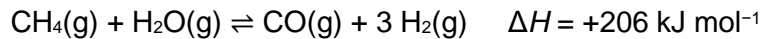**Q1.**

Hydrogen can be prepared on an industrial scale using the reversible reaction between methane and steam.

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

The reaction is done at a temperature of 800 °C and a low pressure of 300 kPa in the presence of a nickel catalyst.

Explain, in terms of equilibrium yield and cost, why these conditions are used.

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

(Total 6 marks)

Q2.

Which statement about the use of a catalyst in a reversible reaction is correct?

A The activation energy for the reverse reaction is increased.   ▭

B The equilibrium constant increases.   ▭

C The rate of the reverse reaction increases.   ▭

D The enthalpy change for the forward reaction decreases.   ▭

(Total 1 mark)

Q3.

This question is about the equilibrium

$$2\ SO_2(g) + O_2(g) \rightleftharpoons 2\ SO_3(g)$$
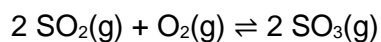
(a) State and explain the effect, if any, of a decrease in overall pressure on the equilibrium yield of SO_3

Effect _____

Explanation _____

_____

_____

(3)

(b) A 0.460 mol sample of SO_2 is mixed with a 0.250 mol sample of O_2 in a sealed container at a constant temperature.
When equilibrium is reached at a pressure of 215 kPa, the mixture contains 0.180 mol of SO_3

Calculate the partial pressure, in kPa, of SO_2 in this equilibrium mixture.

Partial pressure of SO_2 _____ kPa

(4)

(c)   A different mixture of SO_2 and O_2 reaches equilibrium at a different temperature.

The table below shows the partial pressures of the gases at equilibrium.

Gas	Partial pressure / kPa
SO_2	1.67×10^2
O_2	1.02×10^2
SO_3	1.85×10^2

Give an expression for the equilibrium constant (K_p) for this reaction.

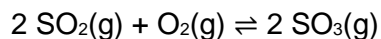Calculate the value of the equilibrium constant for this reaction and give its units.

K_p

K_p _____

Units _____

(3)

(d)   What is the effect on the value of K_p if the pressure of this equilibrium mixture is increased at a constant temperature?

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

Tick (✓) **one** box.

The value of K_p

increases.

stays the same.

decreases.

(1)
(Total 11 marks)

Q4.

This question is about equilibrium.

(a)   1 mol of a diester with molecular formula $C_7H_{12}O_4$ is added to 1 mol of water in the presence of a small amount of catalyst.
The mixture is left to reach equilibrium at a constant temperature.

$$C_7H_{12}O_4(l) + 2\ H_2O(l) \rightleftharpoons 2\ CH_3COOH(l) + HO(CH_2)_3OH(l)$$

At equilibrium, x mol of ethanoic acid are present in the mixture.

Complete **Table 1** by deducing the amounts, in terms of x, of the diester, water and diol present in the equilibrium mixture.

Table 1

Amount in the mixture / mol				
	Diester	**Water**	**Acid**	**Diol**
At the start	1	1	0	0
At equilibrium			x	

(3)

(b)   Deduce the structure of the diester in part (a)

(1)

(c)   A new equilibrium mixture of the substances from part (a) is prepared at a different temperature.

$$C_7H_{12}O_4(l) + 2 H_2O(l) \rightleftharpoons 2 CH_3COOH(l) + HO(CH_2)_3OH(l)$$

Table 2 shows the amount of each substance in this new equilibrium mixture.

Table 2

Amount in the mixture / mol				
	Diester	**Water**	**Acid**	**Diol**
At equilibrium	0.971	To be calculated	0.452	0.273

The value of the equilibrium constant, K_c is 0.161 at this temperature.

Calculate the amount of water, in mol, in this new equilibrium mixture. Show your working.
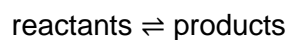
Amount of water _____ mol

(3)

(Total 7 marks)

Q5.

Which statement is **not** always correct for a reaction at equilibrium?

reactants ⇌ products

A The concentrations of the reactants and products are equal. ☐

B The equilibrium can be achieved starting from the reactants. ☐

C The equilibrium can be achieved starting from the products. ☐

D The rate of the forward reaction is equal to the rate of the reverse reaction. ☐

(Total 1 mark)

Q6.

