–N–H bond angle: .... **[2]**

4. A mixture of N_2 and O_2 gases has a total pressure of 1.42 atm.
The mole fraction of N_2 is 0.700.

What is the partial pressure, in atm, of O_2 in the mixture?

A 0.211

B 0.426

C 0.493

D 0.994

Your answer [ ] **[1]**

5. This question is about free energy changes, ΔG, enthalpy changes, ΔH, and temperature, T.

(a) The Gibbs' equation is shown below.

$$\Delta G = \Delta H - T\Delta S$$

A chemist investigates a reaction to determine how ΔG varies with T.
The results are shown in **Fig. 18.1**.

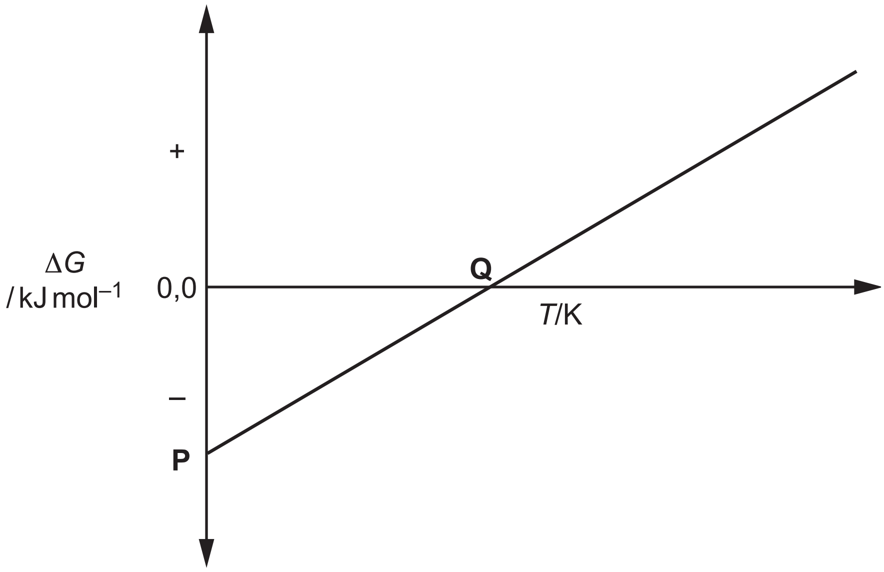

Fig. 18.1

What is significant about the gradient of the line and the values **P** and **Q** shown in **Fig. 18.1**?
Explain your reasoning.

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.... **[4]**

(b) Iron can be extracted from its ore Fe_3O_4 using carbon.
Several equilibria are involved including **equilibrium 18.1**, shown below.

equilibrium 18.1 $Fe_3O_4(s) + 4C(s) \rightleftharpoons 3Fe(s) + 4CO(g)$ $\Delta H = +676.4\,kJ\,mol^{-1}$
$\Delta S = +703.1\,J\,K^{-1}\,mol^{-1}$

(i) Why is **equilibrium 18.1** a *heterogeneous* equilibrium?

....

.... **[1]**

(ii) Write the expression for K_p for **equilibrium 18.1**.

[1]

(iii) The forward reaction in **equilibrium 18.1** is only feasible at high temperatures.

- Show that the forward reaction is **not** feasible at 25 °C.
- Calculate the minimum temperature, in K, for the forward reaction to be feasible.

minimum temperature = ... K **[3]**

(iv) Another equilibrium involved in the extraction of iron from Fe_3O_4 is shown below.

$$Fe_3O_4(s) + 4CO(g) \rightleftharpoons 3Fe(s) + 4CO_2(g) \qquad \Delta H = -13.5\,kJ\,mol^{-1}$$

Enthalpy changes of formation, $\Delta_f H$, for Fe_3O_4(s) and CO_2(g) are shown in the table.

Compound	**$\Delta_f H$ / kJ mol^{-1}**
Fe_3O_4(s)	–1118.5
CO_2(g)	–393.5

Calculate the enthalpy change of formation, $\Delta_f H$, for CO(g).

