How Far

1. 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.

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

The student carries out an 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]**

2. Methanol, CH3OH, 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**

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]**

3(a). The equilibrium constant K_p and temperature T (in K) are linked by the mathematical relationship shown in **equation 5.1** (R = Gas constant in J mol^{-1} K^{-1} and ΔH is enthalpy change in J mol^{-1}).

$$\ln K_p = -\frac{\Delta H}{R} \times \frac{1}{T} + \frac{\Delta S}{R}$$ **Equation 5.1**

The table shows the values of K_p at different temperatures for an equilibrium.

Complete the table by adding the missing values of $\frac{1}{T}$ and $\ln K_p$.

Temperature, *T* / K	400	500	600	700	800
Kp	3.00×10^{58}	5.86×10^{45}	1.83×10^{37}	1.46×10^{31}	1.14×10^{26}
$\frac{1}{T}$ / K^{-1}	2.50×10^{-3}	....	....	....	....
$\ln K_p$	135	....	....	....	....

[2]

(b). State and explain how increasing the temperature affects the position of this equilibrium and whether the forward reaction is exothermic or endothermic.

--- **[1]**

(c). Plot a graph of $\ln K_p$ against $\frac{1}{T}$ using the axes provided on the opposite page.

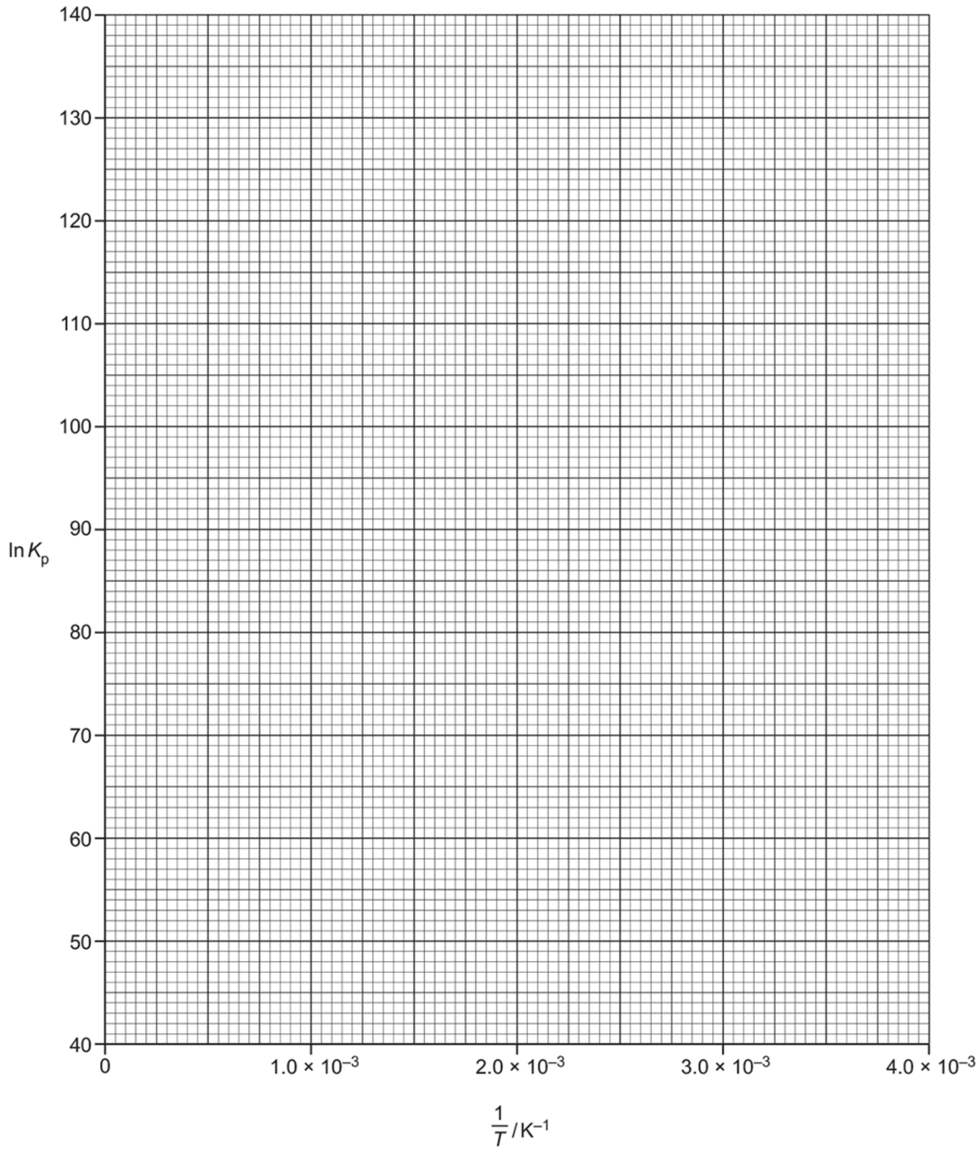
Use your graph and **equation 5.1** to determine ΔH, in kJ mol^{-1}, for this equilibrium.

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

ΔH = ... kJ mol^{-1} **[4]**

(d). Explain how ΔS could be calculated from a graph of $\ln K_p$ against $\frac{1}{T}$.

--- **[2]**



4. What is the partial pressure of O_2 (in Pa) in a gas mixture containing 21% O_2 by volume and with a total pressure of 1.0×10^5 Pa?

partial pressure of O_2 = ... Pa **[1]**

5. Succinic acid $(CH_2COOH)_2$ is esterified by ethanol, C_2H_5OH, in the presence of an acid catalyst to form an equilibrium mixture.
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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]**

6(a). 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**

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	$Kp = 2.03 \times 10^{-1}$

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.

