Past-paper walk-through

Properties of the Equilibrium Constant ▪ 7.6

eXercise

Questions in this set

- 2026 Q3
- 2018 Q2
- 2014 Q4

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\quad K_a = 5.6 \times 10^{-4}$ at 298 K

(a) Identify a conjugate acid-base pair in the equation. Be sure to clearly label which is the acid and which is the base.

Question 3

Table 1

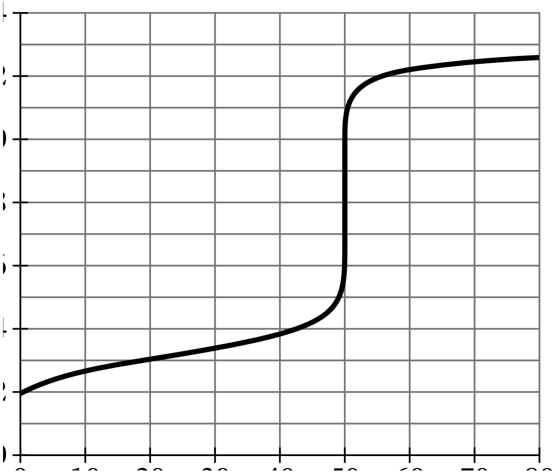
Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftarrows NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 = \ ?$

Question 3

Table 2

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

Question 3



Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(b)(i) A solution of $HNO_2(aq)$ with an initial concentration of 0.125 M has a pH of 2.09.
Calculate the value of $[H_3O^+]$ in the solution. Show the work that leads to your answer.
(b)(ii) **Calculate** $[HNO_2]$ at equilibrium. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(c)(i) In an experiment, the solution of 0.125 M $HNO_2(aq)$ is heated to 333 K. The new equilibrium concentrations are determined to be $[HNO_2] = 0.114$ M, $[NO_2^-] = 0.0109$ M, and $[H_3O^+] = 0.0109$ M.
Calculate the value of K_a for HNO_2 at 333 K. Show the work that leads to your answer.

(c)(ii) Is the reaction represented by Equation 1 endothermic or exothermic? **Justify** your answer by comparing K_a values at 298 K and 333 K.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(d) The following information applies to parts D, E, and F.
In a second experiment, a student is given a bottle containing HNO_2 with an unknown molarity. To determine the concentration of the $HNO_2(aq)$ in the bottle, the student titrates 35.0 mL of the $HNO_2(aq)$ with 0.16 M NaOH(aq) at 298 K, which reacts according to Equation 2.

$$\text{Equation 2: } HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$$

Question 3

The results of the titration are summarized in Figure 1.
[Figure 1: Titration curve, pH vs. Volume of 0.16 M NaOH Added (mL); y-axis pH 0 to 14 in increments of 2, x-axis 0 to 80 mL in increments of 10; curve starts near $(0, 2)$, rises gradually to about $(40, 4)$, then rises steeply (equivalence point) between about 45-55 mL up to about pH 12, then levels off gradually to approximately $(80, 12.7)$.]
Using Figure 1, **identify** the pH at the equivalence point.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(e) Using Figure 1, **calculate** the molarity $HNO_2(aq)$ of in the bottle. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(f) **Draw** an X on Figure 1 to represent a point in the titration where $[HNO_2] > [NO_2^-]$ in the reaction mixture.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(g) Equilibrium constants at 298 K are shown in Table 1 for the acid ionization reaction represented by Equation 1, K_a; the autoionization of water, K_w; and the neutralization reaction represented by Equation 2, K_2.

Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 = ?$

Question 3

Calculate the value of K_2 for Equation 2 at 298 K. Show the work that leads to your answer.

Question 3

2026 ▪ Q3

Nitrous acid, HNO_2, is a weak acid that ionizes according to Equation 1.

$$\text{Equation 1: } HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq) \qquad K_a = 5.6 \times 10^{-4} \text{ at } 298 \text{ K}$$

(h) The student decides to repeat the experiment, this time using an indicator, and has access to the indicators in Table 2.

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

Question 3

The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $HNO_2(aq)$ solution and titrating the solution with 0.16 *M* NaOH(*aq*) until a color change from red to yellow occurs.

The student claims that methyl orange was the best choice for the indicator. Do you agree or disagree? **Justify** your answer.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(a) The particle-level representation of the equimolar mixture of $NO(g)$ and $NO_2(g)$ in the flask at the completion of the reaction between $NO(g)$ and $O_2(g)$ is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of $NO(g)$ and $O_2(g)$ that would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.