$\Delta_f H$, for CO(g) = ... kJ mol^{-1} **[3]**

6. This question is about equilibrium reactions.

(a) Hydrogen gas is manufactured by the chemical industry using the reaction of methane and steam. This is a reversible reaction, shown in **equilibrium 20.1** below.

equilibrium 20.1 $CH_4(g) + H_2O(g) \rightleftharpoons 3H_2(g) + CO(g)$ $\Delta H = +210\,kJ\,mol^{-1}$

Explain, in terms of le Chatelier's principle, the conditions of pressure and temperature for a maximum yield of hydrogen from **equilibrium 20.1**, and explain why the operational conditions used by the chemical industry may be different.

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.... **[4]**

(b) A chemist investigates the equilibrium reaction between sulfur dioxide, oxygen, and sulfur trioxide, shown below.

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

- The chemist mixes together SO_2 and O_2 with a catalyst.
- The chemist compresses the gas mixture to a volume of 400 cm^3.
- The mixture is heated to a constant temperature and is allowed to reach equilibrium without changing the total gas volume.

The equilibrium mixture contains 0.0540 mol SO_2 and 0.0270 mol O_2.

At the temperature used, the numerical value for K_c is $3.045 \times 10^4\ dm^3\ mol^{-1}$.

(i) Write the expression for K_c and the units of K_c for this equilibrium.

[2]

(ii) Determine the amount, in mol, of SO_3 in the equilibrium mixture at this temperature.

Give your final answer to an **appropriate** number of significant figures.

Show all your working.

equilibrium amount of SO_3 = ... mol **[4]**

7. This question is about reactions of hydrogen peroxide, H_2O_2.

(a) Hydrogen peroxide, H_2O_2, iodide ions, I^-, and acid, H^+, react as shown in the equation below.

$$H_2O_2(aq) + 2I^-(aq) + 2H^+(aq) \rightarrow I_2(aq) + 2H_2O(l)$$

A student carries out several experiments at the same temperature, using the initial rates method, to determine the rate constant, *k*, for this reaction.

The results are shown below.

Experiment	Initial concentrations			Rate / 10^{-6} mol dm^{-3} s^{-1}
	$[H_2O_2(aq)]$ / mol dm^{-3}	$[I^-(aq)]$ / mol dm^{-3}	$[H^+(aq)]$ / mol dm^{-3}	
1	0.0100	0.0100	0.100	2.00
2	0.0100	0.0200	0.100	4.00
3	0.0200	0.0100	0.100	4.00
4	0.0200	0.0100	0.200	4.00

(i) Determine the rate equation and calculate the rate constant, *k*, including units.

k = ... units .... **[3]**

(ii) The rate constant, *k*, for this reaction is determined at different temperatures, *T*.

Explain how the student could determine the activation energy, E_a, for the reaction graphically using values of *k* and *T*.

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.... **[3]**

(b) Solutions of hydrogen peroxide decompose slowly into water and oxygen:

$$2H_2O_2(aq) \rightarrow 2H_2O(l) + O_2(g)$$

This reaction is catalysed by manganese dioxide, $MnO_2(s)$.

Standard electrode potentials are shown below.

$O_2(g) + 2H^+(aq) + 2e^-$	$\rightleftharpoons$	$H_2O_2(aq)$	$E^\ominus = +0.70\,V$
$MnO_2(s) + 4H^+(aq) + 2e^-$	$\rightleftharpoons$	$Mn^{2+}(aq) + 2H_2O(l)$	$E^\ominus = +1.51\,V$
$H_2O_2(g) + 2H^+(aq) + 2e^-$	$\rightleftharpoons$	$2H_2O(l)$	$E^\ominus = +1.78\,V$

Using the electrode potentials, explain how MnO_2 is able to act as a catalyst for the decomposition of hydrogen peroxide.

You answer should include relevant equations.

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.... **[4]**

(c) Peroxycarboxylic acids are organic compounds with the COOOH functional group.

Peroxyethanoic acid, CH_3COOOH, is used as a disinfectant.

(i) Suggest the structure for CH_3COOOH.

The COOOH functional group must be clearly displayed.

