CHAPTER 6 EQUILIBRIA

1 Methanol can be synthesised from carbon monoxide by the reversible reaction shown below.

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

The process operates at a pressure of 5 MPa and a temperature of 700 K in the presence of a copper-containing catalyst. This reaction can reach dynamic equilibrium.

(a) By reference to rates and concentrations, explain the meaning of the term *dynamic equilibrium*.

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(2 marks)

(b) Explain why a high yield of methanol is favoured by high pressure.

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(2 marks)

(c) Suggest **two** reasons why the operation of this process at a pressure much higher than 5 MPa would be very expensive.

Reason 1 .....

Reason 2 .....

(2 marks)

(d) State the effect of an increase in temperature on the equilibrium yield of methanol and explain your answer.

Effect .....

Explanation .....

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(3 marks)

(e) If a catalyst were not used in this process, the operating temperature would have to be greater than 700 K. Suggest why an increased temperature would be required.

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(1 mark)

2 At high temperatures, nitrogen is oxidised by oxygen to form nitrogen monoxide in a reversible reaction as shown in the equation below.

$$N_2(g) + O_2(g) \rightleftharpoons 2NO(g) \qquad \Delta H^{\ominus} = +180\,kJ\,mol^{-1}$$

(a) In terms of electrons, give the meaning of the term *oxidation*.

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(1 mark)

(b) State and explain the effect of an increase in pressure, and the effect of an increase in temperature, on the yield of nitrogen monoxide in the above equilibrium.

Effect of an increase in pressure on the yield .....

Explanation .....

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Effect of an increase in temperature on the yield .....

Explanation .....

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(6 marks)

3 Hydrogen is produced on an industrial scale from methane as shown by the equation below.

$$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \quad \Delta H^{\ominus} = +205\,kJ\,mol^{-1}$$

(a) State Le Chatelier's principle.

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(1 mark)

(b) The following changes are made to this reaction at equilibrium. In each case, predict what would happen to the yield of hydrogen from a given amount of methane. Use Le Chatelier's principle to explain your answer.

(i) The overall pressure is increased.

Effect on yield of hydrogen .....

Explanation .....

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(ii) The concentration of steam in the reaction mixture is increased.

Effect on yield of hydrogen .....

Explanation .....

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(6 marks)

(c) At equilibrium, a high yield of hydrogen is favoured by high temperature. In a typical industrial process, the operating temperature is usually less than 1200 K. Suggest two reasons why temperatures higher than this are not used.

Reason 1 .....

Reason 2 .....

(2 marks)

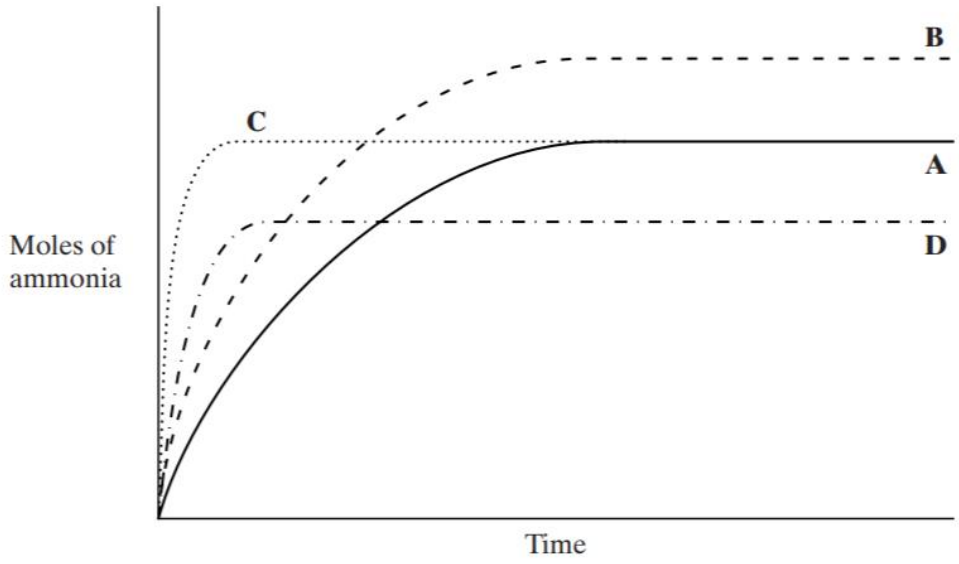
4 The equation for the formation of ammonia is shown below.

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

Experiment **A** was carried out starting with 1 mol of nitrogen and 3 mol of hydrogen at a constant temperature and a pressure of 20 MPa.

Curve **A** shows how the number of moles of ammonia present changed with time.

Curves **B**, **C** and **D** refer to similar experiments, starting with 1 mol of nitrogen and 3 mol of hydrogen. In each experiment different conditions were used.



(a) On curve **A**, mark the point that represents the time at which equilibrium is first reached. Label this point **X**.

(1 mark)

(b) State Le Chatelier's principle.

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(1 mark)

(c) Use Le Chatelier's principle to identify which one of the curves **B**, **C** or **D** represents an experiment carried out at the same temperature as experiment **A** but at a higher pressure. Explain why this curve is different from curve **A**.

Curve .....

Explanation .....

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(4 marks)

(d) Identify which one of the curves **B**, **C** or **D** represents an experiment in which the conditions are the same as in experiment **A** except that a catalyst is added to the reaction mixture. Explain your choice of curve.

Curve .....

Explanation .....

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(3 marks)

5 The reaction of methane with steam produces hydrogen for use in many industrial processes. Under certain conditions the following reaction occurs.

$$CH_4(g) + 2H_2O(g) \rightleftharpoons CO_2(g) + 4H_2(g) \qquad \Delta H^{\ominus} = +165\ kJ\,mol^{-1}$$

(a) Initially, 1.0 mol of methane and 2.0 mol of steam were placed in a flask and heated with a catalyst until equilibrium was established. The equilibrium mixture contained 0.25 mol of carbon dioxide.

(i) Calculate the amounts, in moles, of methane, steam and hydrogen in the equilibrium mixture.

Moles of methane .....

Moles of steam .....

Moles of hydrogen .....

(3 marks)

(ii) The volume of the flask was 5.0 dm^3. Calculate the concentration, in mol dm^{-3}, of methane in the equilibrium mixture.

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(1 mark)

(b) The table below shows the equilibrium concentration of each gas in a different equilibrium mixture in the same flask and at temperature *T*.

gas	$CH_4(g)$	$H_2O(g)$	$CO_2(g)$	$H_2(g)$
concentration / mol dm^{-3}	0.10	0.48	0.15	0.25

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

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(1 mark)

(ii) Calculate a value for K_c at temperature *T* and give its units.

Calculation .....

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Units of K_c .....

(3 marks)

(c) The mixture in part (b) was placed in a flask of volume greater than 5.0 dm^3 and allowed to reach equilibrium at temperature *T*.
State and explain the effect on the amount of hydrogen.

Effect on amount of hydrogen .....

Explanation .....

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(3 marks)

(d) Explain why the amount of hydrogen decreases when the mixture in part **(b)** reaches equilibrium at a lower temperature.

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(2 marks)