Hydrogen gas can be made by reacting ethanol with steam in the presence of a catalyst.

$$C_2H_5OH(g) + H_2O(g) \rightleftharpoons 2\ CO(g) + 4\ H_2(g)$$
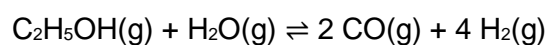
(a) Give an expression for K_c for this equilibrium.

State its units.

K_c

Units of K_c _____

(2)

(b)   The table shows the amount of each substance in an equilibrium mixture in a container of volume 750 cm^3

Substance	$C_2H_5OH(g)$	$H_2O(g)$	$CO(g)$	$H_2(g)$
Amount of substance / mol	0.0750	0.156	0.110	0.220

Calculate K_c

K_C _____

(3)

(c)   The pressure of the equilibrium mixture was increased by reducing the volume of the container at constant temperature.

Predict the effect of increasing the pressure on the equilibrium yield of hydrogen. Explain your answer.

Predict the effect of increasing the pressure on the value of K_c

Effect on equilibrium yield of hydrogen _____

_____

Explanation

_____

_____

_____

_____

_____

Effect on value of K_c _____

_____

(4)
(Total 9 marks)

Q7.

Methanol can be manufactured in a reversible reaction as shown.

$CO(g) + 2 H_2(g) \rightleftharpoons CH_3OH(g)$ $\Delta H^\ominus = -91$ kJ mol^{-1}
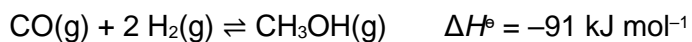
The graph below shows how the partial pressures change with time at a constant temperature.
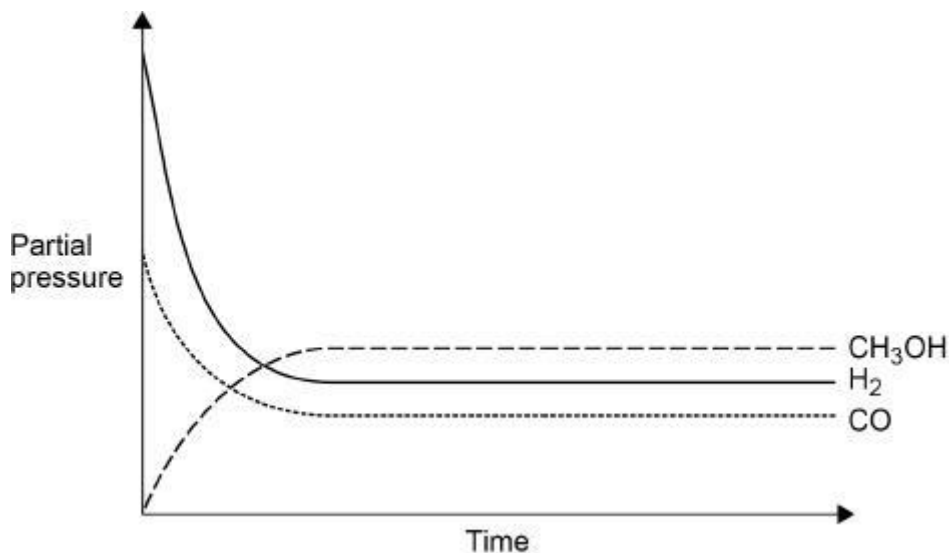
(a)   Draw a cross (x) on the appropriate axis of the graph when the mixture reaches equilibrium.

(1)

(b)   A 0.230 mol sample of carbon monoxide is mixed with hydrogen in a 1:2 mol ratio and allowed to reach equilibrium in a sealed flask at temperature *T*.
At equilibrium the mixture contains 0.120 mol of carbon monoxide.
The total pressure of this mixture is 1.04×10^4 kPa

Calculate the partial pressure, in kPa, of hydrogen in the equilibrium mixture.

Partial pressure of hydrogen _____ kPa

(4)

(c)   Give an expression for the equilibrium constant (K_p) for this reaction.

State the units.

K_p

Units _____

(2)

(d)   Some more carbon monoxide is added to the mixture in part (b). The new mixture is allowed to reach equilibrium at temperature T.

State the effect, if any, on the partial pressure of methanol and on the value of K_p

Effect on partial pressure of methanol _____

Effect on value of K_p _____

(2)

(e)   State the effect, if any, of the addition of a catalyst on the value of K_p for this equilibrium.
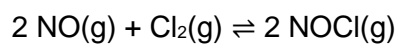Explain your answer.