[1]

(ii) Peroxyethanoic acid can be prepared by reacting hydrogen peroxide with ethanoic acid. This is a heterogeneous equilibrium.

$$H_2O_2(aq) + CH_3COOH(aq) \rightleftharpoons CH_3COOOH(aq) + H_2O(l) \quad K_c = 0.37\,dm^3\,mol^{-1}$$

A $250\,cm^3$ equilibrium mixture contains concentrations of $0.500\,mol\,dm^{-3}$ $H_2O_2(aq)$ and $0.500\,mol\,dm^{-3}$ $CH_3COOH(aq)$.

Calculate the amount, in mol, of peroxyethanoic acid in the equilibrium mixture.

amount = ... mol **[3]**

8. The reversible reaction of sulfur dioxide and oxygen to form sulfur trioxide is shown below.

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

An equilibrium mixture contains 2.4 mol SO_2, 1.2 mol O_2 and 0.4 mol SO_3.
The total pressure is 250 atm.

What is the partial pressure of SO_3?

A 15 atm

B 25 atm

C 100 atm

D 200 atm

Your answer ☐ **[1]**

9. Nitrogen monoxide, NO, and oxygen, O_2, react to form nitrogen dioxide, NO_2, in the reversible reaction shown in **equilibrium 18.1**.

$$2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$$ **Equilibrium 18.1**

(a) Write an expression for K_c for this equilibrium and state the units.

K_c =

Units = ... **[2]**

(b) A chemist mixes together nitrogen and oxygen and pressurises the gases so that their total gas volume is 4.0 dm^3.

- The mixture is allowed to reach equilibrium at constant temperature and volume.
- The equilibrium mixture contains 0.40 mol NO and 0.80 mol O_2.
- Under these conditions, the numerical value of K_c is 45.

Calculate the amount, in mol, of NO_2 in the equilibrium mixture.

amount of NO_2 = ... mol **[4]**

(c) The values of K_p for **equilibrium 18.1** at 298 K and 1000 K are shown below.

$2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$ **Equilibrium 18.1**

Temperature / K	**K_p / atm^{-1}**
298	$K_p = 2.19 \times 10^{12}$
1000	$K_p = 2.03 \times 10^{-1}$

(i) Predict, with a reason, whether the forward reaction is exothermic or endothermic.

....

.... **[1]**

(ii) The chemist increases the pressure of the equilibrium mixture at the same temperature.

State, and explain in terms of K_p, how you would expect the equilibrium position to change.

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.... **[3]**

10. A student carries out two experiments in the laboratory based on succinic acid (butanedioic acid), $(CH_2COOH)_2$.

(a) Aqueous succinic acid can be neutralised by aqueous sodium hydroxide, NaOH(aq):

$$(CH_2COOH)_2(aq) + 2NaOH(aq) \rightarrow (CH_2COONa)_2(aq) + 2H_2O(l)$$

This reaction can be used to determine a value for the enthalpy change of neutralisation, $\Delta_{neut}H$.

The student follows this method:

- Add 50.0 cm^3 of 0.400 mol dm^{-3} succinic acid to a polystyrene cup.
- Measure out 50.0 cm^3 of 1.00 mol dm^{-3} NaOH(aq), which is in excess.
- Measure the temperature of both solutions.
- Add the NaOH(aq) to the aqueous succinic acid in the polystyrene cup, stir the mixture, and record the maximum temperature.

Temperature readings

Maximum temperature of mixture/°C	26.5
Initial temperature of both solutions/°C	21.5

Calculate a value for the enthalpy change of neutralisation, $\Delta_{neut}H$, in kJ mol^{-1}.

Assume that the density of all solutions and the specific heat capacity, *c*, of the reaction mixture are the same as for water.

$\Delta_{neut}H$ = ... kJ mol^{-1} **[4]**

(b) Succinic acid is esterified by ethanol, C_2H_5OH, in the presence of an acid catalyst to form an equilibrium mixture.

The equilibrium constant, K_c, for this equilibrium can be calculated using the amounts, in moles, of the components in the equilibrium mixture, using **expression 5.1**.

$$K_c = \frac{n((CH_2COOC_2H_5)_2) \times n(H_2O)^2}{n((CH_2COOH)_2) \times n(C_2H_5OH)^2}$$ **Expression 5.1**

A student carries out an experiment to determine the value of K_c for this equilibrium.