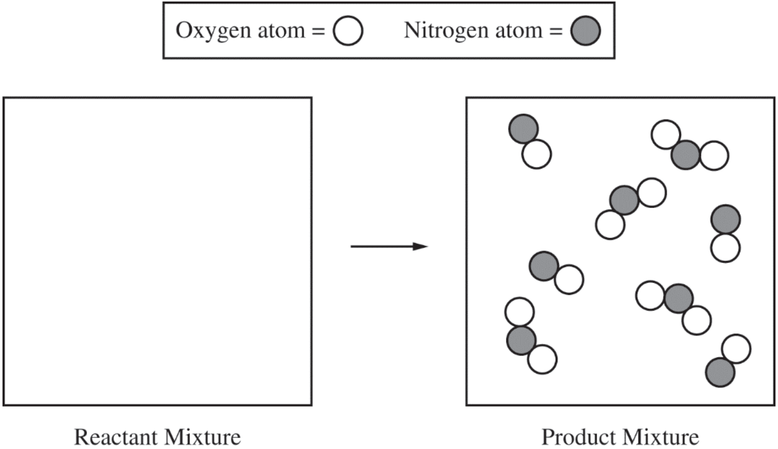
Question 2

[Key: Oxygen atom = open (white) circle; Nitrogen atom = filled (gray) circle.]
[Two boxes side by side connected by an arrow. Left box labeled "Reactant Mixture" is empty (for the student to draw in). Right box labeled "Product Mixture" shows a particle-level representation containing 6 NO molecules (each one open circle bonded to one filled circle) and 6 NO_2 molecules (each one filled circle bonded to two open circles), scattered randomly in the box.]
The student reads in a reference text that $NO(g)$ and $NO_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.

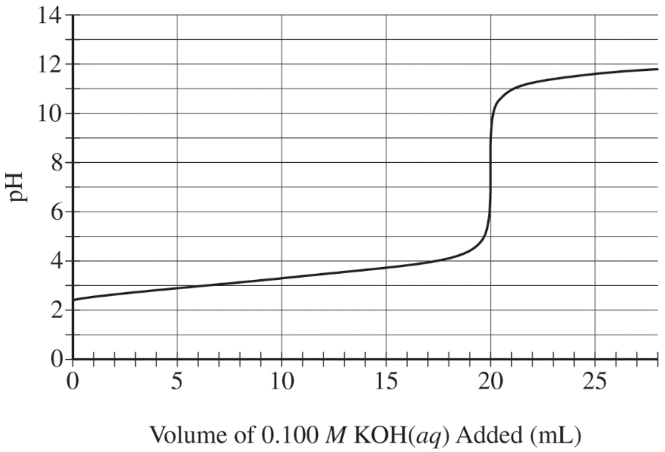
$$NO(g) + NO_2(g) \rightleftharpoons N_2O_3(g)$$

| ΔH°_{298} | ΔS°_{298} | ΔG°_{298} | |—|—|—| | -40.4 kJ/mol$_{rxn}$ | -138.5 J/(K $\cdot$ mol$_{rxn}$) | 0.87 kJ/mol$_{rxn}$ |

Question 2


Oxygen atom =
Nitrogen atom =
Reactant Mixture
Product Mixture

Question 2



Question 2

$$NO(g) + NO_2(g) \rightleftarrows N_2O_3(g)$$

ΔH°_{298}	ΔS°_{298}	ΔG°_{298}
-40.4 kJ/mol$_{rxn}$	-138.5 J/(K · mol$_{rxn}$)	0.87 kJ/mol$_{rxn}$

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(b)(i) The student begins with an equimolar mixture of $NO(g)$ and $NO_2(g)$ in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

Calculate the value of the equilibrium constant, K, for the reaction at 298 K.

(b)(ii) If both P_{NO} and P_{NO_2} in the vessel are initially 1.0 atm, will $P_{N_2O_3}$ at equilibrium be equal to 1.0 atm? Justify your answer.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(c) The student hypothesizes that increasing the temperature will increase the amount of $N_2O_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

$N_2O_3(g)$ reacts with water to form nitrous acid, $HNO_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

Question 2

$$N_2O_3(g) + H_2O(l) \rightarrow 2\,HNO_2(aq)$$

Question 2

2018 ▪ Q2

$$2\,NO(g) + O_2(g) \rightarrow 2\,NO_2(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(d)(i) The skeletal structure of the HNO_2 molecule is shown in the box below.
[Box showing the skeletal structure: H O N O, written left to right in a line.]
Complete the Lewis electron-dot diagram of the HNO_2 molecule in the box below, including any lone pairs of electrons.

(d)(ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO_2 molecule.