Effect on value of K_p _____

Explanation

_____

_____

_____

(2)
(Total 11 marks)

Q8.

Nitrogen monoxide reacts with chlorine to form nitrosyl chloride (NOCl).

$$2\ NO(g) + Cl_2(g) \rightleftharpoons 2\ NOCl(g)$$

(a)   1.50 mol of NO are mixed with 1.00 mol of Cl_2 and the mixture is left to reach equilibrium at a given temperature.
The equilibrium mixture contains 0.350 mol of NOCl

Calculate the amount, in moles, of NO and of Cl_2 in the equilibrium mixture.

Amount of NO _____ mol

Amount of Cl_2 _____ mol

(2)

(b)   Give the expression for the equilibrium constant, K_c, for the reaction between nitrogen monoxide and chlorine to form nitrosyl chloride.

$K_c =$

(1)

(c)   A different equilibrium mixture is prepared in a flask of volume 800 cm^3 at a different temperature.
At equilibrium this mixture contains 0.850 mol of NO and 0.458 mol of Cl_2
For the reaction at this temperature $K_c = 1.32 \times 10^{-2}$ mol^{-1} dm^3

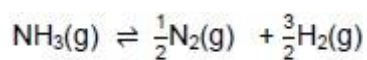Determine the amount, in moles, of NOCl in this equilibrium mixture.

Amount of NOCl _____ mol

(4)

(Total 7 marks)

Q9.

When one mole of ammonia is heated to a given temperature, 50 % of it dissociates and the following equilibrium is established.
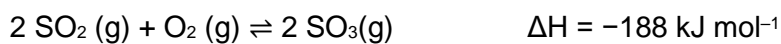
$$NH_3(g) \rightleftharpoons \tfrac{1}{2}N_2(g) + \tfrac{3}{2}H_2(g)$$

What is the total amount, in moles, of gas in this equilibrium mixture?

A   1.5   ⬭

B   2.0   ⬭

C   2.5   ⬭

D   3.0   ⬭

(Total 1 mark)

Q10.

Which change leads to a higher concentration of SO_3 in this equilibrium mixture?

$$2\ SO_2\ (g) + O_2\ (g) \rightleftharpoons 2\ SO_3(g) \qquad \Delta H = -188\ kJ\ mol^{-1}$$

A higher concentration of O_2 ⬭

B higher temperature ⬭

C lower pressure ⬭

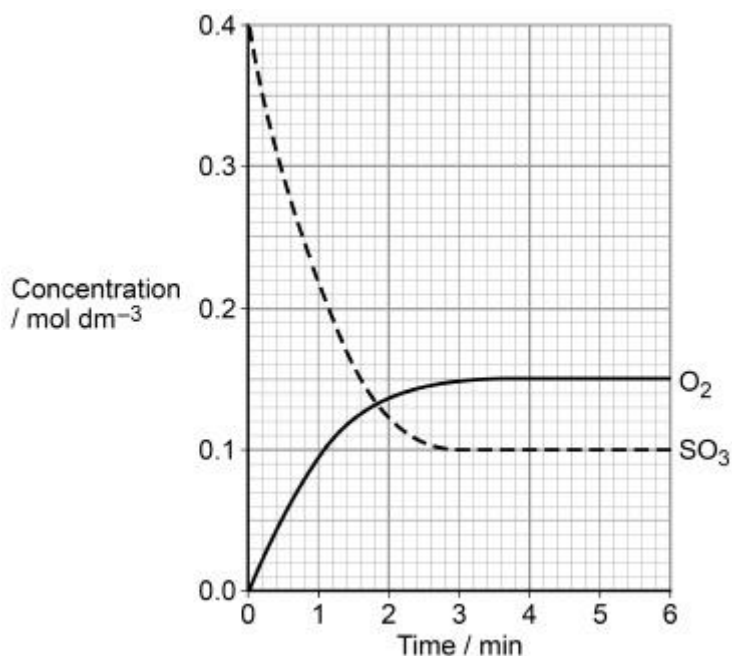**D** use of a catalyst ⬭

(Total 1 mark)

Q11.

This question is about equilibrium.