- The student mixes together 0.0500 mol of succinic acid and 0.150 mol of ethanol, with a small amount of an acid catalyst.
- The mixture is allowed to reach equilibrium.
- The student determines that 0.0200 mol of succinic acid are present in the equilibrium mixture.

(i) Which technique could be used to determine the equilibrium amount of succinic acid?

.... **[1]**

(ii) Write the equation for the equilibrium reaction that takes place.

.... **[1]**

(iii) Draw the skeletal formula of the ester present in the equilibrium mixture.

[1]

(iv) K_c is the equilibrium constant in terms of equilibrium concentrations.

Why can **expression 5.1** be used to calculate K_c for this equilibrium?

....

.... **[1]**

(v) Calculate the value of K_c for this reaction.

Show your working.

K_c = ... **[3]**

11. Sulfuric acid is an important chemical used to make detergents, fertilisers and dyes. It is manufactured in a multi-step process.

(a) In the first step of the manufacture of sulfuric acid, sulfur dioxide, SO_2, can be made from the combustion of hydrogen sulfide, H_2S, shown in **Reaction 1**.

$2H_2S(g) + 3O_2(g) \rightarrow 2SO_2(g) + 2H_2O(l)$ $\Delta_r H = -1125\,kJ\,mol^{-1}$ **Reaction 1**

(i) Explain why the enthalpy change for **Reaction 1** has a negative value.

Use ideas about enthalpy changes associated with bond breaking and bond making.

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....

.... **[1]**

(ii) Some standard entropy values are given below.

Substance	$H_2S(g)$	$O_2(g)$	$SO_2(g)$	$H_2O(l)$
S° / $J\,K^{-1}\,mol^{-1}$	206	205	248	70

Using calculations, explain whether **Reaction 1** is feasible at 20 °C.

Calculations

Explanation for feasible or non feasible ....

.... **[4]**

(iii) Calculate the standard enthalpy change of formation, $\Delta_f H^\ominus$, of hydrogen sulfide using the enthalpy change for **Reaction 1**, and the standard enthalpy changes of combustion below.

Substance	$\Delta_c H^\ominus$ / kJ mol^{-1}
S(s)	−296.8
H_2(g)	−285.8

$2H_2S(g) + 3O_2(g) \rightarrow 2SO_2(g) + 2H_2O(l)$ $\Delta_r H = -1125$ kJ mol^{-1} **Reaction 1**

$\Delta_f H^\ominus$ of hydrogen sulfide = ... kJ mol^{-1} **[3]**

(b) The second step in the manufacture of sulfuric acid is the conversion of SO_2 into sulfur trioxide, SO_3, using **Equilibrium 1**.

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

An industrial chemist carries out some research into **Equilibrium 1**.

- The chemist fills a $10.2\,dm^3$ container with $SO_2(g)$ at RTP, and then adds 12.0 g of $O_2(g)$.
- The chemist adds the vanadium(V) oxide catalyst, and heats the mixture. The mixture is allowed to reach equilibrium at a pressure of 2.50 atm and a temperature of 1000 K.
- A sample of the equilibrium mixture is analysed, and found to contain 0.350 mol of SO_3.

(i) Write an expression for K_p for **Equilibrium 1**.

Include the units.

units = ... **[2]**

(ii) Determine the value of K_p for **Equilibrium 1** at 1000 K.

Show all your working.

Give your answer to **3** significant figures.

K_p = ... **[5]**

(iii) The chemist repeats the experiment in **(b)** at a different temperature.

The chemist finds that the value of K_p is greater than the answer to **(b)(ii)**.

Explain whether the temperature in the second experiment is higher or lower than 1000 K.

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.... **[2]**

(iv) Explain the significance of the expression: $K_p \gg 1$.

....

