Q1. Methanol can be manufactured by the reaction of carbon monoxide with hydrogen

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

In an experiment, 0.73 mol of carbon monoxide was heated with 1.25 mol of hydrogen. An equilibrium mixture was formed that contained 0.43 mol of methanol.

(a) Calculate the amount, in moles, of each reactant present at equilibrium.

Amount of carbon monoxide = ____ mol

Amount of hydrogen = ___________ mol

(2)

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

____

(1)

(c) In another experiment at a different temperature, the equilibrium mixture contained 0.452 mol of carbon monoxide, 0.106 mol of hydrogen and 0.273 mol of methanol in a flask of volume 9.40×10^3 cm^3.

Calculate the value of the equilibrium constant, K_c, at this temperature and state the units.

K_c = __________ Units = __________

(4)

(d) The total pressure of this equilibrium mixture in the flask was 482.9 kPa.

Calculate the temperature, in °C, of the equilibrium mixture.
(The ideal gas constant R = 8.31 J mol^{-1} K^{-1})

Temperature = ________________ °C

(4)

(Total 11 marks)

Q2. Ethanol and ethanoic acid react reversibly to form ethyl ethanoate and water according to the equation:

$$CH_3COOH + CH_3CH_2OH \rightleftharpoons CH_3COOCH_2CH_3 + H_2O$$

A mixture of 8.00×10^{-2} mol of ethanoic acid and 1.20×10^{-1} mol of ethanol is allowed to reach equilibrium at 20 °C.

- The equilibrium mixture is placed in a graduated flask and the volume made up to 250 cm^3 with distilled water.
- A 10.0 cm^3 sample of this equilibrium mixture is titrated with sodium hydroxide added from a burette.
- The ethanoic acid in this sample reacts with 3.20 cm^3 of 2.00×10^{-1} mol dm^{-3} sodium hydroxide solution.

(a) Calculate the value for K_c for the reaction of ethanoic acid and ethanol at 20 °C.
Give your answer to the appropriate number of significant figures.

K_c ____________________

(6)

(b) A student obtained the titration results given in **Table 1**.

Table 1

	Rough	1	2	3
Final burette reading / cm^3	4.60	8.65	12.85	16.80
Initial burette reading / cm^3	0.10	4.65	8.65	12.85
Titre / cm^3				

Complete **Table 1**.

(1)

(c) Calculate the mean titre and justify your choice of titres.

Calculation

Mean titre = ____________________ cm^3

Justification ____

____

(2)

(d) The pH ranges of three indicators are shown in **Table 2**.

Table 2

Indicator	**pH range**
Bromocresol green	3.8–5.4
Bromothymol blue	6.0–7.6
Thymol blue	8.0–9.6

Select from **Table 2** a suitable indicator for the titration of ethanoic acid with sodium hydroxide.

____

(1)

(e) The uncertainty in the mean titre for this experiment is ±0.15 cm^3.

Calculate the percentage uncertainty in this mean titre.

Percentage uncertainty = ______________________ %

(1)

(f) Suggest how, using the same mass of ethanoic acid, the experiment could be improved to reduce the percentage uncertainty.

____

____

____

____

____

(2)

(Total 13 marks)

Q3. 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)

Q4. Many chemical processes release waste products into the atmosphere. Scientists are developing new solid catalysts to convert more efficiently these emissions into useful products, such as fuels. One example is a catalyst to convert these emissions into methanol. The catalyst is thought to work by breaking a H–H bond.

An equation for this formation of methanol is given below.

$$CO_2(g) + 3H_2(g) \rightleftharpoons CH_3OH(g) + H_2O(g) \quad \Delta H = -49 \text{ kJ mol}^{-1}$$

Some mean bond enthalpies are shown in the following table.

Bond	C=O	C–H	C–O	O–H
Mean bond enthalpy / kJ mol^{-1}	743	412	360	463

(a) Use the enthalpy change for the reaction and data from the table to calculate a value for the H–H bond enthalpy.

H–H bond enthalpy = _______________ kJ mol^{-1}

(3)

(b) A data book value for the H–H bond enthalpy is 436 kJ mol^{-1}.

Suggest **one** reason why this value is different from your answer to part (a).

____

____

____

(1)

(c) Suggest **one** environmental advantage of manufacturing methanol fuel by this reaction.

____

____

____

(1)

(d) Use Le Chatelier's principle to justify why the reaction is carried out at a high pressure rather than at atmospheric pressure.

___

___

___

(3)

(e) Suggest why the catalyst used in this process may become less efficient if the carbon dioxide and hydrogen contain impurities.