Sulfur trioxide decomposes to form sulfur dioxide and oxygen at temperature T_1 according to the equilibrium shown.

$$2SO_3(g) \rightleftharpoons 2SO_2(g) + O_2(g) \qquad \Delta H = +196\ kJ\ mol^{-1}$$
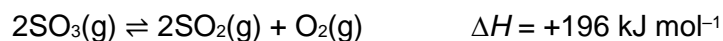
The graph shows the concentrations of sulfur trioxide and of oxygen over a period of 6 minutes at temperature T_1

(a)   State the time, to the nearest minute, when equilibrium is first established.
Explain your answer.

Time _____ minutes

Explanation

_____

_____

_____

_____

_____

(2)

(b) Sketch on the graph above how the concentration of sulfur dioxide changes over these 6 minutes at temperature T_1

(2)

(c) The temperature of the mixture was changed to T_2 and the mixture left to establish a new equilibrium.
In the new equilibrium mixture the concentration of sulfur trioxide was found to be 0.07 mol dm^{-3}

Deduce which of T_1 and T_2 is the higher temperature.
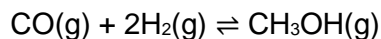Explain your deduction.

Higher temperature _____

Explanation

_____

_____

_____

_____

_____

(2)
(Total 6 marks)

Q12.

Methanol can be manufactured in a reversible reaction as shown by the equation.

$$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g)$$

(a)   State and explain the effect of using a catalyst on the yield of methanol in this equilibrium.

_____

_____

_____

_____

_____

_____

(2)

(b)   Give an expression for the equilibrium constant (K_c) for this reaction.

(1)

(c)   A mixture of carbon monoxide and hydrogen was allowed to reach equilibrium in a container of volume 250 cm^3 at temperature T.

At equilibrium, the mixture contained 0.340 mol of carbon monoxide, 0.190 mol of hydrogen and 0.0610 mol of methanol.

Calculate the value of the equilibrium constant (K_c) for this reaction at temperature T.

K_c _____ mol^{-2} dm^6

(3)

(d)   Methanol decomposes on heating in a reaction that is the reverse of that used in its manufacture.

$$CH_3OH(g) \rightleftharpoons CO(g) + 2H_2(g)$$

Use your answer from part (c) to determine the value of K_c for this equilibrium at temperature T.
State the units for this value of K_c

(If you were unable to complete the calculation in part (c), assume a value of $K_c = 0.825$ mol^{-2} dm^6. This is not the correct value.)
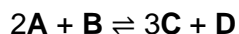
Value of K_c _____

Units of K_c _____

(2)
(Total 8 marks)

Q13.

Compounds **A** and **B** react together to form an equilibrium mixture containing compounds **C** and **D** according to the equation

$$2\mathbf{A} + \mathbf{B} \rightleftharpoons 3\mathbf{C} + \mathbf{D}$$

(a)   A beaker contained 40 cm³ of a 0.16 mol dm⁻³ aqueous solution of A.
9.5 × 10⁻³ mol of **B** and 2.8 × 10⁻² mol of **C** were added to the beaker and the mixture was left to reach equilibrium.
The equilibrium mixture formed contained 3.9 × 10⁻³ mol of **A**.

Calculate the amounts, in moles, of **B**, **C** and **D** in the equilibrium mixture.

Amount of **B** _____ mol

Amount of **C** _____ mol

Amount of **D** _____ mol

(5)

(b)   Give the expression for the equilibrium constant (K_c) for this equilibrium **and** its units.

K_c

Units _____

(2)

(c)   A different equilibrium mixture of these four compounds, at a different temperature, contained 0.21 mol of **B**, 1.05 mol of **C** and 0.076 mol of **D** in a total volume of
5.00 × 10^2 cm^3 of solution.
At this temperature the numerical value of K_c was 116

Calculate the concentration of **A**, in mol dm^{-3}, in this equilibrium mixture.
Give your answer to the appropriate number of significant figures.

Concentration of **A** _____ mol dm^{-3}

(3)

(d)   Justify the statement that adding more water to the equilibrium mixture in part (c) will lower the amount of **A** in the mixture.
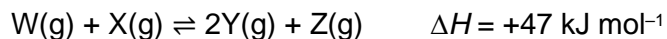
_____

_____

_____

_____

_____

_____

_____

(3)
(Total 13 marks)

Q14.

