1. The following reaction is used in industry to make sulfur trioxide gas, SO_3.

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

This preparation is carried out in the presence of a catalyst.

* Explain the conditions of temperature and pressure that could be used to obtain the maximum equilibrium yield of sulfur trioxide.
Discuss the importance of a compromise between equilibrium yield and reaction rate when deciding the operational conditions for this process.

[6]

2(a). Sulfur trioxide, SO_3, is used for the industrial manufacture of sulfuric acid.

SO_3 is produced by reacting sulfur dioxide, SO_2, and oxygen, O_2, as shown in **equilibrium 25.1** below.

Equilibrium 25.1 $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$ $\Delta H = -197 \text{ kJ mol}^{-1}$

Le Chatelier' s principle can be used to predict how different conditions affect the equilibrium position.

- Using le Chatelier' s principle, show that a low temperature and a high pressure should be used to obtain a maximum **equilibrium** yield of SO_3.
- Explain why the actual conditions used in industry may be different from the conditions needed for a maximum equilibrium yield.

[5]

(b). Under certain conditions, K_c for **equilibrium 25.1** is 0.160 $dm^3\ mol^{-1}$.

The equilibrium mixture under these conditions has the following concentrations of SO_2 and O_2.

Species	Equilibrium concentration / mol dm^{-3}
SO_2	2.00
O_2	1.20

- Using the value of K_c, explain whether the equilibrium position will be towards the right or towards the left under these conditions.
- Calculate the concentration of SO_3 in the equilibrium mixture.

[4]

3. This question looks at equilibrium reactions used by industry for preparing important chemicals.

Methanol can be manufactured by reacting carbon monoxide with hydrogen.

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

An equilibrium mixture contains 3.10×10^{-3} mol dm^{-3} CO, 2.40×10^{-3} mol dm^{-3} H_2 and an unknown concentration of CH_3OH.

i. Write an expression for the equilibrium constant, K_c.

[1]

ii. The value of K_c for this equilibrium is 14.6 dm^6 mol^{-2}.

Determine the equilibrium concentration methanol, $CH_3OH(g)$.

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

equilibrium concentration of $CH_3OH(g)$ = ... dm^6 mol^{-2} **[2]**

4. The equilibrium system below is set up.

$$CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g) \qquad \Delta H = +14 \text{ kJ mol}^{-1}$$

The equilibrium system is compressed at constant temperature.

What is the effect on the value of K_c and the amount, in moles, of CH_3OH?

	K_c	Amount in moles of CH_3OH
A	increases	increases
B	decreases	decreases
C	no change	no change
D	no change	increases

Your answer ☐

[1]

5. A catalyst is added to a system in equilibrium.

What is the effect on the rates of the forward and reverse reactions?

A There is no effect on the rate in either direction.

B Both rates increase by the same factor.

C The rate in the forward direction increases by a greater factor than the reverse direction.

D The rate in the reverse direction increases by a greater factor than the forward direction.

Your answer ☐ **[1]**

6. 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]**

7. 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]**

8. Methane is an important raw material for manufacturing chemicals. Hydrogen can be manufactured from methane and steam as shown below in **equation 17.1**.

$$CH_4(g) + H_2O(g) \rightleftharpoons 3H_2(g) + CO(g) \qquad \Delta H = +210 \text{ kJ mol}^{-1} \qquad \textbf{Equation 17.1}$$

The rate of reaction is increased by using a catalyst.

A chemist investigates the equilibrium shown in **equation 17.1** as outlined below.

$$CH_4(g) + H_2O(g) \rightleftharpoons 3H_2(g) + CO(g) \qquad \Delta H = +210 \text{ kJ mol}^{-1} \qquad \textbf{Equation 17.1}$$

- A chemist mixes together 1.000 mol CH_4 and 1.400 mol of H_2O in a sealed container.
- The mixture is heated to constant temperature and allowed to reach equilibrium. The equilibrium mixture contains 0.200 mol of CH_4 and the total pressure is 30.0 atm.

Use this information to calculate K_p for the equilibrium in **equation 17.1**.

Show all your working.

[7]

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

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

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]**

10. 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]

11. A student mixes hydrogen and iodine at room temperature and pressure and allows the mixture to reach dynamic equilibrium.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \qquad \Delta H = -9 \text{ kJ mol}^{-1}$$ **equilibrium 3.1**

i. A closed system is required for dynamic equilibrium to be established.

State **one** other feature of this dynamic equilibrium.

[1]

ii. The student heats the equilibrium mixture keeping the volume constant.

Predict how the composition of the equilibrium mixture changes on heating.

Explain your answer.

[2]

iii. Predict and explain what effect, if any, an increase in the pressure would have on the position of the equilibrium.

effect
.....

explanation
.....

[1]

12. Methanol, CH_3OH, is an important feedstock for the chemical industry.

In the manufacture of methanol, carbon dioxide and hydrogen are reacted together in the reversible reaction shown below.

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

High pressures and low temperatures would give a maximum equilibrium yield of methanol.

i. Explain this statement in terms of le Chatelier's principle.

[3]

ii. Explain why the actual conditions used by the chemical industry might be different.

[2]

13. A chemist investigates the equilibrium that produces methanol:

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

The chemist mixes CO(g) with $H_2(g)$ and leaves the mixture to react until equilibrium is reached.
The equilibrium mixture is analysed and found to contain the following concentrations.

Substance	**Concentration/mol dm^{-3}**
CO (g)	0.310
$H_2(g)$	0.240
$CH_3OH(g)$	0.260

Calculate the numerical value of K_c for this equilibrium.

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

K_c = ... $dm^6\ mol^{-2}$ **[2]**

END OF QUESTION paper