___

___

___

(1)

(f) In a laboratory experiment to investigate the reaction shown in the equation below, 1.0 mol of carbon dioxide and 3.0 mol of hydrogen were sealed into a container. After the mixture had reached equilibrium, at a pressure of 500 kPa, the yield of methanol was 0.86 mol.

$$CO_2(g) + 3H_2(g) \rightleftharpoons CH_3OH(g) + H_2O(g)$$

Calculate a value for K_p
Give your answer to the appropriate number of significant figures.
Give units with your answer.

K_p = ________________ Units = ________________

(7)

(Total 16 marks)

Mark schemes

Q1.

(a) Mol CO = (0.73 − 0.43) = 0.30 (mol)

1

Mol H_2 = (1.25 − 2(0.43)) = 0.39 (mol)

1

(b) $K_c = \frac{[CH_3OH]}{[CO][H_2]^2}$

1

(c) Divides throughout by volume

1

$K_c = \frac{[0.273/9.40]}{[0.1.06/9.40]^2[0.452/9.40]}$

1

$K_c = \frac{0.029}{0.0000061146}$

$K_c = 4.75 \times 10^3$

1

Unit = $mol^{-2}\ dm^{+6}$

1

(d) pV = nRT

$T = \frac{pV}{nR}$

1

n = 0.452 + 0.106 + 0.273 = 0.831 (mol)

Calculation of moles and substitution of all values

1

$= \frac{482.9 \times 10^3 \times 9.40 \times 10^{-3}}{0.831 \times 8.31} = 657\ K$

Correct conversion of p and V

1

= 384 °C

Conversion to °C

1

[11]

Q2.

(a) Stage 1: Moles of acid at equilibrium

Moles of sodium hydroxide in each titration
$= (3.20 \times 2.00 \times 10^{-1}) / 1000 = 6.40 \times 10^{-4}$

Extended response

1

Sample = 10 cm^3 so moles of acid in 250 cm^3 of equilibrium mixture
= 25 × 6.40 × 10^{-4} = 1.60 × 10^{-2}

M2 can only be scored if = answer to M1 × 25

1

Stage 2: Moles of ester and water formed

Moles of acid reacted = 8.00 × 10^{-2} – 1.60 × 10^{-2} = 6.40 × 10^{-2}

= moles ester and water formed

M3 is 8.00 × 10^{-2} – M2

1

Stage 3: Moles of ethanol at equilibrium

Moles of ethanol remaining = 1.20 × 10^{-1} – 6.40 × 10^{-2} = 5.60 × 10^{-2}

M4 is 1.20 × 10^{-1} – M3

1

Stage 4: Calculation of equilibrium constant

K_c = [$CH_3COOCH_2CH_3$] [H_2O] / [CH_3COOH] [CH_3CH_2OH]

1

= (6.40 × 10^{-2})^2 / (1.60 × 10^{-2})(5.60 × 10^{-2})

= 4.5714 = 4.57

M6 is M3^2 / M2 × M4

Answer must be given to 3 significant figures

1

(b)

	Rough	1	2	3
Final burette reading / cm^3	4.60	8.65	12.85	16.80
Initial burette reading / cm^3	0.10	4.65	8.65	12.85
Titre / cm^3	4.50	4.00	4.20	3.95

1

(c) Mean = 4.00 + 3.95 / 2 = 3.98 (cm^3)

Allow 3.975 (cm^3)

1

Titres 1 and 3 are concordant

Allow titre 2 is not concordant

1

(d) Thymol blue

1

(e) Percentage uncertainty: 0.15 / 3.98 × 100 = 3.77%

Allow consequential marking on mean titre from 2.3

1

(f) Use a lower concentration of NaOH

1

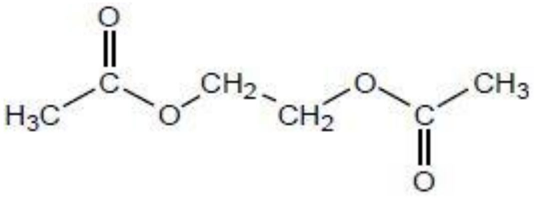
So that a larger titre is required (reduces percentage uncertainty in titre)

1

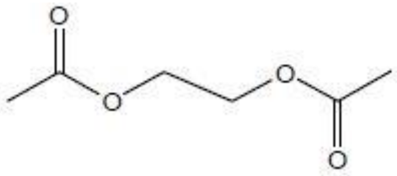
[13]

Q3.