Question 2

To produce an aqueous solution of HNO_2, the student bubbles $N_2O_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $HNO_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $KOH(aq)$. The neutralization reaction is represented below.

$$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$$

The following titration curve shows the change in pH of the solution during the titration.
[Titration curve graph: Y-axis pH from 0 to 14 in increments of 2. X-axis "Volume of 0.100 M KOH(aq) Added (mL)" from 0 to 25+ in increments of 5. The curve starts around pH 2.3 at 0 mL, rises very gradually and slightly through a small buffer region

Question 2

to about pH 4 near 15-18 mL, then rises steeply (equivalence point) around 20 mL up to about pH 12, then levels off gradually toward pH 12-13 by 25 mL.]

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(e)(i) Use the titration curve and the information above to determine the initial concentration of the $HNO_2(aq)$ solution.

(e)(ii) Use the titration curve and the information above to estimate the value of pK_a for $HNO_2(aq)$.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(f) During the titration, after a volume of 15 mL of 0.100 M $KOH(aq)$ has been added, which species, $HNO_2(aq)$ or $NO_2^-(aq)$, is present at a higher concentration in the solution? Justify your answer.

Solution 2

(a)

Mark scheme

- The reactant mixture must contain 8 NO(g) molecules and 2 O2(g) molecules. As 2 NO(g) + O2(g) -> 2 NO2(g) proceeds (O2 limiting), 4 NO react with the 2 O2 to form 4 NO2, leaving 4 NO unreacted, giving the equimolar 4 NO : 4 NO2 product mixture shown. 1 point is earned for correctly representing the molecules of NO and O2 (8 NO + 2 O2, drawn as separate diatomic particles using the given atom key); 1 point is earned for correctly representing atom conservation between the reactant and product boxes (same total number of N atoms and O atoms in both boxes).

Solution 2

(b)(i)

Mark scheme

- DeltaG = -RT ln K, so K = e^(-DeltaG/RT) = e^[-870 J/mol / ((8.314 J/(mol K))(298 K))] = e^(-0.351) = 0.70. 1 point is earned for the correct calculation of K.

Solution 2

(b)(ii)

Mark scheme

- No, P(N2O3) will not equal 1.0 atm at equilibrium. P(N2O3) would only equal 1.0 atm if the reaction went to completion; the value of K (0.70, not much greater than 1) indicates that a substantial amount of reactants (NO and NO2) will remain at equilibrium, so P(N2O3) will be less than 1.0 atm. 1 point is earned for the correct choice ('no') and a valid justification based on the value of K.

Solution 2

(c)

Mark scheme

- Disagree. Because the reaction NO(g) + NO2(g) <=> N2O3(g) is exothermic (DeltaH_298 = -40.4 kJ/mol_rxn), increasing the temperature will favor the formation of the reactants (shift left), according to Le Chatelier's principle, so the amount of N2O3(g) will decrease, not increase. 1 point is earned for the correct choice (disagree) AND a correct justification.

Solution 2

(d)(i)

Mark scheme

- Completed Lewis structure of HNO2 (skeleton H-O-N-O): H is single-bonded to O; that O is single-bonded to N and carries 2 lone pairs; N is double-bonded to the terminal O and carries 1 lone pair; the terminal O carries 2 lone pairs. Formal charges are all zero and every atom (except H) has a complete octet. 1 point is earned for a valid diagram showing all lone pairs and correct bonding (H-O-N=O with 2 lone pairs on each O and 1 lone pair on N).

Solution 2

(d)(ii)

Mark scheme

- The nitrogen atom is sp2 hybridized (it is bonded to 2 O atoms and has 1 lone pair, i.e., 3 electron domains, giving trigonal planar / sp2 geometry). 1 point is earned for the correct answer, sp2.

Solution 2

(e)(i)

Mark scheme

- At the equivalence point (from the titration curve), 20. mL of 0.100 M KOH has been added: 20. mL x 0.100 mol KOH/1000 mL = 0.0020 mol KOH added, which equals 0.0020 mol HNO2 originally present (1:1 stoichiometry of HNO2 + OH- -> NO2- + H2O). Initial concentration = 0.0020 mol HNO2 / 0.100 L = 0.020 M HNO2. 1 point is earned for the correct calculation of the initial concentration.

Solution 2

(e)(ii)

Mark scheme

- pKa is approximately 3.4, read from the pH at the half-equivalence volume (10 mL) on the titration curve, where pH $=$ pKa. 1 point is earned for an acceptable estimate of pKa (values near 3.4 accepted).

Solution 2

(f)

Mark scheme

- NO2-(aq) is present at the higher concentration. The equivalence point is at 20 mL, so the half-equivalence point is at 10 mL; after 15 mL of KOH has been added, the titration is past the half-equivalence point, so more of the conjugate base (NO2-) than the acid (HNO2) is present. 1 point is earned for the correct choice AND a valid justification.