-- **[3]**

7. 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 3.045×10^4 dm^3 mol^{-1}.

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

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 -------------------- mo

8. 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**.

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 = --------------------

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

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

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

Compound	Δ_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]**

9. 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.

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

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

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]**

10(a). Iodine, I_2, is a grey-black solid that is not very soluble in water.
Equilibrium 1 is set up with the equilibrium position well to the left.

$I_2(s) \rightleftharpoons I_2(aq)$ **Equilibrium 1**

Solid iodine is much more soluble in an aqueous solution of potassium iodide, KI(aq), than in water.
Equilibrium 2 is set up.

$I_2(aq) + I^-(aq) \rightleftharpoons I_3^-(aq)$ **Equilibrium 2**

A student dissolves I_2 in KI(aq).
The resulting 200 cm^3 equilibrium mixture contains:

4.00×10^{-5} mol $I_2(aq)$
9.404×10^{-2} mol $I^-(aq)$
1.96×10^{-3} mol $I_3^-(aq)$.

Calculate K_c for **equilibrium 2**.

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

K_c = ... units

....**[4]**

(b). The student adds an excess of aqueous silver nitrate, $AgNO_3(aq)$, to the equilibrium mixture.

Predict what would be observed.

Explain the observations in terms of both **equilibrium 1** and **equilibrium 2** and any species formed.

--- **[4]**

1 1. A chemist investigated methods to improve the synthesis of sulfur trioxide from sulfur dioxide and oxygen.

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

The chemist:

- mixed together 1.00 mol SO_2 and 0.500 mol O_2 with a catalyst at room temperature
- compressed the gas mixture to a volume of 250 cm^3
- allowed the mixture to reach equilibrium at constant temperature and without changing the total gas volume.

At equilibrium, 82.0% of the SO_2 had been converted into SO_3.

i. Determine the concentrations of SO_2, O_2 and SO_3 present at equilibrium and calculate K_c for this reaction.

K_c = ... units .... **[6]**

ii. Explain what would happen to the pressure as the system was allowed to reach equilibrium.

--- **[1]**

iii. The value of K_c for this equilibrium decreases with increasing temperature.

Predict the sign of the enthalpy change for the forward reaction. State the effect on the equilibrium yield of SO_3 of increasing the temperature at constant pressure.

Δ*H*:

....

Effect on SO_3 yield:

.... **[1]**

iv. The chemist repeated the experiment at the same temperature with 1.00 mol SO_2 and an excess of O_2.
The gas mixture was still compressed to a volume of 250 cm^3.

State and explain, in terms of K_c, how the equilibrium yield of SO_3 would be different from the yield in the first experiment.

--- **[3]**

12(a). Ethyne gas, C_2H_2, is manufactured in large quantities for a variety of uses.

Much of this ethyne is manufactured from methane as shown in the equation below.

$$2CH_4(g) \rightleftharpoons C_2H_2(g) + 3H_2(g) \qquad \Delta H = +377\ kJ\ mol^{-1}$$

Write an expression for K_c for this equilibrium.

[1]

(b). A research chemist investigates how to improve the synthesis of ethyne from methane at a high temperature.

- The chemist adds CH_4 to a 4.00 dm^3 container.
- The chemist heats the container and allows equilibrium to be reached at constant temperature. The total gas volume does not change.
- The equilibrium mixture contains 9.36×10^{-2} mol CH_4 and 0.168 mol C_2H_2.

i. Calculate the amount, in mol, of H_2 in the equilibrium mixture.

amount of H_2 = ... mol **[1]**

ii. Calculate the equilibrium constant, K_c, at this temperature, including units.

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

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

iii. Calculate the amount, in mol, of CH_4 that the chemist originally added to the container.

amount of CH_4 = ... mol **[1]**

(c). The chemist repeats the experiment three times.
In each experiment the chemist makes **one** change but uses the **same** initial amount of CH_4.

Complete the table to show the predicted effect of each change compared with the original experiment.

Only use the words **greater, smaller** or **same**.

Change	K_c	**Equilibrium amount of C_2H_2(g) / mol**	**Initial rate**
The container is heated at constant pressure			
A smaller container is used			
A catalyst is added to CH_4 at the start			

[3]

13(a). A research chemist investigates how the value of K_c changes with temperature.

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

- The chemist mixes 0.800 mol of $N_2(g)$ and 2.400 mol of $H_2(g)$ and leaves the mixture to reach equilibrium at 300 °C.
- The total volume of the equilibrium mixture is 5.00 dm^3.
- At equilibrium, 0.360 mol of $NH_3(g)$ has formed.

Calculate the value of K_c under these conditions.

Show all your working.

K_c = ... units .... **[6]**

(b). Ammonia, NH_3, is manufactured by the chemical industry from nitrogen and hydrogen gases.

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

- An iron catalyst is used which provides several benefits for sustainability.
- The chemical industry uses operational conditions that are different from the conditions predicted to give a maximum equilibrium yield.

The chemist adds more nitrogen to the equilibrium mixture in **(b).**

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

The temperature is kept at 300 K and the volume at 5.00 dm^3.

The chemist predicts that the addition of nitrogen will increase the proportion of $H_2(g)$ that reacts.

i. Explain whether the chemist's prediction is correct.

---**[3]**

ii. Suggest why the chemist is more concerned with increasing the proportion of H_2 that reacts rather than the proportion of N_2 that reacts.

---**[1]**

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

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

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

---**[2]**

(b). 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]**

END OF QUESTION PAPER