.... **[1]**

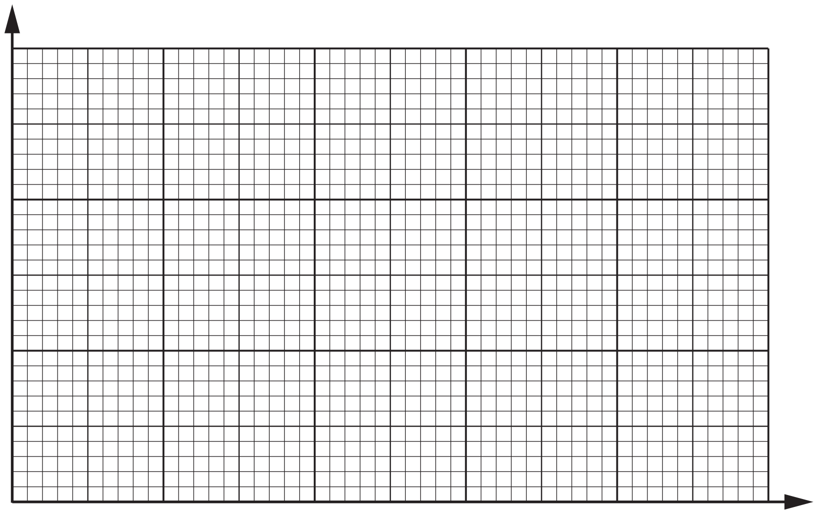
(c) Vanadium(V) oxide, $V_2O_5(s)$, is used as a catalyst in **equilibrium 1**.

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

(i) Explain how the presence of $V_2O_5(s)$ increases the rate of reaction.

Include a labelled sketch of the Boltzmann distribution, on the grid below.

Label the axes.



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.... **[4]**

(ii) Explain whether vanadium(V) oxide is acting as a homogeneous or heterogeneous catalyst.

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.... **[1]**

12. The reversible reaction of nitrogen and hydrogen to form ammonia is shown below.

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

In the equilibrium mixture, the partial pressure of N_2 is 18.75 MPa and the partial pressure of H_2 is 2.50 MPa.
The total pressure is 25 MPa.

What is the value of K_p, in MPa^{-2}?

A 1.2×10^{-4}

B 0.048

C 0.075

D 21

Your answer ☐ **[1]**

13. Methanol, CH_3OH, can be made industrially by the reaction of carbon monoxide with hydrogen, as shown in **equilibrium 1**.

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

(a) Predict the conditions of pressure and temperature that would give the maximum equilibrium yield of CH_3OH in **equilibrium 1**.

Explain your answer.

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.... **[3]**

(b) A catalyst is used in the production of methanol in **equilibrium 1**.

State **two** ways that the use of catalysts helps chemical companies to make their processes more sustainable and less harmful to the environment.

1 ....

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2 ....

....
[2]

(c) Standard entropy values are given below.

Substance	$CO(g)$	$H_2(g)$	$CH_3OH(g)$
$S^{\ominus}$ / $J\,K^{-1}\,mol^{-1}$	198	131	238

A chemist proposed producing methanol at 525 K using **equilibrium 1**.

Explain, with a calculation, whether the production of methanol is feasible at 525 K.

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.... **[5]**

(d) At 298 K, the free energy change, ΔG, for the production of methanol in **equilibrium 1** is $-2.48 \times 10^4\ J\,mol^{-1}$.

ΔG is linked to K_p by the relationship: $\Delta G = -RT\ \ln K_p$.

R = gas constant
T = temperature in K.

Calculate K_p for **equilibrium 1** at 298 K.

Give your answer to **3** significant figures.

K_p = ... units .... **[3]**

14. A student investigates the reaction between ethanoic acid, $CH_3COOH(l)$ and methanol, $CH_3OH(l)$, in the presence of an acid catalyst. The equation is shown below.