For this reaction at equilibrium, which combination of temperature and pressure would give the greatest equilibrium yield of products?

$$W(g) + X(g) \rightleftharpoons 2Y(g) + Z(g) \qquad \Delta H = +47 \text{ kJ mol}^{-1}$$

A   High pressure and high temperature

B   High pressure and low temperature

C   Low pressure and high temperature

D   Low pressure and low temperature

(Total 1 mark)

Q15.

When substances **P** and **Q** react together to form substance **R** an equilibrium is established according to the equation

$$P(g) + Q(g) \rightleftharpoons 2R(g)$$
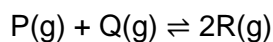
The equilibrium constant expression is $K_c = \dfrac{[R]^2}{[P][Q]}$

1.0 mol of **P** and 1.0 mol of **Q** were mixed in a container with volume 1.0 dm³

At equilibrium, x mol of **P** had reacted.

(a)   The amount, in moles, of each of P and Q at equilibrium is $(1 - x)$.

Deduce in terms of x the amount, in moles, of **R** in the equilibrium mixture.

_____

(1)

(b)   At 298 K the value of the equilibrium constant $K_c = 3.6$

Calculate a value for the equilibrium concentration, in mol dm⁻³, of **R**.

Equilibrium concentration of **R** _____ mol dm⁻³

(3)

(Total 4 marks)

Q16.

The forward reaction in this equilibrium is endothermic

$$COCl_2 (g) \rightleftharpoons CO(g) + Cl_2 (g)$$

Which statement is correct?

A	If the total pressure is increased at constant temperature, the proportion of $COCl_2$ in the equilibrium mixture will decrease	☐
B	Use of a catalyst will increase the proportion of $COCl_2$ in the equilibrium mixture at constant temperature and pressure	☐
C	Reducing the equilibrium concentration of CO will increase the value of the equilibrium constant	☐
D	Raising the temperature from 373 K to 473 K will increase the value of the equilibrium constant	☐

(Total 1 mark)

Q17.

There are several stages in the industrial production of methanol from methane.

(a) The first stage involves a gaseous equilibrium between the reactants (methane and steam), and some gaseous products. **Figures 1** and **2** show the percentage conversion of methane into the gaseous products under different conditions at equilibrium.
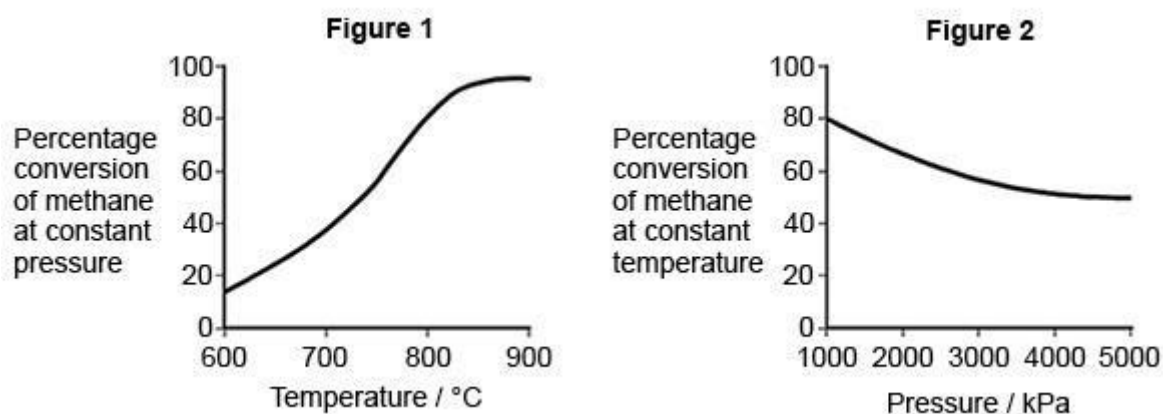
Deduce the optimum conditions for the industrial conversion of methane and steam into the gaseous products.
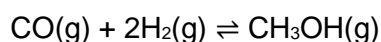
Explain your deductions.

_____

_____

_____

_____

_____

_____

_____

_____

(6)

(b)   The equation shows the final stage in the production of methanol.

$$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g)$$

20.1 mol of carbon monoxide and 24.2 mol of hydrogen were placed in a sealed container. An equilibrium was established at 600 K. The equilibrium mixture contained 2.16 mol of methanol.

Calculate the amount, in moles, of carbon monoxide and of hydrogen in the equilibrium mixture.