Question 4

2014 ▪ Q4

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$$

When heated, calcium carbonate decomposes according to the equation above. In a study of the decomposition of calcium carbonate, a student added a 50.0 g sample of powdered $CaCO_3(s)$ to a 1.00 L rigid container. The student sealed the container, pumped out all the gases, then heated the container in an oven at 1100 K. As the container was heated, the total pressure of the $CO_2(g)$ in the container was measured over time. The data are plotted in the graph below.
[Graph of Pressure (atm) vs. Time (min); x-axis Time (min) 0 to 20 (gridlines at 0, 5, 10, 15, 20), y-axis Pressure (atm) 0 to 1.25 (gridlines at 0, 0.25, 0.50, 0.75, 1.00, 1.25); curve starts at (0, 0), rises steeply and roughly linearly to about (5, 0.65),

Question 4

continues rising with decreasing slope through about (10, 0.95), levels off and becomes essentially flat at a pressure of about 1.0-1.05 atm from about $t = 12$ min to $t = 20$ min.]

The student repeated the experiment, but this time the student used a 100.0 g sample of powdered $CaCO_3(s)$. In this experiment, the final pressure in the container was 1.04 atm, which was the same final pressure as in the first experiment.

(a) Calculate the number of moles of $CO_2(g)$ present in the container after 20 minutes of heating.

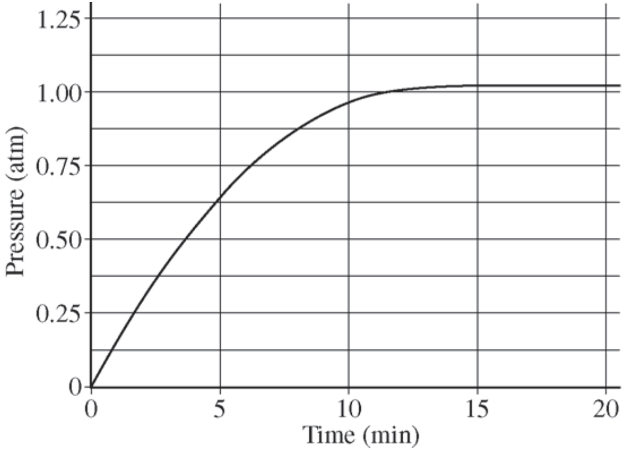
(b) The student claimed that the final pressure in the container in each experiment became constant because all of the $CaCO_3(s)$ had decomposed. Based on the data in the experiments, do you agree with this claim? Explain.

Question 4

(c) After 20 minutes some $CO_2(g)$ was injected into the container, initially raising the pressure to 1.5 atm. Would the final pressure inside the container be less than, greater than, or equal to 1.04 atm? Explain your reasoning.

(d) Are there sufficient data obtained in the experiments to determine the value of the equilibrium constant, K_p, for the decomposition of $CaCO_3(s)$ at 1100 K? Justify your answer.

Question 4



Solution 4

(a)

Mark scheme

- Using the ideal gas law:

$$n = \frac{PV}{RT} = \frac{(1.04\ \text{atm})(1.00\ \text{L})}{(0.0821\ \text{L}\cdot\text{atm/mol}\cdot\text{K})(1100\ \text{K})} = 0.0115\ \text{mol}\ \text{CO}_2.$$

Solution 4

(b)

Mark scheme

- Do not agree with the claim. In experiment 1, moles of CaCO3 = 50.0 g / 100.09 g/mol = 0.500 mol CaCO3; if the reaction had gone to completion, 0.500 mol of CO2 would have been produced, but only 0.0115 mol was produced (part a), so the claim is false. Alternatively: the two experiments (50.0 g and 100.0 g of CaCO3) both reached the same constant final pressure of 1.04 atm; since adding more reactant did not produce more product, not all of the CaCO3 could have reacted — an equilibrium condition was reached instead, with some solid CaCO3 remaining.

Solution 4

(c)

Mark scheme

- The final pressure would be equal to 1.04 atm. Equilibrium was reached in both experiments at this temperature, giving an equilibrium CO2 pressure of 1.04 atm. Raising the pressure to 1.5 atm shifts the reaction toward the reactant (Le Chatelier's principle), and CO2(g) is consumed until the pressure returns to the equilibrium value of 1.04 atm.

Solution 4

(d)

Mark scheme

- Yes. For this equilibrium, at a given temperature the equilibrium pressure of CO2 determines the equilibrium constant. Since the measured pressure of CO2 (1.04 atm) is the equilibrium pressure, $K_p = P_{CO_2} = 1.04$. (Alternate credit: if part (b) claimed all CaCO3 decomposed, the point can instead be earned by stating that the system never reached equilibrium in either experiment, so Kp cannot be calculated from the data.)