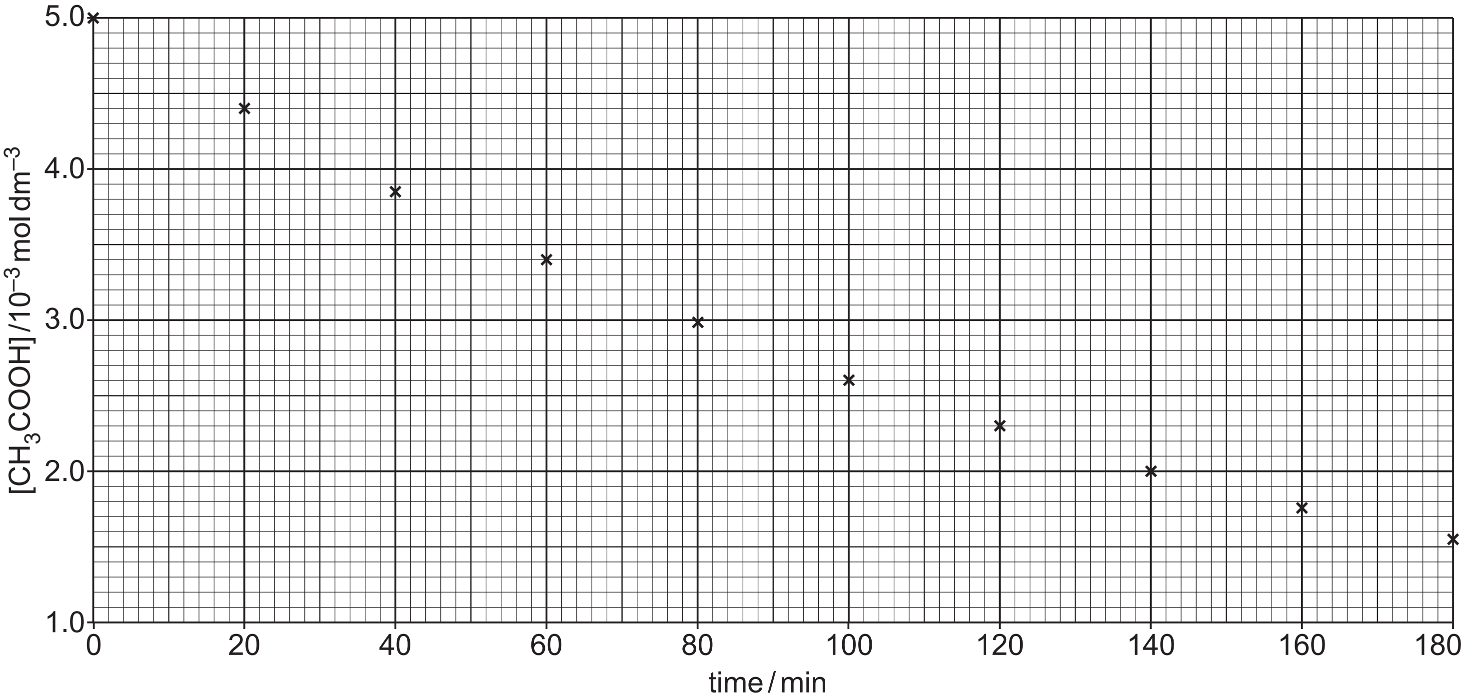
$$CH_3COOH(l) + CH_3OH(l) \rightleftharpoons CH_3COOCH_3(l) + H_2O(l)$$

(a) The student carries out an experiment to determine the order of reaction with respect to CH_3COOH.

The student uses a large excess of CH_3OH. The temperature is kept constant throughout the experiment.

The student takes a sample from the mixture every 20 minutes, and then determines the concentration of the ethanoic acid in each sample.

From the experimental results, the student plots the graph below.



(i) Explain why the student uses a large excess of methanol in this experiment.

....

.... **[1]**

(ii) Use the half-life of this reaction to show that the reaction is first order with respect to CH_3COOH.

Show your working on the graph and below.

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.... **[2]**

(iii) Determine the initial rate of reaction.

initial rate = ... $mol\,dm^{-3}\,min^{-1}$ **[2]**

(b) The student carries out a second experiment to determine the value of K_c for this reaction.

The student mixes 9.6 g of CH_3OH with 12.0 g of CH_3COOH and adds the acid catalyst.

When the mixture reaches equilibrium, 0.030 mol of CH_3COOH remains.

Calculate K_c for this equilibrium.

K_c = ... **[4]**