Amount of carbon monoxide = _____ mol

Amount of hydrogen = _____ mol

(2)

(c)   A different mixture of carbon monoxide and hydrogen was allowed to reach equilibrium at 600 K

At equilibrium, the mixture contained 2.76 mol of carbon monoxide, 4.51 mol of hydrogen and 0.360 mol of methanol. The total pressure was 630 kPa

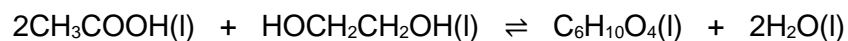Calculate a value for the equilibrium constant, K_p, for this reaction at 600 K and state its units.

Value of K_p _____ Units _____

(6)
(Total 14 marks)

Q18.
Ethanoic acid and ethane-1,2-diol react together to form the diester ($C_6H_{10}O_4$) as shown.

$$2CH_3COOH(l) \ + \ HOCH_2CH_2OH(l) \ \rightleftharpoons \ C_6H_{10}O_4(l) \ + \ 2H_2O(l)$$

(a)   Draw a structural formula for the diester $C_6H_{10}O_4$

(1)

(b)   A small amount of catalyst was added to a mixture of 0.470 mol of ethanoic acid and 0.205 mol of ethane-1,2-diol.

The mixture was left to reach equilibrium at a constant temperature.

Complete **Table 1**.

Table 1

Amount in the mixture / mol				
	CH_3COOH	$HOCH_2CH_2OH$	$C_6H_{10}O_4$	H_2O
At the start	0.470	0.205	0	0
At equilibrium	0.180			

Space for working

(3)

(c)   Write an expression for the equilibrium constant, K_c, for the reaction.

The total volume of the mixture does not need to be measured to allow a correct value for K_c to be calculated.

Justify this statement.

Expression

Justification

_____

_____

(2)

(d)   A different mixture of ethanoic acid, ethane-1,2-diol and water was prepared and left to reach equilibrium at a different temperature from the experiment in part (b)

The amounts present in the new equilibrium mixture are shown in **Table 2**.

Table 2

Amount in the mixture / mol				
	CH_3COOH	$HOCH_2CH_2OH$	$C_6H_{10}O_4$	H_2O
At new equilibrium	To be calculated	0.264	0.802	1.15

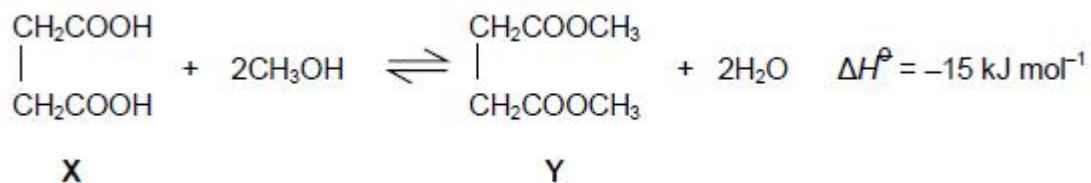The value of K_c was 6.45 at this different temperature.

Use this value and the data in **Table 2** to calculate the amount, in mol, of ethanoic acid present in the new equilibrium mixture.

Give your answer to the appropriate number of significant figures.

Amount of ethanoic acid _____ mol

(3)

(Total 9 marks)

Q19.

Acid **X** reacts with methanol to form an ester **Y**.

(a) Write an expression for the equilibrium constant, K_c, for this reaction. Use **X** and **Y** in your expression.

_____

_____

(1)

(b) A mixture of 0.32 mol of acid **X** and 0.84 mol of CH_3OH was allowed to reach equilibrium in the presence of a small amount of catalyst.
The equilibrium mixture formed contained 0.26 mol of ester **Y**.

Calculate the amounts, in moles, of **X**, CH_3OH and H_2O in this equilibrium mixture.

Amount of **X**

_____

Amount of CH_3OH

_____

Amount of H_2O

_____

(3)

(c) Calculate the value of K_c and state the units.

K_c _____ units _____

(3)

(d) Predict the effect on K_c if the reaction is carried out at a lower temperature.
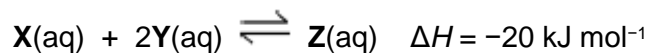
_____

(1)

(Total 8 marks)

Q20.