(a)



Allow $CH_3COOCH_2CH_2OOCCH_3$
OR $CH_3COOCH_2CH_2OCOCH_3$
OR



1

(b) Mol $HOCH_2CH_2OH$ = 6.00×10^{-2} OR 0.06(00)

1

Mol $C_6H_{10}O_4$ = 1.45×10^{-1} OR 0.145

1

Mol H_2O = 2.90×10^{-1} OR 0.29(0)

1

(c)

$$(K_c =)\frac{[\text{ester}] \times [H_2O]^2}{[CH_3COOH]^2 \times [HOCH_2CH_2OH]}$$

Allow words for acid and alcohol

1

The volume cancels out (Penalise a contradictory justification from expression if the volumes do not cancel out)
OR
there are <u>equal no of moles on each side of the equation</u>
<u>OR</u>
there are <u>equal no of molecules on each side of the equation</u>

1

(d)

$$(\text{Mol } CH_3COOH / V)^2 = \frac{(8.02 \times 10^{-1} / V)(1.15 / V)^2}{6.45 \times (2.64 \times 10^{-1} / V)}$$

$$\text{Mol } CH_3COOH = \sqrt{\frac{(8.02 \times 10^{-1}) \times (1.15)^2}{6.45 \times (2.64 \times 10^{-1})}} = \sqrt{0.623}$$ **M1**

Mol CH_3COOH = 0.789 <u>(must be 3 sfs)</u> Allow 0.788 – 0.790 **M2**

M3

0.789 scores 3

Allow without V : $(nCH_3COOH)^2 = \frac{(8.02 \times 10^{-1})(1.15)^2}{6.45 \times (2.64 \times 10^{-1})}$

If $(nCH_3COOH)^2$ =0.623 then award M1 and M2

If K_c is correct in (c) but incorrect rearrangement, then CE=0 except if upside down rearrangement then M3 only awarded for 1.27

If K_c is incorrect in (c) then only M1 can be awarded for correct rearrangement.

[9]

Q4.

(a) Bonds broken = 2(C=O) + 3(H–H) = 2 × 743 + 3 × H–H

Bonds formed = 3(C–H) +(C–O) + 3(O–H) = 3 × 412 + 360 + 3 × 463

Both required

1

–49 = [2 × 743 + 3 × (H–H)] – [3 × 412 + 360 + 3 × 463]

3(H–H) = –49 – 2 × 743 + [3 × 412 + 360 + 3 × 463] = 1450

Both required

1

H–H = 483 (kJ mol^{-1})

Allow 483.3(3)

1

(b) Mean bond enthalpies are not the same as the actual bond enthalpies in CO_2 (and / or methanol and / or water)

1

(c) The carbon dioxide (produced on burning methanol) is used up in this reaction

1

(d) 4 mol of gas form 2 mol

1

At high pressure the position of equilibrium moves to the right to lower the pressure / oppose the high pressure

1

This increases the yield of methanol

1

(e) Impurities (or sulfur compounds) block the active sites

Allow catalyst poisoned

1

(f) Stage 1: moles of components in the equilibrium mixture

Extended response question

$CO_2(g)$ + $3H_2(g)$ ⇌ $CH_3OH(g)$ + $H_2O(g)$

Initial moles	1.0	3.0	0	0
Eqm moles	(1–0.86) = 0.14	(3–3×0.86) = 0.42	0.86	0.86

1

Stage 2: Partial pressure calculations

Total moles of gas = 2.28

Partial pressures = mol fraction × p_{total}

1

p_{CO2} = mol fraction × p_{total} = 0.14 × 500 / 2.28 = 30.7 kPa

p_{H2} = mol fraction × p_{total} = 0.42 × 500 / 2.28 = 92.1 kPa

M3 is for partial pressures of both reactants

Alternative M3 =

pp_{CO2} = 0.0614 × 500

pp_{H2} = 0.1842 × 500

1

p_{CH3OH} = mol fraction × p_{total} = 0.86 × 500 / 2.28 = 188.6 kPa

p_{H2O} = mol fraction × p_{total} = 0.86 × 500 / 2.28 = 188.6 kPa

M4 is for partial pressures of both products

Alternative M4 =

pp_{CH3OH} = 0.3772 × 500

pp_{H2O} = 0.3772 × 500

1

Stage 3: Equilibrium constant calculation

$K_p = p_{CH3OH} \times p_{H2O} / p_{CO2} \times (p_{H2})^3$

1

Hence K_p = 188.6 × 188.6 / 30.7 × $(92.1)^3$ = 1.483 × 10^{-3} = 1.5 × 10^{-3}

Answer must be to 2 significant figures

1

Units = kPa^{-2}

1

[16]