Colourless solutions of **X**(aq) and **Y**(aq) react to form an orange solution of **Z**(aq) according to the following equation.

$$X(aq) + 2Y(aq) \rightleftharpoons Z(aq) \quad \Delta H = -20 \text{ kJ mol}^{-1}$$

A student added a solution containing 0.50 mol of **X**(aq) to a solution containing 0.50 mol of **Y**(aq) and shook the mixture.
After 30 seconds, there was no further change in colour.
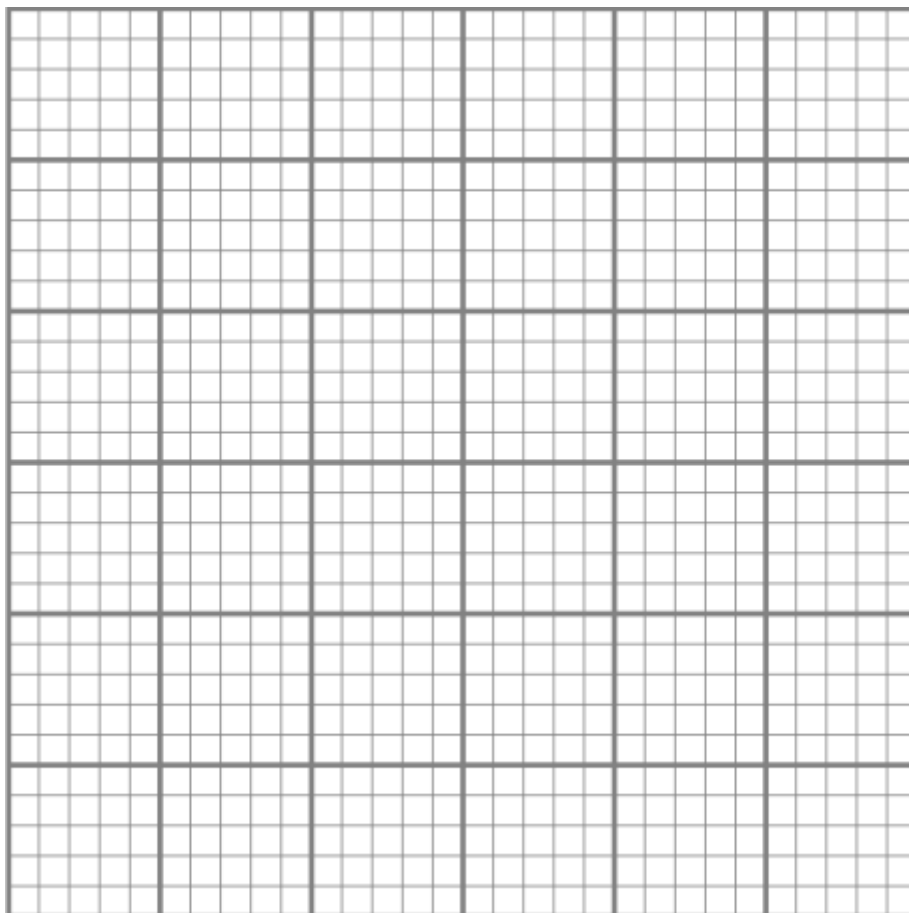The amount of **Z**(aq) at equilibrium was 0.20 mol.

(a)   Deduce the amounts of **X**(aq) and **Y**(aq) at equilibrium.

Amount of **X**(aq) = _____ mol   Amount of **Y**(aq) = _____ mol

(2)

(b)   On the grid below, draw a graph to show how the amount of **Z**(aq) changed from the time of initial mixing until 60 seconds had elapsed.

(3)

(c)   The student prepared another equilibrium mixture in which the equilibrium concentrations of **X** and **Z** were:
X(aq) = 0.40 mol dm^{-3} and Z(aq) = 0.35 mol dm^{-3}.

For this reaction, the equilibrium constant K_c = 2.9 mol^{-2} dm^6.
Calculate a value for the concentration of **Y** at equilibrium.
Give your answer to the appropriate number of significant figures.

[**Y**] = _____ mol dm^{-3}

(3)

(d)   The student added a few drops of **Y**(aq) to the equilibrium mixture of **X**(aq), **Y**(aq) and **Z**(aq) in part (c).

Suggest how the colour of the mixture changed. Give a reason for your answer.

Colour change_____

Reason

_____

_____

_____

_____

(3)

(e)   The student warmed the equilibrium mixture from part (c).

Predict the colour change, if any, when the equilibrium mixture was warmed.

_____

_____

(1)